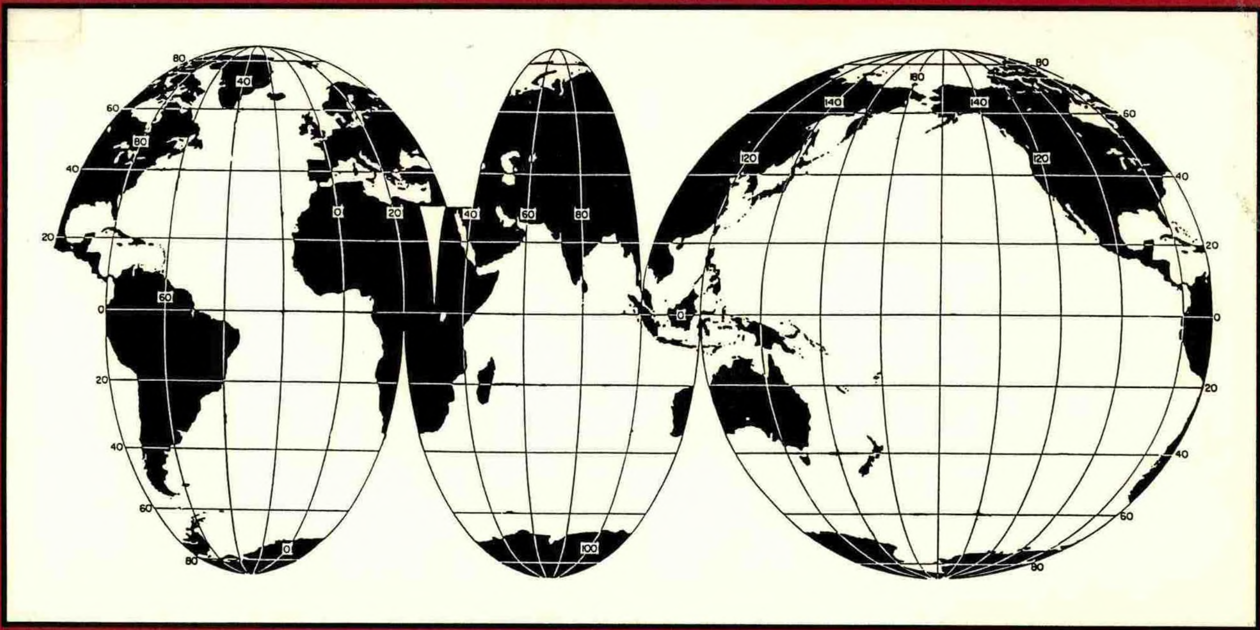
Global Ocean Observing Systems Workshop Report



September 10-12, 1990
Alexandria, Virginia

Sponsored by the
National Ocean Service
of the
National Oceanic and Atmospheric Administration
and the
Office of the Oceanographer of the U.S. Navy

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Executive Summary

Background

A workshop on the topic of Global Ocean Observing Systems (GOOS) was held in Alexandria, Virginia, September 10-12, 1990. Sixty-five scientists from universities, government laboratories and private industry in the United States together with representatives from Canada, Australia, and the U.K. met to consider key scientific issues relevant to the long-term observation of the ocean.

The workshop was held at the request of the National Oceanic and Atmospheric Administration and the U.S. Navy in recognition of the need for long-term ocean observations to support research and operational requirements. The workshop was aimed at finding scientific consensus on the near-term actions that should be taken by the U.S. to enhance the existing ocean observation system and to identify those promising new techniques that need development and support for future use in an operational system. Participants in the workshop were invited by a steering committee which recruited an interdisciplinary mix of physical, biological, and chemical oceanographers with interests in global and regional studies as well as specialized techniques.

The strategy for the implementation of such an operational ocean observing system begins with the enhancement of existing operational measurements and time series, the support of global-scale climate-related research programs, and the development of new observational technology. As these observational improvements are combined with modeling developments, we hope to be able to move towards an affordable operational system that would be a major element of a future global climate observing system. The workshop report is aimed at identifying the major issues of design and operation and the next steps that can be taken in the U.S. for such enhancement. It is hoped that the report can be used as a U.S. contribution to the international planning efforts for global ocean observing systems now underway.

The workshop was held in conjunction with meetings of two international scientific groups: the CCCO/JSC Ocean Observing System Development Panel (OOSDP) and the Ad Hoc Group on Ocean Observations of the Intergovernmental Oceanographic Commission's (IOC) Committee on Ocean Processes and Climate (OPC). The workshop used as part of its background the information that had been collected by the Ad Hoc Group on the needs of various large climate-related programs for long-term ocean observations.

The workshop was sponsored and supported by the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration (NOAA) and the Office of the Oceanographer of the U.S. Navy. Support was provided to Joint Oceanographic Institutions Incorporated for arranging the workshop through the Office of Naval Research Contract N00014-90-J-1636.

Workshop Findings

The findings of the workshop are divided into two parts: system design and operations management. The design category includes the necessary elements of the system and required technology. Operations include management and funding aspects.

System Design

1. *Ongoing Research Programs.* Ongoing climate and biogeochemical related research programs (for example, TOGA, WOCE, JGOFS, California Cooperative Oceanic Fisheries Investigation [CalCOFI]) will provide essential information for the design of a global ocean observing system.

2. *Ongoing Time Series.* Continuation and extension of ongoing physical and biogeochemical time series, such as the Bermuda Biological Station program and the CalCOFI program, are essential to provide data not otherwise available.

3. *Coastal Ocean.* The coastal ocean is sensitive to climate change and coastal populations will put one of the largest demands on the system for information. Therefore, ocean observation systems must include the coastal zone region and products needed for operational nowcasting and forecasting there.

4. *Polar Regions.* The polar regions are sensitive indicators of global change, and include many climate-related feedbacks. Therefore, high latitude observations must be included in a global ocean observing system.

5. *Global Fields.* Global fields of measurements must routinely be collected and distributed to operational and research users including *in situ* and satellite-based measurements.

6. *Flexibility.* The system design must be capable of evolution, to permit changes in technology and new scientific understanding to be incorporated at a later time without massive restructuring.

7. *Existing Technology.* Existing *in situ* and satellite technology such as moorings, drifters, floats, altimeters, scatterometers, and ocean color measurements can provide much of the data needed, and should be fully exploited.

8. *Existing Platforms.* The Volunteer Observing Ships (VOS) program has proven invaluable in providing platforms for operational measurements. It could be extended to more vessels and measurements of additional variables. Improved instruments are desirable. A VOS program with portable manned laboratories should be explored.

9. *New Technology.* New technology will be required to permit full coverage in time and space and allow biological and chemical parameters to be sampled on the same space and time scales as physical variables. This technology will include, for example, autonomous vehicles such as floats, new acoustic averaging techniques, and new technology for biological measurements such as bio-optics, bioacoustics and satellite techniques. New techniques for measuring Dissolved Organic Carbon (DOC) and Dissolved Inorganic Carbon (DIC) are needed.

10. *Technology for Polar Regions.* Development of more sophisticated moored and floating sensors as well as satellite systems such as synthetic aperture radar is needed to aid in collection of routine year-round data from polar oceans.

11. *Role of Models.* One of the ultimate goals of an observational system is to provide data for assessment and prediction models. Data assimilated by numerical models can serve to extend limited observations through dynamical interpolation and extrapolation. Numerical models can also help design through observing system simulation experiments.

Operations Management

1. *Coordination.* Close coordination is needed among the U.S. agencies whose programs are closely linked to an operational ocean observing system. Formal organization is needed to plan for oversight, funding and operation.

2. *Management.* The roles and interaction among federal government and state agencies, the academic community, and private industry must be developed and delineated.

3. *Data Management.* Full attention must be given to the end-to-end data system including multiple communications paths, analysis, quality control, archival, and distribution of data. Adequate funding must be available to provide data to all users.

4. *Quality Control.* Quality control of data from measurement to archive is essential and will require careful attention. This is especially critical for measurements which are derived from a mix of technologies, such as sea surface temperature.

5. *Funding.* The success of the program is closely linked to long-term operation, hence stable long-term funding is required.

6. *Cost Containment.* In order to minimize costs, products must be optimized, and interfaces with ongoing efforts must be carefully planned.

Major Recommendations

The workshop recommendations are presented below in summary form. Detailed and specific recommendations are presented on pages 21-23 of the report.

1. *Build System from Existing Operational and Research Programs.* The initial program must build on existing regional and global climate-related research programs and existing long time series programs. This ensures adequate input of scientific information and the continuation of time series vital to the development of climate-related data bases.

2. *Technology Development.* An early start on the development of more capable and cost-effective *in situ* platforms, sensors, and telemetry systems is essential. Maximum use of satellite systems is essential for global data sets. A long-term technology development program must be maintained, to include such examples as autonomous vehicles, acoustic techniques, biogeochemical instrumentation, and new satellite techniques. The development of low-cost instruments and expendables to encourage participation by developing nations and interactions with changing computer and communications policy is an important aspect of this activity. Improvements are needed in measuring components of the ocean carbon cycle.

3. *Establish an Interagency Coordinating Mechanism.* The initial steps in Federal Agency organization must be taken to set down plans for oversight, funding, and operational planning. A lead agency must be identified, and would logically be NOAA, with Navy, NSF and NASA also playing key roles. EPA, DOE, USGS, MMS and USCG should also be involved.

4. *Develop a Plan for a U.S. Contribution to an International Global Ocean Observation System.* The initial plan can be a combination of current efforts now supported by federal and state agencies, guided by identified future needs. NOAA should work with other agencies including the State Department and the academic community to develop the U.S. plan.

5. *Interact with the National and International Scientific Community.* A truly global ocean observation system will be an international effort. The planning effort must interface with international planning by the OOSDP and the IOC. Agreements on issues from funding to measurement and access protocols will be needed.

1. *Introduction*

During the past decade, as new measurement techniques and computer technology have opened the way to global ocean observation and modeling, it has become increasingly obvious that a global ocean observing system will be required to understand the ocean, its dynamics and its role in weather, climate, biogeochemical cycles, and marine ecosystems. Long-term systematic measurements of the ocean are widely recognized as an essential element of global change research.

But there is significant documentation that current ocean observation elements are inadequate, with few exceptions, for even the limited needs of ongoing research programs. The space and time distribution of available *in situ* data is not systematic and often biased by the seasonal distribution of sampling platforms. Entire areas of the world such as the south Pacific Ocean and Arctic Ocean are undersampled. Only a few satellite sensors are operationally available and others, critical to ocean observations, are missing. Current operational data management systems have problems with both communications and quality control. Fully operational coupled global atmosphere-ocean models which can provide routine products or boundary conditions for regional ocean models do not yet exist.

The general recognition, on an international basis, of the importance of understanding global environmental change and of the ocean as a key component of the Earth system provides a new context for the development of an operational ocean observing system. Such an ocean system would be part of a proposed global climate observing system. The U.S. interagency Committee on Earth and Environmental Science (CEES) has identified the need for documentation of Earth system change with observational programs and data management systems as the first of their integrating priorities. The ocean system would provide the necessary documentation of the ocean processes on the proper time and space scales.

To address this need, the international scientific community has begun a long-term planning effort. The Scientific Committee for Ocean Research (SCOR)/IOC Committee on Climatic Changes and the Ocean (CCCO) and the World Meteorological Organization (WMO)/International Scientific Council of Unions (ISCU) Joint Scientific Committee for the World Climate Research Program (WCRP) are jointly sponsoring an Ocean Observing Systems Development Panel (OOSDP) that is starting the process towards design of a global system. The OOSDP is being assisted in this task by an Ad Hoc Group on Ocean Observing Systems of the IOC. Representatives of the U.S. ocean science community are participating in these formative efforts. In all of this planning it is recognized that strong national efforts by the operational agencies of participating states will be required to support the international planning. The workshop reported on here was one of the first steps in the U.S. to start this process towards a strong national activity.

A. User Requirements

An operational ocean observing system would serve two sets of requirements. The first set comes from nowcasts and forecasts in support of such civil uses as fishing, shipping, offshore oil and gas recovery, recreation, environmental protection, and public safety. Other operational users include the Navy who routinely must forecast ocean conditions in support of operational missions. Near-real-time data is required. The second set supports the user who needs long-term data bases on which to perform climate and ecosystems research and prediction. Climatology is also used as input to design of marine structures and shoreline construction. An operational ocean observation system will provide baseline data for climate and biogeochemical analysis; data for initialization and update of predictive models; and data useful for ongoing climate research programs and model development.

In the U.S., such a system would be of direct benefit to the programs of NOAA, the National Science Foundation (NSF), the U.S. Navy, the Environmental Protection Agency (EPA), the Department of Energy (DOE), the United States Geological Survey (USGS), the United States Coast Guard (USCG), the Minerals Management Service (MMS) and the National Aeronautics and Space Administration (NASA). The comprehensive data sets would lead to significant progress in understanding ocean physics, dynamics, chemistry and biology. Significant improvements in the assessment of the state of the ocean and in real-time forecasting for weather, climate, fisheries, ship routing, environmental protection, and national security requirements would be the hoped-for result. The information needs of state governments and regional coordinating bodies must also be included.

B. Support of Research

We do not yet adequately understand ocean variability well enough to define the spatial and temporal optimal sampling strategy to collect data for climate prediction (interannual to decadal and century time scales). Given existing data, it is not yet possible to discern the possibly small anthropogenic long term climate change signal from the background of "natural" climate variability with statistical certainty. Long time series will be required to detect patterns of change.

For that reason the oceanographic community is faced with large challenges of both making observations and archival of data in a manner such that the data remain scientifically useful some years to decades hence. Inherent in such concerns are the specifics of making the measurement, any subsampling or averaging scheme employed, recording or standardization of methods, archival of data (at what level, raw or partially processed) and calibration of instruments and the flagging of problems.

Thus the development of a global ocean observation system must proceed in close interaction with ongoing international research efforts such as the Tropical Ocean and Global Atmosphere (TOGA) program, the World Ocean Circulation Experiment (WOCE) and the Joint Global Ocean Flux Study (JGOFS). Along with the U.S. CalCOFI program, each of these programs brings some aspect of experience to the design and conduct of large scale long-duration ocean observations. It should be noted that neither WOCE nor TOGA has any long-term duration biogeochemical ocean observations, while JGOFS time series are at present limited to two stations that have operated for 2 years. The forty year time series measurements of the CalCOFI program is one of the best ecosystem samples available at present, though it is limited to a few components sampled on fairly coarse scales in the Pacific Ocean. The Continuous Plankton Recorder (CPR) has provided an Atlantic time series.

A global observational system would aid all these large scale programs by providing large scale long-term data sets for use in coupled ocean-atmosphere modeling. Two new large-scale efforts, the Global Ocean Ecosystems Dynamics (GLOBEC) program and the Arctic System Science program (ARCSS), would also benefit from a global ocean observations program.

C. Support of Operations

The typical operational user is interested in some raw oceanographic data (e.g.,wind speed, water temperature, wave height) but usually desires information processed as a nowcast or short term forecast. Other users need not only forecast products but also value-added interpretation that is related to the operation being performed, for example positioning of an oil rig or the prediction of sonar system performance. The latter may call for information on acoustic conditions at a number of different frequencies on long space scales.

Meeting operational uses is an inherently challenging part of the ocean observation system. Some users need to receive, quality control, process and add value to observations in near- real-time to meet their customers needs, while others (such as the research community) do not require such time constraints. All these needs result in large impacts on sampling strategies, data communication, and data processing, archival and distribution to customers in the operational and research communities. Some customers, such as the Navy and private industry, appear at both ends of the timeline, on the one hand needing highly sophisticated real-time forecasts to support operations, while on the other hand needing accurate long term climatologies for the engineering design of future systems that will operate worldwide and last for decades.

The need for close interaction between research and operations is seen in the record of "ocean surface temperature" data where we have measurements taken with a variety of devices and at different locations including buckets, ship engine water intakes, buoys, and satellites. These very real concerns cause the research community to be somewhat cautious about ocean observation systems which will remove the academic investigator totally from the long-term monitoring activity leaving the measurement and calibration activity in the hands of disinterested parties. To be successful, an ocean observation system must not only "make measurements and record some value for archival"; the measurements must be scientifically credible and quality controlled downstream. This calls for a special long-term blend of expertise between the academic and governmental sectors.

D. Support for Policy Decisions

Today, it is clear that the output of global measurement programs can affect public policy on many levels. While this level of interest has the positive aspect of possible support for much needed systematic observations of the ocean, it brings with it the chance for the misinterpretation of results by policy makers. The science community must take great care that results are not promised that cannot be delivered and that experimental results are not misinterpreted. We also must be candid about the nature and costs of long time series observations. The efforts to establish such a system will be large and the costs at least comparable to what is being spent on ocean research today.

2. *Coverage and Elements of an Ocean Observing System*

A. Air-Sea Interface/Upper Layer

Elements of a functioning global ocean observing system must be capable of making measurements in the upper layers of the ocean, that portion of the ocean generally above the permanent thermocline, and at the air-sea interface. The upper layers are the regions of coupling to the atmosphere and the initial sites of the transfers of heat and momentum to the ocean and vice versa. Most ocean models and coupled air-sea models require data or derived parameters from this region. This region is also the site where interactive processes form most of the interior water masses of the deep ocean.

Historically, some of our longest time series of ocean observations come from the surface. This is the primary region where satellite borne sensors can derive measurements. Since the upper ocean is the site of photosynthetically-driven primary production in the ocean and the location of significant chemical interactions with the atmosphere, the region is also critical for an understanding of biogeochemical cycles and the routes of carbon in the ocean system. A detailed discussion of the need for measurement of carbon flux in the ocean is found in the Biogeochemical Working Group Report in the Technical Appendix.

B. Intermediate and Deep Ocean

Circulation and mixing processes in the intermediate and deep ocean distribute heat, nutrients, and other properties which are essential to most life in the ocean below the permanent thermocline. Monitoring of this circulation may be one of the most sensitive measures of ocean response to altered forcing from global warming. However, only a few long-term systematic observations of the deep and intermediate circulation exist. For the deep ocean, location of strategic sites, such as major eastern and western boundary currents, areas of water mass formation, or the Antarctic Circumpolar Current may be candidate locations for long time series observation. The Working Group Report on the Intermediate and Deep Ocean in the Technical Appendix provides further information.

C. Special Regions of the Global Ocean

There are areas of the global ocean which must be included in a viable ocean monitoring system either due to special physical and biological significance or due to their direct interactions with human populations. The Arctic region with a strongly coupled ice, ocean and atmosphere system is sensitive to global warming. Feedbacks from the Arctic region to the global system in terms of circulation, output of less dense water to the Atlantic and albedo changes with changing ice cover potentially link with the formation of deep ocean waters and with initial or update conditions for global models. The coastal regions of the world ocean are the sites of most human interaction with the ocean and the regions of high primary productivity and large populations of fish and invertebrates linked in complex food webs often harvested by man. As discussed above, the coastal ocean is a region where forecasting of conditions and properties has a high impact on human life and industry. Additional detail on these special regions can be found in the papers prepared for the Workshop found in the Technical Appendix.

D. Coupling of Biological, Chemical and Physical Fields

Measurements of biological and chemical fields are essential in tracing the flow of carbon through the ocean environment and to make use of the integrating and often highly sensitive features of biological systems as indicators of ocean change. For example, the availability of global ocean color data from satellite imagery has provided a first global picture of pigment bearing plankton standing stock. Such data, when coupled with *in situ* physical, chemical, and biological measurements, will be a powerful tool in understanding the patterns of variability of a primary driver of life in the world ocean and potentially of the pathways of carbon in the biological system.

E. Global Coverage

One of the most important elements of the global ocean observing system will be to provide data for improving models of the ocean and the coupled ocean/atmosphere system. Data will be used to initialize and verify developmental models and later to initialize and update operational forecast models. To reach such goals, data must be available on a global basis. The frequency of observations and time sensitivity for use in operational models will vary with the frequency of the forecast product. The needs of operational modeling for conditions in the coastal zones and for national security concerns also determine the frequency of observations and data transmission and processing. International participation will be essential to achieve global coverage.

Elements of a Global Ocean Observing System

A. *In Situ* Observations

In situ measurements have long been the stock in trade of the oceanographic community and will be a necessary feature of a global ocean observing system. Chemical and biological process studies will rely on *in situ* sampling to obtain fluid volumes and marine organisms for laboratory analysis. In the past, *in situ* sampling usually envisioned a sample taken from shipboard. Today, technology is permitting the use of instruments like drifting buoys, current meters, subsurface floats, smart sensors on moorings, bottom mounted arrays, acoustic beacons, and floating sediment traps to take measurements in the ocean either directly or at some distance from the device. The data is either stored for later recovery or communicated to shore by various means including satellite telecommunications.

Such *in situ* sensors have been steadily growing in numbers and compatibility over the past two decades. Increasing sophistication and automation both in measurement techniques and especially in communication technology continue to open new opportunities for largely unattended *in situ* sampling of physical, chemical, and biological parameters. *In situ* measurements will be required to provide model input, verify remotely sensed data and to validate model output. *In situ* observation is critical in algorithm development.

B. Satellite Based Measurements

Satellites, both operational systems and those flying sensors for research, should be a major part of any global ocean observation system. The sheer size of the world ocean means that satellite systems are necessary to provide near synoptic samples of the entire ocean on a frequency needed for input to operational forecast models. No presently affordable distribution of ships and sensors can replace the coverage potential of spaceborne sensors.

A number of existing and past sensors including the AVHRR on the NOAA polar orbiters, the SSM/I, Visible and IR channels on the Defense Meteorological Satellite Program (DMSP), CZCS and SMMR on the NIMBUS satellite, the altimeter on the GEOSAT satellite, and the sensors on LANDSAT have all contributed to the present understanding of the ocean, cloud and sea ice environment. In addition to spaceborne observational systems, extensive use has been made of communication and navigation satellites in the conduct of ocean research.

In 1991, scatterometer, altimeter and synthetic aperture radar sensors will be flown from the European Space Agency ERS-1 Satellite. This will be followed by the joint U.S./ France altimeter mission, TOPEX/Poseidon, scheduled for launch late in FY92. Plans are also underway for launch of a U.S. ocean color satellite in the Mid 1990's. The U.S. plans to launch a scatterometer sensor on the Japanese ADEOS mission also scheduled for flight in the mid 1990's.

The favorable oceanographic results of the GEOSAT extended mission for oceanography has prompted the U.S. Navy to plan for a follow-on altimeter mission. A synthetic aperture radar satellite is also in planning by Canada, as are discussions of a follow-on ERS-2 mission by the European space community. NOAA plans to continue polar-orbiting operational environmental satellites throughout the decade. These sensors will provide opportunities to measure ocean currents, near surface wind speed and direction, wave height, ice edge, ice extent and type, cloud climatology, sea surface temperature and ocean color.

Late in the decade, NASA and its international partners are planning an ambitious Earth Observing System (EOS) program which would launch a series of polar orbiting platforms of varying sizes with a variety of sensors. The final instrument selection for the initial set of platforms has not yet been announced. The planned missions could provide a number of earth-oriented sensors on a number of satellites on orbit for some fifteen years. While EOS is a research program, its sensor suite is expected to contain some of the sensors needed for the operational satellite portion of a Global Ocean Observing System.

C. Models

The use of models for tasks from the design of experiments to the forecasting of geophysical systems is a well established aspect of science. A functional ocean observing system should provide data at the density and frequency to drive the science of ocean and coupled air-ocean model development. The ultimate goal is the development of forecast models that may be initialized and regularly updated by data from the global ocean observing system.

The continuing development of computational power is rapidly providing the technology needed for the development of coupled ocean-atmosphere models with a high degree of skill. Several classes of model systems may be needed to match with the desired output ranging from short-term operational forecasting to the running of climate change models with 100 year projections. As noted earlier, *in situ* measurement programs will be needed to validate developmental model outputs.

D. Information Systems

Perhaps one of the most difficult and often either overlooked or under funded aspects of a large-scale and long-term observational program is the management and analysis of data. If quality data are not available on a regular basis to researchers and analysts a decade after the start of a global ocean observing system, the effort will be a failure. The data management effort must receive international attention and agreement if the resources of all nations are to be brought to bear on a global ocean observation system. Data links from operational sensors to national centers must be identified, protocols for archival, communications and networks must be planned and agreed to, and resources must be made available to support this effort. A close connection must be made to NOAA data centers and to NASA's EOS Data and Information System.

Fortunately the WMO established protocols and communications links developed for worldwide meteorological data which can serve as a guide. Additionally much experience has been gained through incorporation of data management elements into such programs as TOGA, WOCE and JGOFS. Incorporation of biogeochemical information into such a system may also draw on the long experience of the CalCOFI program.

E. Evolving Design

The ocean observation system which is instituted in the near-term must be capable of evolutionary change. It is reasonable to predict that our understanding of the ocean system will evolve, which may lead to a shift in goals and design for the observational network over time. It is generally believed that the density of measurements needed to determine a system is larger in the research mode than in the monitoring mode. To this we must add potential changes in technology which would permit system improvements and perhaps cuts in cost. This foresight would dictate that the system be modular and that the observations be handled and stored in a manner relatively independent of current technology.

F. Coordination and Oversight

A mechanism for coordination and oversight must evolve for a multifaceted effort such as the global ocean observation system. On the national level we are dealing with the resources of several federal agencies, the academic oceanographic community and the interests of states and locales as expressed by their elected officials.

Long term funding for the effort must be arranged and, if residing in more than one federal agency, joint management will be needed. As mentioned previously, the scientific community needs to be involved in the management, data collection, and the quality control aspects of data collection and processing. On the international scene, the WMO may be a model system to be emulated, with tuning, for the special needs of the ocean community.

3. *Existing Systems and Programs*

Workshop participants who prepared papers prior to the workshop (see Appendix A, Part II) provided a brief discussion of existing systems which might be applied to a global ocean observing system, suggested required new systems and discussed potential impacts of new technologies on the development of future capabilities.

A. Air-Sea Interface

The air-sea interface and the ocean above the permanent thermocline has been perhaps the most intensively sampled region of the ocean. From the Secchi disc, intake temperature, bucket temperature, mechanical BT and Nansen bottle with reversing thermometers to the CTD and XBT, the upper ocean has been sampled for physical, biochemical and optical properties from largely shipboard platforms.

To this must be added generations of net systems and large water collection devices for biology and chemical sampling. Automation, electronic and communication advancements as well as the posing of a new generation of scientific questions have led to more sophisticated devices for physical, optical and biogeochemical sampling too numerous to name. The new systems employ conventional ship deployment, expendable technology, freely cycling instruments and a number of moored and drifting platform technologies.

The trend has been toward higher data rates, more continuous profiles, digital data streams and unattended sampling with communication of data either to a platform or ashore via satellite link or onboard storage of data for later recall and readout. Above the surface a number of systems from buoys, towers, and vessels have been constructed to measure near- surface ocean and atmospheric variables. Added to this must be the active and passive remote sensing devices flown from aircraft and earth orbiting satellites.

The majority of the most sophisticated devices for upper ocean sampling have been fielded by academic investigators either working on individual projects or in concert with multiple investigators on larger but not usually long-term experiments. Several long-term multi-investigator programs have emerged perhaps the most notable being the TOGA and CalCOFI programs with highly defined, multi-year multi-investigator research efforts.

Since these programs are driven largely as research efforts, a broad spectrum of measurement systems are employed some of which are uniquely designed for specific experiments. A large upper ocean data collection effort from tide gauges, drifting and moored buoy systems, vessels of opportunity, research vessels and from Navy platforms has been ongoing for many years and forms a significant part of the data stream used to update ocean modeling efforts at operational forecasting centers. Data from polar orbiting satellites in low earth orbit are also used for routine forecasting of ocean parameters.

In the Arctic, a long duration program of drifting buoys has collected both atmospheric and oceanic data. This system has made use of both satellite tracking and communication technology. The use of satellite tracked drifting buoy technology is coming into wide use. Ocean station ships (now almost gone) and the generation of large moored ocean buoys have also contributed long time series records of upper ocean and atmospheric conditions.

Given all the programs discussed above, there are still major gaps in the distribution of upper ocean samples in space and time. The Southern Ocean, especially the South Pacific, is largely undersampled on a routine basis. In the Northern Hemisphere, sampling tends to fall along the major shipping lanes and is shifted by season. High latitudes, both North and South, are undersampled in winter months. Some data are simply lost in the present communication system while a significant fraction does not reach forecast centers in time to be quality controlled and used in the appropriate forecast run. Satellite measurements of sea surface temperature and sea ice are masked by the presence of clouds. This produces gaps in daily data sets.

B. Intermediate and Deep Ocean

This region of the ocean has been largely sampled by instruments deployed from oceanographic research vessels. The majority of samples are in conjunction with academic research efforts or with Navy programs usually linked to investigation of ocean acoustic properties. Few long-term systematic observations of the intermediate and deep ocean exist. The South Pacific is a good example of an area poorly covered. While deep and intermediate water masses were characterized based on salinity and temperature relationships some time ago, only now is a zero order description of the intermediate and deep circulation and its variability emerging. Because the deep ocean is insulated from atmospheric exchange, radioisotopic measurements of "age" have also been informative.

Early descriptions of the intermediate and deep ocean were largely derived from temperature and salinity relationships derived from deep sampling with Nansen bottles. The time consuming hydrocasts of the pre 1970's were made easier with the advent of the CTD. Reliable deep current meter arrays also allowed longer term sampling of intermediate and deep ocean currents. The use of SOFAR floats and acoustic techniques have increased the ability to sample the fields of mid and deep ocean velocity. Profiling instruments, long-term moorings of sensors and the use of ocean bottom cables all are increasing our understanding of the mid and deep velocity fields.

The WOCE Hydrographic Program should do much to add to our understanding of the deep ocean. The use of satellite altimeters such as in the TOPEX/Poseidon mission, especially if in conjunction with *in situ* measurements from the WOCE program, will provide data on ocean circulation in all major temperate and tropical ocean areas.

C. Biogeochemical Sampling

Although both the biology and chemistry of the open ocean have been studied intensively ever since the Challenger Expedition in 1872, there have been relatively few attempts to describe the large scale distribution of biogeochemical properties or the pattern of natural boundaries where state changes occur. A better knowledge of these patterns will be necessary to understand regional variations in the carbon cycle and the effects of changing climate. The Geochemical Ocean Sections Study (GEOSECS) was an attempt to describe the large scale distribution of chemical properties, and was quite successful, but its program did not include many euphotic zone measurements and large segments of the carbon cycle were not studied. Attempts have also been made to construct composite maps of biological properties (such as biomass) on very large, global scales, and these are consistent with both large-scale geochemical pattern and physical circulation systems. But both the geochemical and biological schemes are based on relatively few measurements and, since they are composites, made up of data taken months and years apart. They suffer from the weakness of all such composites (including those from satellites) that, if parts of the system(s) are out of phase in time, the spatial composite pattern is bound to be wrong to some unknown degree. Further, even the biological studies did not include important components of the carbon cycle or the methods used have been called into question by subsequent work. So at the present time there are large uncertainties in our knowledge of the circumstances under which the oceans take up CO_2 from the atmosphere or release it to the atmosphere. The spatial scale and magnitude of these processes cannot be quantified nor can temporal change be recognized.

There have been even fewer systematic studies of how biogeochemical entities change with time and most (but not all) of these studies are limited to short or very short time periods such as weeks or months, and even seasonal studies are rare away from coastal marine stations. Further, most of these represent only small, often single, locales. However, there are several very long time series (>40 yrs.) where space averaging was done. One of these is in the Atlantic, called the Continuous Plankton Recorder (CPR) survey, and the other in the Pacific is CalCOFI. Both of these have shown that biological variations at mid- and low latitudes have a "red" spectrum, that is, the largest amplitude and therefore the most important ecological changes in the ocean are the interannual ones. They also show these are of large-scale. This is very strong evidence that important variations in the dynamics, especially that of the carbon cycle, are likely to be interannual as well. In both cases these large magnitude, low frequency changes were clearly correlated with climatic events and a substantial amount of null hypothesis testing was done. This led to a better understanding of the mechanism(s) leading to the environmental changes.

Although these time series studies are very informative, they covered only fractions of the global oceans and cannot now be taken to be representative of larger regions. Further, rather few geochemical properties were measured so the database for time-series studies of chemical change is limited.

Most biological work in the ocean is devoted to the details of small scale interactions on the flux of materials between nutrients, plants, grazers or degraders. Seldom are all four components studied at once although they interact strongly. Of necessity these studies are small scale in both time and space and are often not based on *in situ* observation but rather laboratory manipulation. There are serious problems in extrapolating such information upward and outward to include large areas and long time periods. These problems have to do with the inherent difficulties in duplicating oceanic conditions and climatic variability in experimental situations, the fact that interacting systems are complex and are almost always out of steady state when we measure them, and that our pre-conceived ideas of which components are the most important to manipulate experimentally may be wrong. Large-scale, repeated *in situ* measurements of variations in time and space are essential to validate even our basic concepts of biogeochemical cycling and to interpret the results of experimentation designed to reveal mechanistic detail. Further such time-series can keep us informed of the state of the system as compared to some earlier time or the mean state, and can do this independently of predictive models. Such time-series data are really the only way that models of complex systems, such as the carbon cycle, that are affected by physical, biological <u>and</u> anthropogenic forces can be validated. This is the only way to specify the nature of "change", its direction, amplitude and rate.

4. *Required New Systems and Technology*

For upper ocean and air sea interaction most of the current technology is applicable. Development of more sophisticated drifting and moored buoy systems which collect data on a routine basis and transmit data to shore via communications satellites would be a desirable adjunct to current capabilities. Launch of operational satellite altimeter and scatterometer sensors in conjunction with the operational temperature sensors now on the Polar-orbiting environmental satellites would provide powerful tools for upper ocean research.

Addition of an operational ocean color satellite would provide a new dimension to biological oceanography. Provisions for routine, all-season sampling in areas such as the South Pacific and Arctic (and adjacent high latitude regions) would provide an improved network of *in situ* data for use in models and for the validation of satellite data.

For the intermediate and deep ocean, new systems or system improvements are needed. Repeated sections need to be made across major gyres to establish large-scale decadal changes. An operational satellite altimeter would add information on ocean eddies and general basin-wide circulation. More use of cable systems to measure strong currents and develop statistics on their variability over long periods would also be of use. More sophisticated sensors on long-term deep moorings would also be of assistance in development of time series.

Use of acoustic tomography or long range acoustic sampling (such as that recently tried in the Heard Island Experiment) may provide remote tools for sampling the deep ocean over long paths in a manner sensitive to changes in average ocean conditions.

Biogeochemical sampling efforts would profit from increased emphasis on the ability to make measurements on the same time and space scales as the physical oceanographic measurements. Additionally, it would be of significant improvement to be able to make such measurements in a digital nature, which is more readily adaptable to rapid processing and ease of communication and archival. The continued development of bio-acoustic, chemical, and bio-optical sensors capable of functioning for long periods on a mooring and reporting data via a satellite link would be most beneficial for monitoring studies. There is a strong need to be able to make better measurements of the components of the ocean carbon cycle especially DOC and DIC.

There appears to be significant benefit across the disciplines in the development of autonomous sensors that can either function on moored, drifting or cycling systems. This would certainly be of benefit to both deep ocean and biogeochemical considerations. A significant capability for studies of the energy budget, and to establishing modeling parameters would come from using unattended systems to measure incoming irradiance. Current techniques require frequent manual cleaning. Accurate sensors capable of long-term use near the sea surface (on a drifting buoy for example) or at high latitudes would be beneficial. The development of sensors that can measure the carbon cycle, to measure dissolved inorganic and organic carbon and nutrients are essential.

Development of low cost and small size satellites for altimetry, scatterometry and ocean color could hasten the time when these sensors are truly operational with backups either on orbit or quickly available for launch to permit long uninterrupted time series. Autonomous vehicles capable of long ocean observing missions could revolutionize the field of long-term measurements.

The Volunteer Observing Ships is a resource that is vastly underutilized, and needs more serious consideration. Presently, XBTs are commonly used on VOS because other expendable options are limited. Just as mechanical BTs have been replaced by expendables, electronic CTDs could now be used the same way - free-fall lowered from a ship underway and winched back in. Such data could then be transferred optically to a shipboard computer. Similarly, bottles could be automatically lowered and hauled onboard to get water samples from various depths of the upper ocean. This might require a small laboratory or laboratory van onboard the VOS. For the future, we should think of VOS as moving laboratories that would routinely revisit a number of sites along the vessel's route. Oceanographers would no longer be restricted to physics (XBTs) but could conduct chemical and biological studies as well. Accoustic Doppler Current Profilers (ADCPs) could provide valuable continuous information on biomass and upper ocean circulation.

VOS's can also pick up data from underwater instrumentation while they are underway. A the ship passes a current meter mooring or an inverted echo sounder, etc., it can send down a command to telemeter all data collected for the last several weeks. These data could be stored on the ship or relayed by satellite to the appropriate user. Acoustic telemetry technology is reaching a high level of capability and modularity for routine use.

Effective use of VOS requires the development of instrumentation optimized for their use rather than for use on research vessels. Examples include the electronic profilers and water samplers mentioned above, deep acoustically telemetering XBTs, the ADCP, towed electromagnetic systems, downward looking ocean color scanners, fluorometers, and measurement of acoustic backscatter at various frequencies to resolve biomass as a function of size class. VOS could help meet many of the needs of a climate change program.

International participation in a global ocean observing system might be helped by increasing the number of parameters that can be measured by simple expendables and by decreasing the cost and size of the expendables.

5. *Coordinating and Management Mechanisms*

A. National Coordination

In the U.S. there are several federal agencies with interest in global long-term operational ocean observations due to their statutory responsibilities and the scope of their normal programs. The two primary agencies are: (1) NOAA, due to its civil responsibilities for environmental data acquisition, management, and forecasting and its management of polar and geostationary operational environmental satellites, large experimental and operational numerical modeling centers and environmental data archives; and (2) Navy, for its national security responsibilities for ocean forecasting, use of ocean satellite data and interest in data bases, data collection and ocean models. The U.S. Coast Guard will be an interested party due to its statutory missions including work in high latitude regions and support of research.

NSF will also play a key part in this overall effort due to its large investment in ocean research programs such as TOGA, WOCE,and JGOFS, atmospheric research programs and commitment to the development of large scale geophysical modeling capabilities at academic institutions and centers like the National Center for Atmospheric Research (NCAR). Both the DOE and the EPA will be interested in the global ocean observing system data and model output for use in their programs. USGS and MMS will also have an interest because of their role in coastal areas. NASA, with its role in satellite R & D and development of EOS family of platforms and sensors, will have key interest in an ocean observing system for algorithm development and validation of ocean-related sensors. State governments and regional bodies may play a strong role in the use of data and as a potential source of support. The CalCOFI program is an excellent example of state participation in a long-term effort.

Other agencies/departments with interest in this program will include the Department of State for the obvious international aspects of such a global undertaking and the U.S. Air Force since it also runs a truly operational series of polar orbiting meteorological satellites (DMSP) which carry ocean-related sensors. The Air Force also conducts large-scale geophysical modeling and weather forecasting. NOAA, the Navy and the Air Force are even now participating in a "Shared METSAT" Program where they cooperate in processing operational geophysical satellite data with interlocking data networks.

It appears that a strong management body will be required to deal with this spectrum of interagency interest and logical funding responsibilities. This will be of critical importance if one expects the global ocean observing system to remain funded and function permanently. It would also seem reasonable that a lead agency should be named to ensure coordination of this program. NOAA would be the proper lead agency for such an undertaking.

B. International Cooperation

There is strong international interest in the development of a global ocean observation system. As discussed in the introduction, international scientific and governmental organizations are actively working to outline a global ocean observing system. It is evident that multinational funding (at a governmental level) of an ocean observing network will be required. However, it is too early to speculate on what international framework will be established to coordinate and manage this cooperative effort beyond the planning groups which are already in being.

C. Development of Protocols

If the global ocean observing system is to become an operational reality on an international basis, measurement protocols will have to be developed which involve placement of sensors or collection devices, calibration of instruments used in the sampling and details for coding and transmission of data to regional and national centers. The meteorological community has set down workable precedent for much of what has to be established. However, special attention must be given to differences in oceanographic data and the unique inclusion of biogeochemical parameters.

The development of protocols should proceed from an extensive period of draft protocols. The eventual set should be designed with a review process which is amenable to change as mutually acquired experience evolves through either operational experience or new research findings. An initial working group, with technical representation from the WMO, is recommended in order to take advantage of WMO's prior experience with international protocols. If broad international participation in the global ocean observation is an important goal, protocols should not be overly complicated nor require equipment and facilities beyond the reach of all participating nations.

D. Data and Information Management

Data and information management, must be planned in advance. This includes sampling the sensor record, transmission of the data stream to a collection facility, initial quality control and processing into geo-located data sets and distribution or archival-ready data sets. This effort is neither trivial with respect to the amount of manpower nor the funding required. Information management is the most often under funded aspect of science and often the first to be cut with funding pressure.

For a successful global ocean observation system, preserving access (over long periods) to the sensor records is a primary goal of the program. Information management must be a part of the design of each observation network from sensor to archive. In the case of ocean data sets, there are several levels of users some with operational time constraints to enter observations into numerical models on a near-real-time basis, while other equally valid programs simply require easy access to the data weeks to months after collection for more fundamental research.

Both levels must be satisfied if the system is to be truly operational and worthy of funding by the agencies with operational needs. Information management design should take into consideration the ongoing systems within NOAA and Navy for distribution and archival of data, NASA's EOSDIS, the systems being employed by the TOGA and WOCE programs, and also the structure of the Global Telecommunications System (GTS) system. A working group should be established on communications with the WMO and the managers of the GTS.

6. *Findings and Recommendations*

The findings discussed below were distilled from the workshop presentations, working group deliberations and the discussion during the plenary sessions. They represent both the consensus of the meeting participants and the special knowledge of discipline and subject area experts. An effort was made to focus on near-term implementation of those activities which are essential for long-term progress. The findings are divided into two parts: (1) design and (2) operations and management. The design category includes the necessary elements of the system and required technology. The operations category includes management and funding aspects.

A. *System Design*

1. Support of Existing Climate-Related Programs

The initial program must build on existing regional and global climate and biogeochemical research programs such as TOGA, WOCE, JGOFS, and CalCOFI. This will ensure adequate input of scientific information for design of a long-term observing system and the continuation of time series vital to the development of climate data bases.

2. Extension of Ongoing Time Series

Examination must be made of all ongoing long time series measurement programs to identify those programs with the most valid records that may be continued or expanded. This will give us the most return for initial investment. A most promising candidate is the CalCOFI 40 year time series off of California. A second tactic is to expand the Bermuda and Hawaii time series stations now funded via JGOFS, adding additional measurements of other variables and also adding transects to determine the relevance of these stations to larger-scale signals.

3. Inclusion of the Coastal Ocean

The coastal regions comprise the most fertile ocean areas on earth and are the regions where human activities most strongly interact with the global ocean. For the federal agencies with statutory products and services to be provided or those with permit and regulation authority, the coastal ocean is where their forecast models must provide reliable products. The population in the U.S. coastal zone is rapidly increasing and worldwide some of the largest population centers are located in the coastal region.

The coastal ocean is sensitive to global climate change, especially sea level rise and water mass shifts. Its role in the global carbon cycle, because the region is so productive and because it sequesters carbon in sediments, is crucial. On special landforms, such as islands and deltas, changes in the ocean such as a change in sea level, could drastically impact available land. Man is also increasingly expanding operations in the coastal region, such as for offshore oil and gas recovery, that are sensitive to ocean conditions. In a practical sense, this region represents the primary customer base for civil operational ocean forecasting. In the U.S., this region will be the political base which will heavily dictate the funding of an ocean observation system. Any ocean observation system must collect measurements which consider the needs of the coastal region.

4. Polar Regions

The full role of the polar regions in the global climate system is poorly understood. Simulations with global climate models portray an arctic marine environment where global warming is amplified due to a combination of effects including sea ice retreat and stable atmospheric warming. Both Arctic and Antarctic regions are areas which affect deep water mass formation.

In the Arctic this is affected by the circulation of freshwater out of the basin which is a highly coupled process between river influx, precipitation, ice formation and circulation, and atmospheric forcing. Highly seasonal phytoplankton blooms occur, with some of the highest pigment levels observed in the ocean, but the real impact of the Arctic marine ecosystem in sequestering carbon is not determined (true of other regions as well). In the Arctic the amount of open water has a significant impact on heat flux and can impact operational weather forecast models. The initial objectives of a polar component of a global ocean observing system would be to characterize the budgets for fresh water, carbon, ice, kinetic energy, heat and salt.

5. Resolving the Global Field

The description and prediction of climate and global change will rely heavily on statistical and numerical models of the global ocean, its carbon cycle and atmosphere. For successful operation of these models, the following near surface variables must be provided in a uniformly distributed field in space and time adequate for resolving a global field: sea surface temperature; upper ocean temperature/salinity structure; momentum/buoyancy fluxes across the air-sea interface; near-surface currents; dissolved inorganic and organic carbon dioxide concentrations; and nutrient concentrations, biomass of important trophic levels and productivity.

6. Flexibility

It was generally agreed that any system be designed to accept future change in both technology and instrumentation. Computer and communication technologies have continued to rapidly evolve over the last two decades. This is expected to continue and may bring with it economies of operation and capabilities not easily predicted at this date. Second, as we reach a better understanding of the ocean system, the nature, and spatial and temporal extent of what we need to measure may change. With today's level of understanding our research programs and our initial systems may over-sample what is eventually needed for operational monitoring. Present research satellite instruments may evolve into operational systems. We must be able to take advantage of these changes to save manpower and money and provide better products.

7. Existing and New Technology

Moorings and floats, satellite altimeters, scatterometers, acoustics, and ocean color instruments and sea level gauges should be exploited to their maximum and supported as routine operational data collection systems.

New and cost effective approaches to sampling the deep ocean are important. Approaches such as the use of cables to monitor current systems, use of acoustic tomography, use of satellite altimetry and the concept of the Heard Island experiment will all make contributions if they can be linked into a long-term operational data collection program. Increasingly capable ocean buoy systems can collect much intermediate data, replace weather ships and communicate remotely to shore.

Upper ocean physical and biogeochemical monitoring programs would also be aided by development of sophisticated buoys that would collect time series data. Use of floats and tracer technology coupled with gyre scale sections would add to the understanding of mean flow. New inexpensive and reliable expendables and simple sampling devices would help expand the role of developing nations in a global ocean observing system and ensure more global data sets are obtained from the intermediate and deep ocean.

Use of satellite monitored ocean color coupled with *in situ* studies of ocean optics and biomass offer the first operational opportunity for the ocean biologist to have a global view of at least the standing stock of primary producers. The linkage of this new data set to the understanding of the global carbon cycle and the long term monitoring of the marine ecosystem is of extreme importance.

Increased effort to develop autonomous optical, acoustic, and chemical sensors which are capable of being deployed from ships, midwater floats, and moorings and which can communicate digital data sets for shore-based analysis will greatly enhance the ability of biological oceanographers to monitor the ocean on the same space and time scales as physical observations are made, and communicate and process data.

Such techniques will also allow more economical sampling of the high frequency component of ocean ecosystems. Expansion should be made of programs using ADCP systems to collect data on marine populations. Other technologies which might be expanded include automated biochemical sampling packages to operate from vessels of opportunity and consideration of deep ocean observatories to obtain long-term time series in the deep ocean. The VOS program could be greatly expanded to include measurements of many other variables beyond what is now being done.

8. Special Use for Technology in Polar Regions

There is a special need for the use of advanced technology in the Arctic due to the remote location, hostile environment, and the absence of light for a portion of the year. The use of satellite technology is especially important in providing year-round data on sea ice cover, biomass, cloud cover, temperature of open water, wind forcing over open water, distribution of ice types and the amount of open water within the pack.

Automated systems to measure ice cover, particulate material settlement, productivity, and physical properties would accelerate the ability to make year-round measurements in the polar regions. An Arctic drifting buoy network has been successfully used for measurement of atmospheric pressure and determination of sea ice flow. This program should be continued and expanded. Development of automated analysis methods for the extremely high data rates of the Synthetic Aperture Radar (SAR) sensor would permit greater use of this sensor for detailing the distribution of sea ice.

B. *Operations Management*

1. Improved Coordination is Needed

It appears that several U.S. agencies including NOAA, the DOD (Navy and Air Force), NASA, NSF, DOT, EPA, DOE, DOS and the DOI will have some level of direct interest in the structure, management, funding and data acquired by a Global Ocean Observation System. State agencies will also play a crucial role. These concerns will be on a national and international level. The need for data to support these agency programs varies widely from near-real-time operational support to the analysis of long-term data sets for global change research. To field a single or network of systems over a long period without disruption or degradation will require strong coordination between the agencies, interagency bodies and with the Administration and Congress. For example, the CalCOFI program has worked in such a multiagency/state cooperation environment.

2. Quality Control

It is obvious that quality control of data is of utmost importance. Long-term data records such as those being discussed are only as useful in the future as the quality control put into instrument calibration, observation, data analysis and data management. The issue revolves around who exercises this quality control and where is it accomplished. Sound compromises are necessary to maintain high levels of quality control over all measurements.

Some research scientists insist that quality control start as close to the point of observation as possible and that only scientists (not government technicians) will do this task correctly on a long-term basis. Others argue that long-term data collection and associated quality control in support of essentially statutory provisions of government services and international agreements is a function of government however they decide to carry it out, for example, using government employees or contractors. In the end, some partnerships will be required.

3. Management of the Program

There are many options and questions regarding management of a Global Ocean Observing System. Putting aside the international side of the picture, and assuming that it will work out to be some system agreed to and funded by governments, what U.S. national structure will evolve to directly manage the system? Will it be governmental with a lead agency, or funding by several agencies as their program interests dictate? As another option, could academic centers or laboratories be designated as responsible for a certain area or certain suite of observations from data acquisition to archival and then the information be made available via networks? From experience it has been demonstrated that end-to-end management from data acquisition to the archive is needed for assurance of credible data, especially over the long haul. In addition, various protocols for data collection must be agreed to and maintained. Once again, partnerships between the academic community and government agencies will be required.

4. Data Management Requirements

A workable Global Ocean Observation System will require a major effort in data management from the time of observation through archival. Present operational systems have significant difficulty with the quality control and loss of data. Several large research programs such as TOGA, WOCE, and CalCOFI have evolved special data management systems with their own needs in mind. There is a trend to use a distributed network of data centers responsible for receiving and processing data. Data sharing procedures must be developed both for the national and international scale, and they must consider the needs of operational forecasting centers and the individual principal investigators. National security and sovereignty issues must be addressed early in such negotiations. The long-term experience of WMO should be drawn upon.

5. Funding

The Global Ocean Observation System must have a reliable and steady source of funds. In the past direct funding by agencies for this type of long term program has been fraught with funding difficulties as agency programs and budgets fluctuate. To counter this, some propose that the best way is to fund the effort through scientists who have long term interest in the data for their science. Others pose the same argument as for the collection of observations and quality control, that this is essentially a government function linked to the provision of data necessary to provide services to the public and in the interest of national security. The European Center for Medium-Range Weather Forecasting (ECMWF) is a good example of what can work on an international, intergovernmental basis; the Scripps CO_2 measurement program and CalCOFI are examples of long term support of programs at academic institutions.

6. Varying Drivers for Structure and Cost

Projects must be optimized and costs minimized. Interfaces with ongoing efforts must be planned to contain costs and allow rapid start-up. The needs of the various constituents will have a strong impact on the design and cost of the ocean observing system. Those agencies, such as the Department of the Navy within DOD, that have a operational forecasting mission, will require data sets which arrive ready for final incorporation into operational forecast models on a routine, near-real-time basis. For more global change oriented research the data from GOOS will be used primarily to understand the relationships between climatic forcing - physical water movement - the carbon cycle, and how the carbon cycle feeds back into atmospheric changes such as the greenhouse effect.

This type of requirement structure is also true for segments of NOAA such as the NOS groups which produce ocean products in support of many nearshore and fisheries activities, and supply frequent ocean information to the weather service for incorporation into coupled ocean atmosphere forecast models. Many types of nearshore activities are best served with either nowcasts or short term forecasts of conditions. These operational users can be contrasted to the large community of research users who can deal with data that is a week to a month later than actual observation time.

7. Expansion of Existing Systems

At its inception, the long-term Global Ocean Observing System should be constructed through expansion of regional and basin scale ocean observing systems that have demonstrated effective operation during the last ten years in a variety of regional climate and research programs (e.g., VOS, WOCE, TOGA, CalCOFI). Consideration should also be given to expansion of recently initiated time series such as the JGOFS time series in Hawaii and Bermuda. Through analysis of existing sample material and data sets ongoing programs must receive high priority in order to impact the design of later measurement efforts.

Recommendations

The general recommendations below are taken from the pre-workshop papers, working group reports, discussion in plenary sessions and comments by reviewers. More specific suggestions can be found in the working group reports in the Technical Appendix.

SYSTEM DESIGN

Recommendation 1: Build Operational Program in Years 1-5 on Existing Operational and Research Programs

- select operational steering committee
- start by using results of TOGA, WOCE, and ACCP programs
- augment/upgrade tidal gauge network
- support, enhance CalCOFI program and data analysis
- conduct gyre scale sections
- support ocean satellite efforts
- expand VOS effort
- continue Arctic data buoy efforts
- improve current data recovery and QC programs
- continue effort to use satellite data in operational forecasting
- develop data management strategy

- build communications with WMO
- stay involved with academic Community
- analyze initial specifications for GOOS and cost/benefit
- build performance requirements documentation
- intercalibrate new measurements with existing databases

Recommendation 2: Start a Program in Years 1-5 Using Technology to Upgrade Sensors, Communications, Autonomous Operations, Expendables and Techniques

- continue development of coupled air-ocean models
- develop new techniques for sampling mid, deep, and polar ocean
- develop new technology for autonomous data collection/storage and communication
- improv instruments for Arctic
- improve expendables with reduced cost, and small reliable sensors
- move to operational satellite ocean sensors
- use expanded/improved cable systems to monitor current systems
- develop smart moorings, buoys and autonomous vehicles to replace ship platforms for routine observations
- employ four-dimensional data assimilation
- intercalibrate measurement techniques

Recommendation 3: Long-Term Technology Developments

Technology development for impact in the 5-15 year program window

- advances in computer technology
- advances in Communication technology
- new generations of expendables
- expanded programs with developing nations
- new sensors associated with carbon cycle (DIC, DOC, particulates,nutrients)
- integration with EOS data stream
- 4 D data assimilation
- advanced networks
- advanced all year systems for Arctic and Antarctic
- advanced autonomous digital systems for biology
- research into cost reduction strategies
- acoustic tomography, and related techniques
- advanced autonomous vehicles
- advanced ecosystem models

OPERATIONS MANAGEMENT

Recommendation 4: Establish an Interagency Coordinating Committee

Establish an interagency coordinating committee to perform the following tasks:

- determine U.S. operational and research requirements for a GOOS
- document the existing U.S. components of a GOOS
- draft a coordination plan for the agency oversight of GOOS
- nominate a lead agency to coordinate GOOS
- develop a 5-year funding profile for GOOS based on current budget projections,
- nominate a small committee to work with the NRC to draft plan for GOOS which has both participation by the federal and academic sectors

Recommended participants NOAA (Chair), Navy for DOD, DOE, NSF, NASA, DOS, EPA, USGS, MMS and USCG for DOT. Invite OSB/MB and academic participation from the outset. Coordinate with U.S. individuals currently having a role in OPC Ad Hoc Committee and CCCO/JCS OOSDP. Coordinate with the OMB and CEES from the outset.

Recommendation 5: Prepare a Plan for U.S. Contribution to International Global Ocean Observation System

- measurements
- space scales
- time scales
- communication
- networks and data sharing policy
- agency roles
- modeling centers
- data archival
- interactions with other programs TOGA, ACCP, WOCE, JGOFS, CalCOFI, CPR, GLOBEC, ARCSS, Mission to Plant Earth, etc.
- research and operational satellite programs
- cost/benefit studies

Recommendation 6. Continue Cooperation with International Community

Continue support and interaction with international groups working on plans for the ocean observing system. Advocate strong scientist-to-scientist level effort to identify basin and global scale systems (bottom up approach):

- OPC/Ad Hoc Committee
- CCCO/JCS OOSDP
- Interaction with the WMO
- IOC
- Measurement and communications protocols
- Data sharing protocols

Appendix A: Technical

I. Working Group Reports

This section is devoted to the reports of three working groups. The reports were drafted at the workshop and then revised by the group for the overall report.

Working Group Report I
Upper Ocean and Air-Sea Interactions

Members:
David Adamec
Peter Cornillon
David Goodrich
Richard Hayes
Geoffrey Holland
Ronald Lavoie
Ants Leetmaa
Hugh Milburn
Christopher Mooers
Robin Muench
Peter Niiler (Chair)
James O'Brien
James Rigney
Neville Smith
Tom Spence
Peter Taylor
Ferris Webster
Robert Weller
Warren White
Klaus Wyrtki

The working group discussed three major topics concerning global ocean observations in the upper ocean and the air sea boundry. These included: (1) enhancement of present measurements with respect to both changes in programs and the use of existing systems; (2) required developments in instrumentation and technology; and (3) requirements and the role of modeling. The report of the working group was presented in outline form, highlighting specific recommendations in each category. For additional detail the reader is referred to the presentation paper *Scientific Issues on the Establishment of the Long-term Global Observing System for the Surface and Upper Ocean* in Part II of the Technical Appendix.

ENHANCEMENTS OF PRESENT MEASUREMENTS

I. Global SST

The definition of a Global SST field requires the combined use of satellite data, which is required for spatial and temporal sampling, and use of buoys and VOS data, which will detect spatial biases that may occur in the satellite SST's and to ensure calibration of the system throughout various climatic regions. Enhancements to these measurement systems are required as follows:

A. VOS. At present many VOS Sea Surface Temperature (SST) measurements are of unacceptable quality. Potential improvements include automatic sampling, logging, and transmission over ARGOS; use of GPS to ensure correct positions, better calibrated SST sensors (engine intake, hull mounted or trailing thermistor), and accurate documentation of the measurement system used and evaluation of the biases for individual ships. The most cost effective way to enhance SST retrieval from shipping routes is to improve the VOS system.

B. Drifting buoys. All drifting buoys should be equipped to measure and report SST. The need is most pressing in areas, such as the Southern Hemisphere that are not traversed by ships, however, a distribution throughout various climatic and oceanic regions should be maintained to ensure meaningful calibrations and updating.

C. Satellite data. Research into the surface skin effect is needed to properly merge satellite data with other systems. The synergistic use of AVHRR and the ATSR (on ERS-1) systems should be developed since the ATSR has the potential to remove atmospheric effects and to give a calibrated skin temperature, whereas the AVHRR provides much better sampling.

II. Sea Surface Salinity

Measurement of sea surface salinity will contribute to estimation of the fresh water and the buoyancy fluxes. It is recommended that specially selected VOS be equipped with thermosalinographs or similar instruments to give continuous measurements of surface temperature and salinity. These ships should be those participating in the XBT (or XCTD) program which serve the global research programs. These VOS vessels would also be prime candidates for enhanced meteorological measurements systems (see below).

III. Wind Stress

Moored buoys provide platforms for measurements of critical parameters in the upper ocean and the marine boundary layer from which wind stress can be calculated. Other parameters of interest are temperature with depth ($T_{(z)}$), salinity, and velocity with depth ($V_{(z)}$), and precipitation and SSS at the interface. The computation of stress requires the wind velocity, barometric pressure, relative humidity, air temperature, downwelling short and long wave radiation, all of which can be measured from buoys. TOGA has demonstrated that cost-effective mooring of this specific measurement capability can be deployed in a large scale array to obtain fields of variables required for the determination of stress over the tropical ocean and the response of temperature within the water column. WOCE has supported the development of moored buoys capable of measuring all of the variables listed above in more severe weather conditions.

Enhancement of the deployment of both types of buoys should begin. TOGA has proposed the TOGA-TAO array for the purpose of enhancing El Niño monitoring and prediction and for testing of numerical models which do ENSO prediction. This array should be fully deployed and maintained for ten years. The more fully instrumented buoys should be deployed in areas where it is essential to validate remotely sensed fields of air-sea interaction and for identifying biases in VOS fields and for motivating continued research on the parameterization in both models and scientific studies of the air-sea fluxes. Further, moored buoys permit the collection of continuous time series at a point. Such measurements, including also measurements of biochemical parameters, will be part of the verification experiments of oceanic fluxes as derived from remote sensing or from atmospheric assimilation models.

A. VOS observing capability enhancements: Ships already at sea, including research vessels, Navy, NOAA and USCG and especially the Volunteer Observing Ships (VOS) are an invaluable source of windstress data. Immediate action should be taken to make full use of these platforms to enhance the reporting of meteorological variables. Automated data collection and reporting by a computer driven system should be used for collection of high quality meteorological data, including wind velocity air temperature, barometric pressure, relative humidity, downwelling shortwave and longwave radiation, and precipitation, on all research vessels and a select number of Navy and VOS (300 platforms) ships. The technology presently exists to meet this observational requirement. Installation should begin as soon as possible. Data quality checking and cross-comparison with the existing U.K. high quality VOS should be given priority.

B. Navigation equipment: Position as well as the computation of the absolute wind velocity (relative wind combined with course and speed), should be upgraded. GPS positioning and ship logs are both required.

C. Further enhancements of measurements from VOS is recommended as the technology becomes available and proven: Acoustic Doppler Velocity Profilers (ADCP) and measurements of biochemical parameters including PCO_2, pH, transmissivity, and chlorophyll content. These measurements should begin on the WOCE WHP Vessels, because of the high quality of technical support that is on board to support these measurements.

IV. Sea Level Pressure

Enhancements of sea level pressure observations can be made from drifting buoys which carry a barometer. A systematic improvement of observations of sea-level pressure will dramatically improve the analysis and the prediction of marine weather by the operational weather centers of WMO and the Navy. Several types of drifters which have this capability have been developed by the Navy, NOAA, and WOCE. Their utilization within the Global Surface Velocity Program (SVP) (of WOCE, TOGA, ACCP, Navy, etc.) is recommended.

V. Global Upper Ocean T (z)

Enhanced Science and Operational Needs: Recent requirements for temperature measurements have been expressed for the sampling densities in the Atlantic Climate Change Program (ACCP) and TOGA for the Pacific and the Indian Oceans. Besides these programs, there is developing a need for global updating and prediction of the upper ocean thermal structure both from the operational Navy needs and from the needs of the long range weather prediction and prediction of short term climate change. Significant areas of the ocean are not now sampled by with sufficient resolution to support model updating or validation.

A. VOS/XBT Enhancements: The technology exists for deployment of XBTs from VOS, and reporting the data in real time. Large areas of the oceans not now sampled can be covered with an expansion of this system. The timeliness of the data from VOS must be ensured by attention to communication systems (ARGOS, GTS, INMARSAT). The important contributions by VOS operators should be encouraged by implementing shipboard systems that provide real time on board display of the data to ship's officers and crew and, if possible, provide a path for delivery of resultant marine forecasts and other information to the vessel.

B. Drifting Thermistor Chain Buoys: After ten years of development, the drifting thermistor chain buoy is not fully operational, although a few of these have been made to work for a few months at a time. Developments are under way to make air-deployable mini-drifters for Navy use. These drifters offer a potential for filling in areas not sampled with VOS.

C. Moored ATLAS Buoys: TOGA has designed and justified an array of 67 moored ATLAS thermistor chain buoys for the tropical Pacific. This array should be deployed and maintained for ten years, commencing in 1993.

D. One of the most promising techniques is to use the Autonomous Lagrangian Circulation Explorer (ALACE) to sample the temperature profiles of the upper ocean in remote areas of the ocean. It can be programmed to cycle through the upper 1000m of the ocean several hundred of times, returning the data via ARGOS and it can be deployed by air.

E. Modeling. The upper ocean models are at a stage where these can assimilate T(z) data and can be used both for prognosis and prediction of the upper ocean thermal field. Both Navy and NOAA have such a capability, and these represent a valuable asset for providing the upper ocean thermal fields on a global basis. They require field data sets of T(z) for regular updating and for improving their prediction skills. An enhancement of the modeling effort, to specify enhanced field data requirements is needed.

REQUIRED INSTRUMENTATION DEVELOPMENTS

I. Short Term and Emerging Needs

- Large scale computing for the continued development of ocean modeling and ocean prediction
- Basin wide use of acoustic tomography
- Measurement of sea ice roughness and structure from synthetic aperature radar
- Satellite remote sensing of sea ice, atmospheric humidity and surface wind speed
- Use of acoustic doppler current profilers from moorings and platforms of opportunity such as VOS
- Continued development of expendable probes such as the XCTD
- Development of stable sensors for sea surface salinity
- Validation of Over The Horizon (OTH) radars for ocean measurements
- Ambient noise for wind and precipitation measurements
- Continued development of autonomous vehicles for ocean sampling
- Expansion of the capabilities of Voluntary Observing Ships to add parameters such as:
    - automatic launchers
    - GPS
    - automatic met measurements
    - thermosalinographs
    - data relay and feedback
    - biochemical indexes

  - underway telemetry of VOS data

- Develop down looking radiometers for use with surface drifters
- Develop atmospheric pressure sensors for Lagrangian drifters
- Improve satellite data communications both to and from vessels and buoys especially for the purposes of data exchange and data loading
- Develop ALACE capabilities for the upper ocean measurements

II. Long Term Technology and Instrument Needs

- Develop satellite technology for remote all weather measurement of sea surface temperature
- Develop a miniturized and air-deployable meteorological drifter
- Develop technology to measure absolute sea level
- Develop technology and systems for global acoustic tomography

MODELING REQUIREMENTS

A. Accessibility of data on time scales of hours and days; the amount of data has to increase significantly.

B. Synthesis of fields will produce deliverables of dynamically and statistically smoothed data streams.

C. Quality control of the products depends on the feedback from the users. There must be a continuity of analysis techniques so the changes these techniques may produce are well understood.

D. Observing system simulation is an important modeling objective. This will improve modeling and data acquisition interactions.

Working Group Report II
Intermediate and Deep Water Observations

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Review of Existing Observations and Measurement Techniques

A number of techniques are presently used to describe the structure and circulation of the interior of the ocean. These techniques can be broadly grouped in three categories, direct current observations using moored current meters, neutrally buoyant floats and dropsondes, indirect current observations using hydrographic measurements of temperature, salinity and chemical constituents plus physical assumptions such as geostrophy, and acoustic and electromagnetic remote sensing.

The number of direct current observations in the deep ocean is small. Direct current observations in the deep ocean have been obtained from moored current meters since the 1960s. At present, there are approximately 2,370 instrument years of long-term current meter data (Dickson, 1989). Long-term is defined here by deployments longer than six months. For the instruments below 2000 m, approximately 70% have mean currents less than 1 cm/s. Reliably estimating these weak mean currents requires multi-year deployments given the large fluctuating currents. Lagrangian current measurements have been obtained from neutrally buoyant SOFAR and RAFOS floats since the early 1970s. These observations are almost entirely limited to the North Atlantic. Float data provide a spatial coverage of the ocean which is not practical for moored instrumentation at the expense of temporal resolution.

The largest number of deep ocean observations are obtained from hydrographic measurements of temperature and salinity. Using these data, indirect estimates of the velocity can be obtained by assuming geostrophic flow. To obtain estimates of the absolute velocity from the geostrophic shear requires additional assumptions about the flow and its dynamics. The coverage is uneven in time and space. For much of the world, inadequate data exists to define the annual cycle of variability. Only in a few locations have time series with any significant duration been obtained.

Background for Recommendations

The criteria for the design and implementation of a global ocean observing system in the intermediate and deep waters of the ocean include building upon the few existing long-term, systematic observations with a focus on expanding these observations into key regions for particular goals and the development of new techniques to obtain integrating measurements of oceanic variables. A serious difficulty exists for the intermediate and deep ocean in that few long-term systematic observations exist presently. Thus, the base of observations from which to build is small. In addition, the basic description of the intermediate and deep circulation of the ocean and its variability on long time scales is just emerging. Indeed, one of the major goals of the World Ocean Circulation Experiment (WOCE) is the description of the global ocean circulation and its variability. WOCE is just starting and will continue for the next 5 years. The WOCE data sets will enhance the design of an observing system. Finally, the working group recognized that it is not possible to continue the observing of the ocean at the WOCE level of effort in the long term. Thus, integrating measurements and diagnostics are needed. New and emerging measurement technologies and techniques will play an important role in a global observing system.

Recommendations

The recommendations of the working group are presented below. These recommendations fall into three general groups, near term actions which extend existing observations, coordination issues and actions involving new and emerging technology requiring further study prior to any implementation. These recommendations are summarized in Tables 1, 2, and 3 with an indication of the expected impact on the NOAA Climate Research Program (CRP) and Navy operational needs plus a suggestion for the lead agency to implement these recommendations.

An ocean observing system must build upon the historical data base using existing technology. Maintaining the few existing long term observations must have the highest priority.

The estimates of the transport of the Florida Current between Florida and the Bahamas by voltage measurements using the submarine cable are one of the few such time series in existence. The cable voltages have been monitored since the early 1960s providing nearly three decades of estimates of the transport variability. During the Subtropical Atlantic Climate Study (STACS), the cable voltages were compared with numerous direct transport estimates and the necessary calibration factors determined to transform the voltages into absolute transport. These transport measurements provide an important diagnostic of the wind-driven circulation of the subtropical gyre of the North Atlantic. In addition, these Florida Straits transport measurements are important to any attempt to estimate the meridional heat flux in the North Atlantic. Continuing these measurements is an important component of any ocean observing system. However, a number of actions are required in the near term to maintain this unique time series. The submarine cable has passed its useful lifetime and the voltage measurements are being degraded badly. The cable needs to be repaired or possibly replaced as soon as possible. The original bilateral agreement governing the use and access to the cable refers to military use only. Continued use for civilian climate research studies may require a new or amended bilateral agreement. Because of the connection to existing NOAA programs and the potential value of these measurements to climate change studies, the working group suggests that NOAA be the lead agency in maintaining these measurements.

Single point time series observations of temperature, salinity, and currents provide useful information for both, climate studies and short term forecasting. Until the mid- 1970s, many such time series were obtained by the ocean weather ships. These data have been used for many upper ocean studies providing the surface initial conditions for the ocean interior as well as observatories for internal changes in the ocean such as the advection of large scale salinity anomalies such as described by Dickson, et al. (1988). In addition, Roemmich (1989) shows that long-term trends observed in the Panulirus time series of hydrographic observations are correlated with basin wide trends. Recently, under the Global Ocean Flux Studies Program (JGOFS), a time series of hydrographic stations and current meter moorings has been started off Hawaii, designated the Hawaii Ocean Time-Series (HOTS, Chiswell, et al., 1990) and the Panulirus hydrographic station program off Bermuda has been expanded. The existing time series measurements have been limited to sites near islands or infrequent hydrographic cruises to weather ship locations such as the quarterly cruises to OWS Papa location in the northeast Pacific run by the Institute for Ocean Sciences in Canada. These programs are manpower and ship resource intensive. Under the

Tropical Oceans-Global Atmosphere Program (TOGA), the technology has been developed to deploy satellite telemetering surface buoys measuring currents, temperature and salinity (Milburn and McClain, 1986; McPhaden, et al, 1990, 1991). Expansion of this program to mid- and high latitude oceans for a number of time series locations is water mass formation regions and the center of ocean gyres is recommended.

Zonal hydrographic sections have been used to estimate the meridional fluxes of heat and salt in the ocean. Repeating two sections across the North Atlantic initially occupied during the International Geophysical Year (1957-58), Roemmich and Wunsch (1985) found that while the heat flux was nearly the same 23 years later, substantial changes in the heat content and internal structure of the transport had occurred. A global observing system designed to detect the impact of man's activity on climate as well as providing the necessary data to understand climate change must include repeated trans-oceanic hydrographic sections through all major circulation gyres. While further studies are needed to determine the frequency of these repeated sections, the value of these sections is high as suggested by the work of Roemmich and Wunsch (1985). The planned hydrographic program of WOCE will provide an excellent baseline of sections as well as a consistent one-time description of the state of the ocean.

Sea level rise due to global warming potentially results from changing levels of greenhouse gases. The existing network of tide gauges on island and coastal sites have the potential for detecting such a rise. However, before such information can be obtained, these gauges must be converted into absolute sea level gauges and the local effects of steric sea level monitored. Thus, the network of gauges needs to be augmented by the addition of Very Long Baseline Interferometry (VLBI) and Global Positioning System (GPS) to place the relative sea level from the gauges into an absolute coordinate system plus measurements of the local gravity field and local oceanic density field to detect steric sea level changes.

Satellite altimetry provides an excellent technique to monitor the global sea level to detect changes in the ocean circulation and volume. The Navy Geodetic Satellite (Geosat) has returned a wealth of information about the ocean circulation and new techniques to exploit these data are still being developed. Because of the power of this measurement technique, the working group recommends that a permanent constellation of at least three satellite altimeters be developed and maintained. A three satellite altimeter constellation will allow resolution of mesoscale eddies in the ocean and better sampling characteristics for the description of the large scale circulation. When altimetry is combined with a network of absolute sea level tide gauges, an unique observing system for ocean circulation and sea level rise will exist.

While the Florida Straits transport measurements from cable voltages are given a high priority since these measurements presently exist with nearly three decades of continuous data, the transport of all major boundary currents and the exchanges between ocean basins are important quantities to measure. These transport measurements are an important diagnostic of large scale changes in the ocean circulation. For example, in a recent model study, the cessation of bottom water formation around Antarctica lead to a decrease in the transport of the Antarctic Circumpolar Current (ACC) by more than 50%. In this model, fluctuations in the rate of bottom water formation occurred with approximately 300 year periodicity and periods of little or no bottom water formation lasted for nearly a century. Thus, natural climate variations can be very large and these fluctuations can be seen in the transport of the major ocean currents. The transport of the ACC through Drake Passage was monitored by pressure measurements for approximately 5 years between 1976 and 1982 (Peterson, 1988). Based upon the results of the Drake Passage transport measurements, monitoring the transport through a passage requires sea level and subsurface pressure measurements plus hydrographic stations to measure steric sea level changes. A program for monitoring the transport of the major ocean currents and the inter-ocean exchanges should be established. Since a number of issues regarding the design of such a monitoring network exist, it is recommended that NOAA and academic researchers take the lead in the implementation.

One important aspect of the ocean's role in moderating the earth's climate is the ability of the ocean to store and advect large amounts of heat. On the decadal time scale, the intermediate water masses of the upper thermocline provide the link between atmospheric forcing and changes in the oceanic heat content and meridional heat flux. As part of WOCE, the pathways by which intermediate waters spread throughout the ocean should be determined from subsurface float measurements. Building upon these observations, the rates of formation of intermediate waters should be estimated using periodic measurements of time-dependent tracers, such as tritium and freons. A reduced subsurface float program should be maintain to determine if the basic flow patterns change.

The measurements recommended above build upon existing observations and techniques. However, an affordable global ocean observing system must take advantage of new and emerging technologies as well as encourage evaluation of these technologies and the development of new integrated measures of change in the ocean. For example, long range sound propagation may provide a measure of the change in heat content of ocean basins. The Heard Island Experiment (Munk and Forbes, 1989) provides an opportunity to test the feasibility of this concept. Further study and evaluation should be encouraged. Similarly, acoustic tomography (Munk and Wunsch, 1979) may provide an effective technique to monitor ocean currents and thermal structure. While a number of tomographic experiments have been performed, further evaluation is necessary.

Similarly, existing observations should be augmented with new techniques. For example, the Voluntary Observing Ships presently make atmospheric and XBT measurements. These ships could be instrumented with thermosalinographs to obtain surface salinity and with towed electromagnetic sensors to observe the barotropic currents in the ocean. These data could be telemetered in real-time to provide input to ocean forecast models as well as augmenting the climatological data base.

To increase the involvement of other countries in an observing system as well increase the total number of observations made, development of expendable and low cost instrumentation is necessary. Making the instruments simple and relatively inexpensive will allow more instruments to be deployed. In particular, many countries have access to ships to make oceanic observations, but lack the resources for elaborate measurement techniques.

Autonomous vehicles are another emerging technology with great promise for a global observing system. For example, the Autonomous Lagrangian Current Explorer (ALACE) floats under development at the present for WOCE can cycle over the upper kilometer to give an average current velocity in the thermocline every two weeks for approximately 5 years. Combining this technology with a CTD could give a density profile on every cycle which would greatly increase the number of deep velocity and density observations. The addition of other types of measurements may be possible. Further study and development of this class of platform and associated measurements is recommended.

An important question for the design and implementation of a global ocean observing system is the type of measurement to be made. For example, should measurements of the state of the ocean or the inventory of some property be made or should the focus of the measurements be the fluxes of various properties? Measurements of heat storage or the average temperature are relatively easy to make. Measurements of fluxes are more difficult and depend upon the integrals of velocity and the correlation between velocity and some property such as temperature. Numerical model-based sensitivity studies should be started to find new diagnostics for climate change in the ocean.

The requirement that the observations be both global and long-term represents a severe constraint. The existing observational techniques and systems are expensive. The likelihood of obtaining these observations is enhanced by making observations intended for climate change research available for operational applications by timely communication of the data. Increased coordination is required to provide a link between the research on climate change and agency operational requirements. An increased exchange of data by timely reporting of research data for operational use and by the inclusion of operational data into the climate research data base should be encouraged. Similarly, it can not be assumed that measurements be made presently will be continued in the future. An oversight committee should be established to coordinate the implementation of the observing system and to maintain its long-term continuation.

Summary

A number of recommendations leading towards the implementation of a global ocean observing system are made in this report. A set of recommended near-term actions which extend and enhance the few existing observations of the deep ocean circulation are summarized below. The transport of the major ocean currents and inter-basin exchanges should be monitored. The submarine cable voltage measurements across the Florida Straits should be upgraded and maintained into the future. Cross-passage pressure measurements such as those made in Drake Passage should be instituted at other locations and for other current systems. A network of absolute sea level observations through enhanced tide gauge measurements and a permanent constellation of satellite altimeters should be developed. Single point time series measurements of ocean currents and density should be established in regions of water mass formation and the interior of the major oceanic gyres. A program of repeated trans-oceanic hydrographic sections through each major oceanic gyre should be established as well as a program to monitor the formation and spread of intermediate water masses.

The continuation of a long-term global observing system requires the development of new technologies and measurement techniques as well as the development of new measures of change in the ocean. Long-range acoustic propagation and autonomous vehicles are two emerging technologies which need further evaluation. The development of low-cost and expendable instrumentation should be encouraged to increase the opportunities for involvement by other countries. Present observational systems should be enhanced by the addition of new measurements. New diagnostics of climate change in the ocean should be developed using model-based sensitivity studies.

The implementation of a global ocean observing system requires good coordination between researchers in climate change and operational agencies. Timely reporting of all data will enhance its value for both operational use and climate change research. The inclusion of data collected for operational use in climate research data bases is important. An oversight committee should be established to coordinate the implementation of the observing system and ensure its continuation in the long term.

References

Chiswell, S., E. Firing, D. Karl, R. Lukas, C. Winn, 1990. Hawaii Ocean Time-series. Data Report 1 1988-1989. SOEST Technical Report 1. University of Hawaii, Honolulu, HI, 269 pp.

Dickson, R. R., J. Meincke, S.-A. Malmberg, and A. J. Lee, 1988. The "Great Salinity Anomaly" in the northern North Atlantic 1968-1982. Prog. in Oceanogr., 20, 102-151.

McPhaden, M. J., H. P. Freitag, and A. J. Shepard, 1990. Moored salinity time series measurements at 0°, 140°W. J. Atmos. Ocean. Tech., 7, 568-575.

McPhaden, M. J., H. B. Milburn, A. I. Nakamura, and A. J. Shepard, 1991. PROTEUS: Profile Telemetry of upper ocean currents. Sea Tech., 32, 10-19.

Milburn, H, B., and P. D. McClain, 1986. ATLAS--A low cost satellite data telemetry mooring developed for NOAAUs climate research mission. Proc. MDS '86 Marine Data Systems International Symposium, 393-396.

Munk, W. H., and A. M. G. Forbes, 1989. Global ocean warming: an acoustic measure? J. Phys. Oceanogr., 19, 1765-1778.

Munk, W. H., and C. Wunsch, 1979. Ocean acoustic tomography: a scheme for large scale monitoring. Deep-Sea Res., 26, 123-161.

Peterson, R. G., 1988. On the transport of the Antarctic Circumpolar Current through Drake Passage and its relation to wind. J. Geophys. Res., 93, 13,993-14,004.

Roemmich, D., 1989. Sea level and the thermal variability of the ocean. Chapter 1. in NRC Study on Sea Level. R. Revelle, ed. Washington, DC.

Roemmich, D. and C. Wunsch, 1985 Two trans-Atlantic sections: meridional circulation and heat flux in the subtropical North Atlantic Ocean. Deep-Sea Res., 32, 619-644.

Table 1: Extending Existing Observations

Recommendation	Motivation	Implementor	Impact NOAA CRP	Impact Navy Ops
Maintain Florida Straits transport measurements by cable voltage	Diagnostic of wind-driven circulation	NOAA	H	L
Augment island and coastal tide gauges for VLBI/GPS, local gravity and steric sea level	Absolute sea level for total oceanic mass and heat content	NOAA	H	M
Develop permanent satellite altimeter constellation	Global sea level for mass and heat content	Navy/NOAA	H	H
Repeated sections through ocean gyres	Large scale decadal changes in heat content and transport	NOAA/ Academia	M(H)	L
Long-term time series from hydrographic stations and moored buoys	Increase number of single point observations similar to Bermuda (Panulirus), Hawaii Ocean Time Series (HOTS) and NE Pacific (OWS Papa)	NOAA	H	M
Transport monitoring of major ocean currents such as Antarctic Circumpolar Current (ACC)	Diagnostic of large scale change	Academia/ NOAA	M(H)	L(M)
Monitor Intermediate water formation rate and pathways using subsurface floats and tracer ratios	Decadal change in the thermocline and its relation to surface forcing	Academia/ NOAA	M(H)	L

Table 2: Coordination Issues

Recommendation	Motivation	Implementor	Impact NOAA CRP	Impact Navy Ops
Research and Operations data exchange	Increase climate data base from Navy data and increase timely reporting of research data for operational use	Navy/NOAA	H	H
Establish oversight committee to coordinate GOOS implementation	Maintain long term continuation of observing system	NOAA	H	M

Table 3: New and Emerging Technology and Study Issues

Recommendation	Motivation	Implementor	Impact NOAA CRP	Impact Navy Ops
Evaluate long-range acoustic techniques	Develop integrated measures of heat content and currents	Navy/NOAA	?(H)	M
Develop expendable and low cost instrumentation	Increased and opportunistic data coverage	Navy/NOAA/ Industry	M	H
Augment VOS with electromagnetic observations of barotropic currents	New data on barotropic flow for large scale circulation changes	NOAA	H	L
Develop ocean climate diagnostics using model-based sensitivity studies	Need new measures of change in ocean for climate monitoring and prediction	Academia/ NOAA/Navy	H	L
Evaluate autonomous vehicle profiling	Increase observ-ations of deep velocity and density	Navy/NOAA/ Academia	M(H)	M

Working Group Report III
Biogeochemical Measurements

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INTRODUCTION

I. The Problems

There is general agreement that certain radiatively active gases are responsible for warming the planet and that human activity is significantly increasing the concentration of some of these (Dickinson and Cicerone, 1986; Henderson - Sellers, 1990). The concentrations of two of the more important of these gases, CO_2 and CH_4 , are affected by both anthropogenic and natural processes. The rising levels of these are predicted to warm the earth and the consequences of this rise in temperature constitutes a massive, uncontrolled experiment on the earth's geophysical, geochemical and biotic systems (Shugart, 1990; Bolin *et al.*, 1986). However little else about this anticipated warming is well understood. There is great uncertainty about rates of change and magnitude of effects and this is especially true of the ocean and its biota. But if international policy for emission targets and/or other mitigation is to be agreed upon, these uncertainties must be resolved...the nature of the threat must be made clear by use of a large body of convincing scientific evidence. Much more information about virtually every aspect of the problem must be obtained.

The ocean is of prime importance in this quest, for it and its populations must play a key role in the regulation of climate and in global change. It stores and redistributes large amounts of heat and absorbs, redistributes and releases carbon dioxide on a massive scale. The ocean contains at least 60 times more carbon as CO_2, HCO_3, and CO_3 than the atmosphere (Oeschger *et al.*, 1984). It also has very large reservoirs of dissolved organic carbon and, of course, biomass. The $CaCO_3$ in pelagic sediments and coral reefs represent a long-term sink of carbon that is totally of biological origin. Dissolved organic carbon is thought to turn over more rapidly than $CaCO_3$ but still has a relatively long residence time. Methane is also an important radiatively active gas that is strongly influenced by biological activity. Even atmospheric water vapor may be influenced by biology through the production of dimethyl sulphide by oceanic plankton, its subsequent volitilization and oxidation in the atmosphere, thus forming condensation nucleii for cloud formation (Charlson *et al.*, 1987).

There is much biogeochemical, paleontological evidence of the connection between increased CO_2 in ice cores at the close of glacial times and biological activity in the ocean (Broecker and Takahashi, 1984). Ice cores have shown that atmospheric CO_2 has changed before, as for example during and after the last glaciation when there were also large atmospheric and oceanic temperature changes (Shackleton, 1977). That these were accompanied by productivity and faunal changes in the ocean is clear (CLIMAP 1976). Further, estimates of present marine-global photosynthesis of 30-50 Gt of carbon per year are much greater than the annual 6 Gt of carbon released by fossil fuel combustion (Williamson and Holligan, 1990). Although most of the organic carbon produced is respired quickly, some of the carbon fixed by biological activity is not, as is evidenced by the large amount of old calcareous sediments (produced by organisms), old dissolved organic carbon, and by the existence of fossil fuel itself. Further, the deep waters are known to be greatly oversaturated with CO_2 as compared to the surface. This oversaturation is almost entirely due to the flux and subsequent respiration of particulate organic carbon from the upper layers. The existence of the vast oxygen minimum layer at intermediate depths of the North Pacific is another example of the role of the respiration of organic matter in influencing the large scale chemistry of the oceans. That these processes are not in local steady state, in the upper layers, is clear from direct measurement, and that there can be more than one global equilibrium state, is evident from the biogeochemical paleontology. However, we do not at present understand how shifts in these multiple equilibrium states came about or what feed-back loops eventually stabilize them. But there is plenty of evidence that the physics of water movement, especially stirring and mixing, plus the chemical and biological response, are intimately involved in gas exchange between the atmosphere and the ocean and the establishment of equilibria. Oeschger *et al* (1984), show how the observed changes in CO_2 in ice cores may be linked to the production of organic matter. They suggest that "atmospheric CO_2 concentrations are regulated by changes in the oceans total CO_2 concentrations, alkalinity, temperature and nutrient content; the latter controls the biospheric activity in the surface ocean and thus the reduction in CO_2 partial pressure." Since there are regional differences in these processes now (Williamson and Holligan, 1990) and in the expected changes in them (Ramanathan, 1988), extrapolation to the global scale from composites based on short term, local studies is unwarranted.

It is a matter of broad consensus that a large scale program of measurement and observations in the world's oceans will be required to gain more insight and understanding of the processes that regulate the global carbon cycle. In addition to the measurements and monitoring necessary to detect the state of physical-chemical-biological systems, and the conditions under which changes occur, it is of equal importance to establish, now, programs for the development of chemical and biological time-series so that we may acquire long-term means. Such means and their standard deviations in the atmospheric sciences are called climatologies and are used to determine frequency spectra and the amplitude and direction of changes. These are a basic input to dynamical circulation models. Similar information is also needed, and for similar reasons, for physical-biogeochemical conceptual models of the ocean. "Change" must be defined in terms of direction, rate and amplitude and this can only come from serial observations through time and over sufficient space. Records such as these over enough time... "provide a valuable means to test our understanding of feedback mechanisms even in the absence of a complete understanding of what caused the climate change" (Hansen *et al.*, 1984).

II. Plan Outline

In view of the strong evidence for a pivotal role of the biology and chemistry of the ocean in the regulation of global cycles of carbon and because of the possible consequences of large scale climatic perturbations to ecosystems, our working group examined a number of measurements that should be a part of a global ocean observing system. We distinguished three major classes of effort, one of them immediate and the other two requiring longer development time and larger scale commitment. It is our belief that our recommended programs of measurement will be essential to describe, in a quantitative way, *how* the systems are structured on large scales and *how* they change. These sorts of descriptions must precede or at least parallel the generation of hypotheses designed to help us understand the processes behind *why* the observed changes occur. Information derived from this *how* and *why* sequence can form the bases for both numerical and statistical predictive models which incorporate biological and chemical "climatology" in a fashion similar to the GCM inclusion of atmospheric climatologies.

III. The Framework

We should be able to describe the frequency spectra of basic biogeochemical variables from high frequency of measurement made over a significant period of time (perhaps decades) and space (basin-wide) so that any changes in the relevant chemistry and biology of the oceans may be detected against a very noisy background; so that the statistical inter-relationships between variables may be examined through cross spectral studies and so that the response of the system to climatic perturbations can be quantitatively described.

The set of observations we recommend will enable us to do such studies. But these observations need not and, indeed, cannot include the full array of community-ecosystem components nor all of their complex functional relationships. The general behavior of any natural ecosystem can be adequately described from a relatively small number of index measurements without knowing all of the details of the intermediary mechanisms (Fig. 1). This sort of information will provide a solid basis for both hypotheses testing and, eventually, the development of predictive models of the biogeochemical system. For the use of planners and policy makers, such models do not need to contain the details of the system nor forecast the exact timing of change nor depict all of the altered functional relationships. They need only to capture the ensemble statistics of a large number of these details to detect trends.

Although such a shortcut approach will greatly simplify one aspect of our measurement problems, it will not reduce the temporal or spatial extent of data required. This is because of the highly variable systems we are dealing with, because regions are out of phase and because all of the (few) available biotic time-series show a very clear red-spectrum, that is, much of the variance is of low frequency and large scale (Haury *et al.*, 1978; Chelton *et al*, 1982). We know that productivity and biomass, and therefore carbon utilization, vary on many time/space scales. Although there is an observed red spectrum there are good reasons to suspect that other, higher, frequencies are of importance in the regulation of the system and that perhaps some of our low frequency observations could be aliased by events on other time scales. On the basis of these considerations it seems that relatively high frequency, large scale, long term measurements are essential.

The processes responsible for variations in ocean biogeochemical cycles, and their interactions with the atmosphere, represent one of the largest sources of uncertainties in the prediction of the future climate. To reduce these uncertainties and to evaluate the response of the marine ecosystem to climate change, will require synoptic observations on global scales over at least several decades, with sufficient spatial and temporal resolution to resolve the dominant frequencies and wavenumbers of variation. These measurements can now be made using a combination of observational platforms in space, in the air and at sea; it is only through the use of such observations that the objectives on the global scale can be achieved.

Remote observations cannot stand alone; they require for their interpretation a rigorous parametrization of small-scale physics and biology. This parametrization is dependent on critical field observations and experiments, and on the development of appropriate models of the upper ocean. The models in turn will depend on the observations for initialization and constraints. Therefore, the satellite and *in situ* observational data are integral parts of an iterative coupling between observations, experimentation, and modeling efforts. Any of these in isolation will prove insufficient.

We have divided our specific recommendations into three categories: A. "Near term enhancement of existing time-series programs," B. "New long term observational systems," and C. "Additional Considerations."

IV. Programs of Measurements

A. Near Term Enhancements

We conducted an inventory of biogeochemical time-series. This included both coastal and oceanic programs with durations ranging from several months of repeated measurements to four decades of monthly measurements. Most of these programs have been terminated for one reason or another; others have just begun and two, of long term duration, are on-going. It is our recommendation that three of these extant programs be selected for enhancement. These are as follows:

1. JGOFS Bermuda

The International JGOFS (Joint Global Ocean Flux Study) has established two long term time-series stations, one near Bermuda and one near Hawaii. Other such stations may be established in high latitude areas, in coastal regions, and in areas representative of additional large ocean basins. A suite of measurements is made at least at monthly intervals to provide information on biogeochemical cycling and flux of carbon and other biologically important elements (Table 1). This set of stations will be an important component of the planned global observing network for biogeochemical variables. They will serve as anchor points of the network that will provide not only a time record of a rich suite of descriptive ocean variables, but also a set of process measurements and correlative analyses that will provide insight on the how and why of observed changes in the ocean.

These anchor points should be augmented by a more abundant set of measurements, perhaps from instrumented moorings and buoys. These will provide the needed information on spatial as well as higher frequency temporal variability of a limited set of key variables. These variables include meteorological data (wind speed and direction, air pressure, humidity), incident solar radiation, sea surface temperature, upper ocean profiles of temperature, salinity, transmissometry and/or fluorometry, *in situ* optical properties, and ideally dissolved oxygen and partial pressure of carbon dioxide. An ADCP instrument should be included to provide depth-resolved currents and zooplankton biomass.

Although the physical measurements taken here, at Bermuda, are of long duration, it has only been in the past 2 years that a spectrum of biology and chemistry have been added (Table 1). This monthly series is not far from the island and there were some doubts expressed about the degree to which measurements taken here are representative of a larger area of the North Atlantic. Consequently, we also recommend that a study be made of the correlation length scale of variables measured at this point be determined on a number of occasions. These should be done from ships running transects where replicated measurements are made at various distances from the time-series station location. A further recommendation for this station is that a series of much higher frequency measurements be made at the site of all of the properties for the purpose of determining that part of the frequency spectrum missed by monthly measurements and in order to begin the process of assessing the effects of aliasing on the monthly measurements. If these high frequency measurements are to be derived from the buoys mentioned earlier they must be compatible (i.e., intercalibrated) with the existing time-series methods.

2. JGOFS Hawaii

Our second recommendation, essentially repeats our first, but for the JGOFS station off Hawaii. This station also is occupied monthly and is near enough to the island chain to perhaps be influenced by island effects. Therefore, correlation length scale or spatial coherence studies should be done here also. Since these data too might suffer from aliasing, we feel that high frequency (at least daily for two weeks) be done here on a seasonal basis, but for more than one seasonal cycle.

Buoys may be developed for this purpose but, as above, their measurements must be compatible with the main series.

3. CalCOFI

Our third recommendation is that the on-going NOAA-SIO collaborative study of the California Current (CalCOFI) be enhanced. This 40 year spatial time-series of monthly and (later) quarterly measurements is the largest, longest, and most detailed oceanic time-series in existence anywhere. However, since most of the financial support in the past 10 years or so has been directed to data acquisition and processing rather than analyses, there is a great need to update the data analyses and interpretations in order to describe the conditions of the decade 1980 to 1990 as compared to the previous three decades. The time-series analysis of this first 30 years (Chelton *et al*, 1982) showed that large variations in biomass were intimately tied to changes in the mass transport from the north rather than local events. This is a clear demonstration of the role of climatic forcing of changes in large scale ocean circulation and the biological response to those changes. We do not know if this relationship persisted in the decade of the 80s during which there was a major Californian El Niño. The purpose of this updating being to ask if a "change" has occurred and to determine if the excellent relationship between large-scale ocean physics and ocean biology still holds. This program also may suffer from the aliasing problem and the need for high frequency measurements exists. However, in this case, because the program is spatial as well as temporal and because of the known heterogeneity and strong horizontal gradients of the region, a different approach was suggested. A closely spaced grid of perhaps as many as six stations where a spectrum of physical - chemical - biological variables are measured should be installed and funded for an indeterminant time (but not perhaps forever). These may even be moored buoys with automated sensors if the appropriate ones can be developed and calibrated within a reasonable time frame. These intercalary high frequency measurements imbedded in the grid of stations now sampled quarterly should provide adequate data on high frequency and episodic events and a test of the aliasing argument. In general the CalCOFI data set has been underutilized due mainly to lack of support. Further analyses of all of these data should be encouraged.

In addition to being vital components of the operational biogeochemical observing network, all of the above time-series stations can serve as test beds for providing calibration for new *in situ* sensing systems. They provide the advantage of already funded traditional measurements of variables for which sensors can be developed, and of logistics support for deploying and servicing prototype sensor packages.

B. New Long Term Observational Systems

In order to provide useful global coverage of the sea surface and the ocean interior a large measurement program must evolve. However, it is possible now to recommend components which will clearly serve as a basis for such future growth and from which we can learn much. Traditional oceanographic platforms such as ships and moored buoys will play an important role for the foreseeable future, but satellite observations, Volunteer Observer Ships (VOS) systems and perhaps large Deep Sea Observatories (Wiebe *et al*.. 1987) will also be needed. Of these possible systems we concentrated on the VOS concept by discussing the development of a "super package" of unattended sensors which could make measurements along a ship's path via a flow-through sea water system. This is to be used in a VOS program of measurement similar in concept to the CPR program already in existence (Oceanographic Laboratory Edinburgh 1973; McGowan, 1990), but with greatly improved and expanded measuring capabilities (Table 1). We also agreed that a manned VOS program be created. The development and deployment of a sensor package in combination with a trained operator would provide a major return for a relatively small investment. For example, such a program would constitute a minimal interference with the activities of WOCE or TOGA and yet yield a superlative biogeochemical data set.

Our working group examined a number of measurements that should be part of such a global ocean observing system. For example, studies of the carbon dioxide system in sea water need a global series of measurements urgently, so as to obtain information about the extent of variation that exists in time and space. We distinguished between two major classes of measurement approaches: those that could, in principle, be made part of a VOS program using instruments that are presently available; and other possible instrumental approaches that require substantial further development.

Complete information about the carbon dioxide system in sea water can be obtained if two analytical measurements are made (in addition to measurements of temperature and salinity), thus a system to be used by a VOS or buoy program should have parallel measuring systems for two carbon dioxide parameters. Although it is possible to make assumptions about the value of one of these parameters, for example assuming a constant ratio between salinity and total alkalinity, the necessary error from this assumption degrades the measurement quality substantially.

At present, limited progress has been made towards automating measurement systems for the various carbon dioxide parameters. Most work has gone into determining one of the more important parameters: the mole fraction of carbon dioxide in equilibrium with surface sea water. A number of prototype research instruments have been constructed to measure this. These systems typically flow a high volume of sea water through a spray chamber equilibrating a small amount of air with the sea water: they subsequently analyze the amount of carbon dioxide in this air using either a non-dispersive infra-red analyser, or gas chromatograph. Such instruments are capable of being highly automated, and of running with minimal operator attention.

Another parameter susceptible of direct automated measurement is pH (a measure of the hydrogen ion concentration of sea water). Nowadays, oceanic pH is only measured infrequently. The reasons for this are manifold, and reflect problems both with the experimental measurement itself and with its interpretation. Nevertheless, pH is potentially a very valuable measurement. It reflects the thermodynamic state of all the various acid-base systems present in sea water, particularly the geochemically important carbon dioxide system, and is thus indicative of the processes involved in production and respiration. Furthermore, it is possible to make pH measurements with a high precision and accuracy, and at a high sampling rate. Again, prototype research systems have been developed already to measure surface water pH electrometrically. An alternate approach which holds out significant promise is based on making spectrophotometric pH measurements using a diode array spectrophotometer. If both pCO_2 and pH are measured, the other two important inorganic parameters (total dissolved inorganic carbon, DIC and carbonate alkalinity) can be calculated.

These two analytical measurements are capable of use in a VOS program with only a small amount of further development, provided that the system is accompanied by a trained analyst to identify and deal with any problems. In contrast, placing instrumentation on buoys requires a substantial rethink of our present approach to these analyses so as to devise analytical systems that have a high degree of stability and low power requirements. Although some developmental work is in progress to develop systems based on optical fiber sensors, they are far from being deployed in the immediate future.

Zooplankton grazing is a fundamental process in the transfer and transformation of organic carbon at all depths. Knowledge of biomass changes are of further significance because the two 40 year spatial time-series in the North Atlantic and North Pacific have provided us with our unparalleled record of biotic long term means and standard deviations (McGowan, 1990). This component of the ecosystem can when properly "calibrated" serve as a proxy indicator for entire system changes over the past four decades during which there were significant climatic perturbations (the two large El Niños, for example). Any large changes in the biomass of zooplankton suggest concomitant changes in the processes that produced that biomass. Further there is abundant evidence from the North Pacific that most of the flux of organic matter to intermediate and deep water is of animal origin, not plant. Thus provisions should be made to continue such measurements and to expand them as part of a large scale VOS program. At the present we have only one commercially produced instrument for observations of zooplankton biomass that is non-invasive and capable of untended deployment for extended periods of time. This is the Acoustic Doppler Current Profiler (ADCP).

The ADCP was chosen as an essential instrument because it records several important variables simultaneously (current speed with depth, current direction with depth, biomass of zooplankton with depth) and thus provides a cost-effective method of investigation of physical and biological parameters. The non-invasive characteristic ensures that zooplankton biomass is estimated without the errors normally occurring because of avoidance and clogging of towed samplers. The untended and long term recording capacity of this instrument enable its widespread use.

1. Initial VOS Programs

It is recommended that initially two VOS programs be established. One of these in the Northwest Atlantic and the other in the Northeast Pacific. The Atlantic program should consist of repeated line-transect data between New York/Boston and Bermuda. Such a line would provide a valuable tie between the JGOFS time-series at Bermuda and measurements being made along the eastern seaboard, especially those planned off Georges Bank, a site chosen for extensive study by GLOBEC. The other line section would run from Los Angeles/San Francisco to Hawaii. Such a line would tie together the 40 year studies of CalCOFI with those of the JGOFS series off Hawaii. These two projects would not only serve as pilot studies but would provide invaluable and virtually unique information on large scale processes and events and the connections between their respective end members *and* between the two oceans.

Table 1 summarizes the measurements of on-going time-series recommended for enhancement and those of our VOS proposed program.

2. Autonomous Technology and New Measurement Systems

A well balanced system for making new, large scale, dense sets of observations will require more than ships and satellites. Platforms such as moored instrumented bouys and Lagrangian surface drifters will be necessary. Such platforms can provide continuous information from isolated ocean regions and high temporal resolution information in areas of special interest.

In addition to the, by now, standard wind, air and SST, pressure and subsurface currents, instruments are under development which are intended to autonomously measure upwelling and downwelling radiation, water transparency, oxygen, fluorescence, bioluminescence and ADCP derived estimates of zooplankton biomass. The development and extensive calibration of these should be encouraged. Free floating Lagrangian drifters can now or in the near future provide platforms for biogeochemical measurements. BIOSPAR now in final stages of prototype development dual-beam acoustics to measure zooplankton biomass, size and numbers to depths of 50 to 100m.

New systems must be developed. As indicated above, our working group examined a number of variables that should be part of a global ocean observing system. We distinguished three major classes of measurements: one was those that can, with little more effort, be incorporated into a "package" to be used routinely within the context of a VOS program; another was similar but required specialized expertise, i.e., a "manned" VOS program. A third category were those that we felt could be developed within a 1 to 3 year time frame, given sufficient support becomes available. Table 2 summarizes our conclusions on new measurement systems.

3. Data Processing and Modelling

A large, eventually global, network of observing programs and autonomic sensors will generate an unprecedented amount of data. These will require an assimulative, processing and quality control apparatus of a large capacity and high standards. Our committee foresaw two generic users of such large data banks: those who wished to describe the fields in time and space, do correlative studies, conduct spectral studies and search for change through time-series analyses, basically employing strong inference statistics, the other group consists of those who will use the distribution of variables provided by GOOS in coupled biological/physical models in a predictor/corrector mode to allow nowcasting and short term forecasting of biological fields. Such multiple uses of the data are entirely compatible and can be complimentary. However considerable thought and effort must be put into the design and organization of a data processing group and the format of their products.

C. Additional Considerations

The recommendations, above, were our main considerations and conclusions. However in the brief period of our meeting there were other topics introduced but not thoroughly discussed. With subsequent discussions and study, some of these have assumed real importance. Although we recommend only two regular VOS transects, it is obvious that more will be needed to describe the conditions in the upper layers of the Global Ocean, therefore, any effort by the U.S.A. should be coordinated with the larger international effort. In this connection we view our two VOS sections as critical immediate new pilot studies that should provide us with the preliminary experience and data that will be essential in designing a larger effort.

Another important point involves the recognition of the forty year time series of the Continuous Plankton Records (CPR) of "tape color" and zooplankton abundance in the North Atlantic done by British workers (see McGowan 1990 for review) and the French continuous chlorophyll records from central equatorial and South Pacific (Dandonneau 1979; Dandonneau and Gohin 1984). These are extremely valuable historical data sets and they must somehow be intercalibrated with any new efforts. Further the experience of these two groups in setting up and maintaining very successful VOS programs is worth emulating. Collaborative studies with South American countries should be considered. A network of coastal and island based monitoring sites in the great South Pacific could make great contributions.

Our emphasis in the main body of this report has been on measurements in the surface layers (VOS) or in the water column at only three sites (JGOF Bermuda, JGOF Hawaii, CalCOFI). These are not enough to provide even the preliminary information for a carbon balance sheet, which is itself a pre-requisite to modelling. Detailed biogeochemical measurements in entire water columns, far from land, at open ocean sites must be made. These would feature close sample spacing (in the vertical) for water column profiles of a number of hydrographic and biogeochemical properties. Replicate profiles should be done so that means and standard deviations can be reported. Such sites could be occupied once a year or so over the next few decades. The purpose being to detect long term variations and trends and to separate these from local short term variability ("noise"). Since the intermediate, deep and bottom waters are such large reservoirs of carbon, nutrients and other chemical species, the data derived from such a project will be of great immediate and future value.

FINAL REMARKS

Our group expressed two basic concerns about the study of global change and the ocean. The first was "how do we detect such a change as it is occurring" given that we are dealing with a highly variable mobile system? Secondly "what will be the consequences of such a large scale perturbation" to the structure and function of oceanic ecosystems? Evaluation of these, poses questions at large spatial scales over long periods of time relative to traditional chemical or biological studies of the ocean. It is entirely possible that there will be fundamental changes in the functioning of given ecosystems, changes in boundaries between major ecosystems and even the development of new ecosystems (Shugart, 1990). A new array of environmental observations are called for to evaluate these consequences all of which will have feed-back loops to the carbon cycle itself.

While our immediate top priority is given to global oceanic carbon dioxide system and chlorophyll measurements in the upper layers we recognize the need for a broader approach to biogeochemical measurements in the context of GOOS. The rates of change with respect to time of dissolved oxygen, plant nutrients, dissolved inorganic carbon, dissolved organic carbon, micro-organisms, phytoplankton and zooplankton abundances are also key parameters in the ocean-atmosphere-climate system.

The role of biogeochemical processes in the fluxes and residence times of oxygen, carbon, nitrogen, phosphorus, sulfur and many other elements is of vital importance in the balance of the earth's habitability (Lovelock, 1989). These processes must be better known and documented through three dimensional global ocean observations. Vastly improved determination of the spatial and temporal scales of variability of these parameters is required. Programs for long term systematic time-series not only in the surface waters but in the entire water columns will be needed. Advances in measurement technology and sampling design will be essential. It is the purpose of this report to suggest practical ways we can begin these tasks.

SUMMARY RECOMMENDATIONS

A. Enhancement of Existing Time Series

1 JGOFS Bermuda station needs higher frequency of measurements to evaluate the aliasing problems. Studies of the degree to which this station is representative of a larger area must be done, therefore, correlation length scale of variables should be determined.

2. JGOFS Hawaii suffers the same problems as Bermuda. Higher frequency measurements and correlation length scale programs should be done.

3. CalCOFI 40 yr spatial data set has been underutilized. Time series analyses should be brought up to date. Higher frequency studies should be done.

B. New Long Term Observation Systems

1. Two pilot VOS programs should be instituted, one in the Northwest Atlantic, the other in the Northeast Pacific. These are to include biological and geochemical measurements as well as physical.

2. Several deep-water sites should be occupied periodically to obtain detailed entire water column measurements for statistical descriptions of the "State of the Oceans."

3. New observational systems, to be effective, will require the substantial improvement of existing technology and, in some cases, new technology. This should be supported.

LITERATURE CITED

Bolin, D., Döös, B.R., Jager, J. and Warrick, R.A., eds. 1986. The Greenhouse Effect, Climatic Change and Ecosystems. John Wiley.

Broecker, W.S., and Takahashi, T. 1984. Is there a tie between atmospheric CO928 content and ocean circulation? Climate Processes and Climate Sensitivity. Hansen, J.E. and Takahashi, T., eds. *Geophysical Monograph, 29*:: 314-326.

Charlson, R.J., Lovelock, J.E., Andreae, M.O., and Warren, S.G. 1987. Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature,* London, 326: 655-661.

Chelton, D.B., Bernal, P.A. and McGowan, J.A. 1982. Large scale physical and biological interaction in the California Current. *Jour. Mar., Res., 40*: 1095-1125.

Climap. Project Members. 1976. The surface of ice-age earth. *Science, 191*: 1131-1137.

Dandonneau, Y. 1979. Concentrations en chlorophylle dans le Pacifique tropical sud-ouest: comparaison avec d'autres aires oceaniques tropicales. *Oceanologica Acta, 2*(2): 133-142.

Dandonneau, T. and Gohin, F. 1984. Meridional and seasonal variations in the southwestern tropical Pacific (14 to 32°S; 160 to 175°E). *Deep-Sea Research, 31*(12): 1377-1393.

Dickinson, R.E. and Cicerone, R.J. 1986. Future global warming from atmospheric trace gases. *Nature, 319*: 109-115.

Hansen, J., Lacis, A., Rind, D., Russell, G., Stone, P., Fung, I., Rudy, R., Lerner, J. 1984. Climate sensitivity: analysis of feedback mechanisms. Climate Processes and Climate Sensitivity. Hansen, J.E., and Takahashi, T., eds. *Geophysical Monograph, 29*: 130-163.

Haury, L.R., McGowan, J.A. and Wiebe, P.H. 1978. Patterns and processes in the time-space scales of plankton distribution. Spatial Patterns in Plankton Communities. Steele, J.H., ed. pp. 277-327. Plenum Press.

Henderson-Sellers, A. 1990. Modelling and monitoring "greenhouse" warming. *Trends in Ecology and Evolution, 5*(9): 270-274.

Lovelock, J.E. 1989. The first Leslie Cooper memorial lecture given at Plymouth on 10 April 1989. Gaia. *Jour. Mar. Biol. Ass'n., 69(4): 746-758.*

McGowan, J.A. 1990. Climate and change in oceanic ecosystems: the value of time-series data. *Trends in Ecology and Evolution, 5*(9): 293-299.

Oceanographic Laboratory, Edinburgh. 1973. Continuous plankton records: a plankton atlas of the North Atlantic and the North Sea. *Bull. Mar. Ecol., 7*(1): 1-174.

Oeschger, H., Beer, J., Siegenthaler, V., Stauffer, B. 1984. Late g lacial climate history from ice cores. Climate Processes and Climate Sensitivity.Hansen, J.E. and Takahashi, T., eds. *Geophysical Monographs, 29*: 299-306.

Ramanathan, V. 1988. The greenhouse theory of climate changes: a test by inadvertent global experiment. *Science, 240* : 293-299.

Shackelton, N.J. 1977. The oxygen isotope record of the last Pleistocene. *Phil. Trans. Roy Soc. Lond. B., 280::* 169-182.

Shugart, H.H. 1990. Using ecosystem models to assess potential consequences of global climatic change. *Trends in Ecology and Evolution, 5*(9): 303-307.

Wiebe, P.H., Miller, C.B., McGowan, J.A., and Knox, R.A. 1987. Long time series study of oceanic ecosystems. EOS. *Trans. Amer. Geophys. Union, 60*(44): 1178-1190.

Williamson, P. and Holligan, P.M. 1990. Ocean productivity and climate change. *Trends in Ecology and Evolution, 5*(9): 299-303.

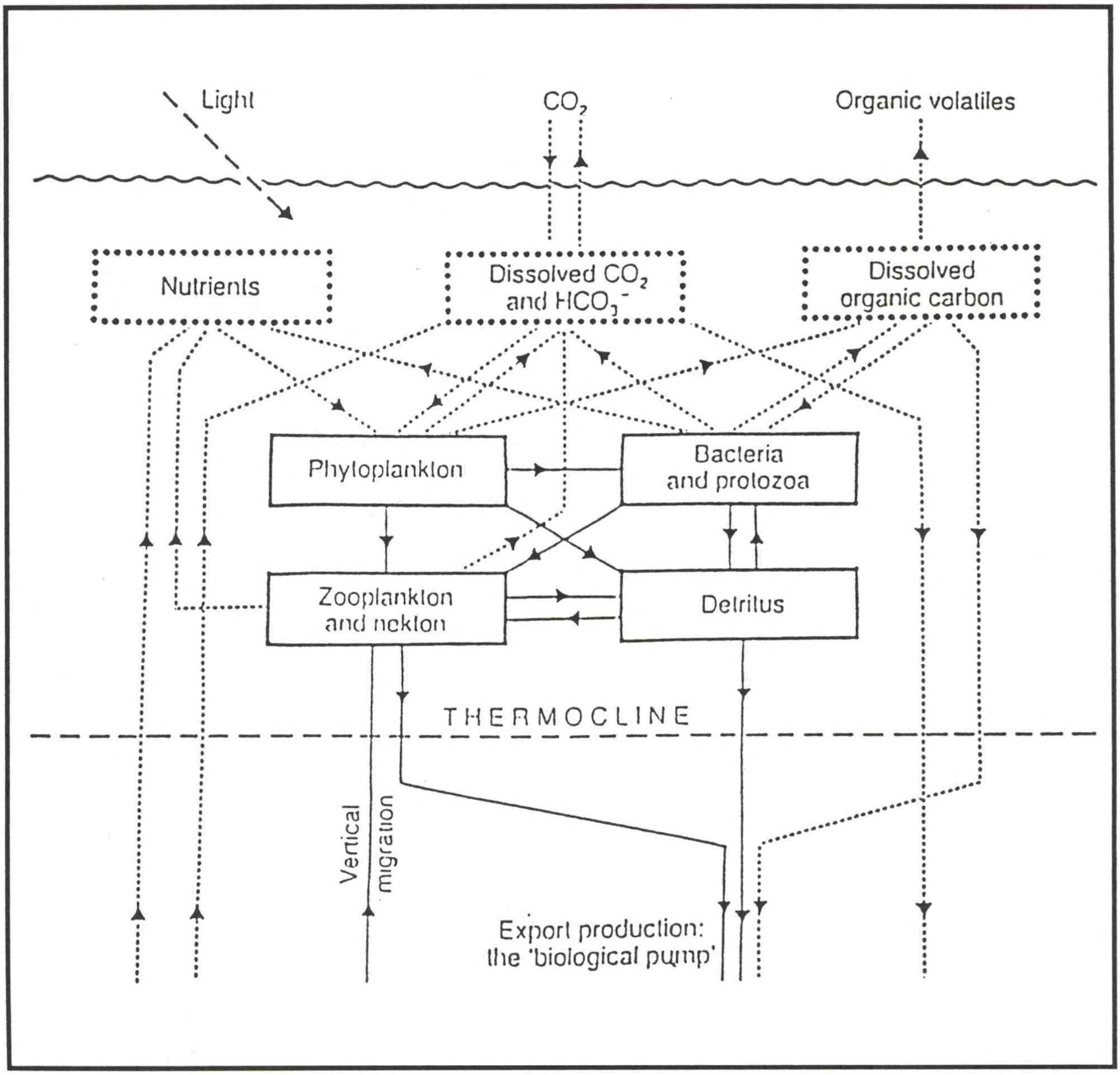

Figure 1. This box model of the "main pathways of dissolved and particulate material controlling carbon fluxes into, out of and within the upper ocean" (Williamson & Holligan 1990) is typical of most such concepts. While it does show the main parts of the system (the boxes) the "pathways" (the arrows) are far less certain and the fluxes along them virtually unknown. Most of these functional rates or "fluxes" are density dependant and non-linear and are, therefore, very difficult to measure. However, the time rate of changes of concentrations within the boxes can be measured, between box sequences of rates of change determined, and the amplitude and direction of non-seasonal anomalies calculated.

Table 1. Measurements being made by existing time series programs CalCOFI and JGOFS and those frequently made by NSF, NOAA, Navy and C G ships. Many of these may be automated for the suggested unmanned VOS program. More may be included in a manned VOS program and also could be done as underway sampling on WOCE or TOGA cruises with a minimum of interference.

Parameters	Time-Series Programs		NSF, NOAA NAVY, CG Research Ships	VOS Unmanned	VOS Manned	WOCE TOGA
	CCOFI	JGOFS				
Temp	X	X	X	X	X	X
Sal	X	X	X	X	X	X
MET (incident light)	X		X	X	X	X
GPS navigation	X	X	X	X	X	X
O_2	X	X			X*	X
Nutrients (AA)	X	X			X	X
DIC/pCO_2	X	X			X (pH)*	X
Ocean Color, Upwelling irradiance			X	X	X	X
DOC		X*				
Fluorometry	X	X	X	X*	X*	X*
Chlorophyll	X	X			calibration	
Phyto Sp.	X					
Pr. Prod.	X*	X*				
Transmissometry	X		X	X*	X	X
Zooplankton Net	X					
Zooplankton Acoustical ADCP	X		X	X?	X?	X

*Some development required.

Table 2. Critical measurements for which further technological development is needed for the sensors to exist as autonomous system.

Sensors	Measurement	Development Comment
Oxygen	Dissolved O_2	Need sensor for long term autonomous deployment, calibration needed
Auto-analyzer	Nutrients	Faster analyses, autonomous instrumentation
Various	DOC	Faster analyses, calibration needed
ADCP	zooplankton biomass	Improved calibration needed
Optical Electrical Acoustic Mooring Drifter	zooplankton size and numbers as well as biomass	All need substantially more development to become autonomous and reliable instruments. Also needed are studies of how these measurements relate to the physical attributes of the organisms.
Satellite Scatterometer	Gas Exchange and Flux	Waiting for them to be deployed More algorithm development needed
Satellite OCI	Phytoplankton pigments	More validation
Fluorometer	Phytoplankton fluorescence	Needs more development to become autonomous and reliable must be calibrated for entire photic zone biomass estimates.
DIC	Dissolved Inorganic carbon CO_2, HCO_3, CO_3	Faster analyses, autonomous instrumentation

II. Workshop Presentations

These papers were prepared by the authors and submitted to the workshop as presentations to provide background material and stimulate discussion.

Observations of the Intermediate and Deep Ocean: A Review of Existing Data and Future Requirements for Climate Research

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Introduction

As we look towards the prediction of climate on time scales of weeks to decades and towards determining the impact of man's activities on climate, the inability to describe and model the ocean circulation and its role in modifying the climate becomes increasingly problematic. The processes that govern the ocean circulation and mixing provide a link between the changes in surface forcing of the ocean and the resulting changes in the fluxes of energy, water and gases to the atmosphere For example, a change in the surface radiation balance will lead to changes in the oceanic heat content, which results in a change in the sea surface temperature and consequently a change in the rate of oceanic cooling of the atmosphere. On a decadal time scale, the changes in oceanic heat content are not confined to the surface mixed layer, but through deep winter convection and Ekman pumping can reach substantial depths in the ocean. The involvement of a greater mass of water increases the time scale of response to any change in forcing, which in turn allows ocean currents to redistribute the change in heat content over great distances.

The estimates of the oceanic transport of heat and fresh water have a large uncertainty. In Figure 1, indirect estimates of the oceanic transports of fresh water in the Atlantic and heat in the Pacific calculated from the surface fluxes are shown. These indirect estimates are compared with direct estimates at a single latitude from oceanic observations. As can be readily observed, the indirect and direct estimates differ substantially. Indeed in the southern hemisphere even the sign of the transport is uncertain.

Traditionally a zonal hydrographic section is used to estimate the meridional oceanic volume and heat flux. In Figure 2, a section taken in 1981 along 24° N in the Atlantic is shown (Roemmich and Wunsch, 1985). This particular section is a repeat of an International Geophysical Year section taken 23 years earlier, although the number of stations has been increased and the distance between stations decreased. The gross features between the two sections are similar with 17 Sv of surface and intermediate water flowing northward in the upper 1.3 km. However, the geostrophic shear between 3 km and 4 km changes markedly between the two sections with the 1981 section having 7 Sv less southward flow between 1.3 km and 3 km and 8 Sv more southward flow deeper. The oceanic heat flux is nearly the same for the two sections, suggesting a change in the heat content of the deep North Atlantic over the past two decades.

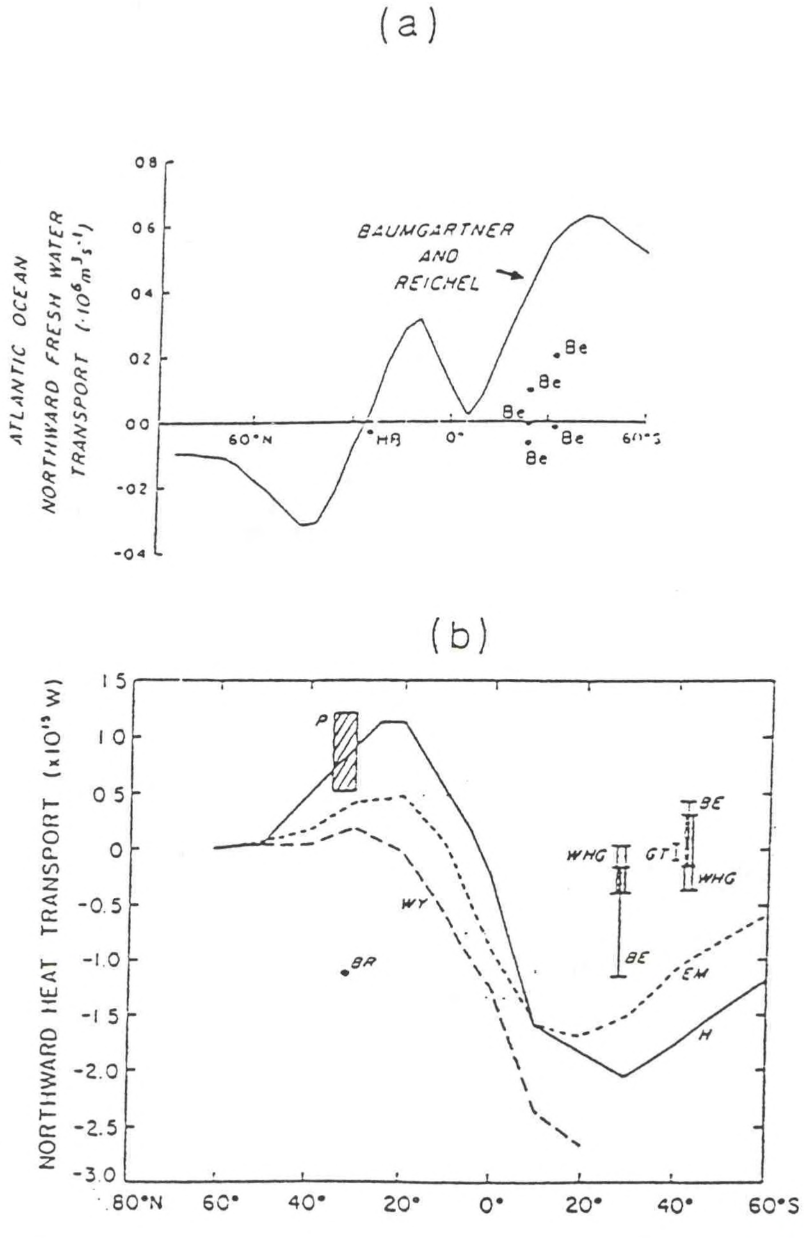

Figure 1. The fluxes of freshwater in the Atlantic Ocean (a) and the heat transport in the Pacific Ocean (b). For the Atlantic Ocean, the solid curve is the indirect estimate from evaporation, rainfall and river input of Baumgartner and Reichel (1975) and the points are direct estimates from hydrographic sections by Hall and Bryden (1982) and Bennett (1978). For the Pacific Ocean heat transport three indirect estimates by Hastenrath (1980; solid curve), Emig (1967; short dashes) and Wyrtki (1965; long dashes) and direct estimates using hydrographic data from Bennett (1978), Bryan (1962), Georgi and Toole (1982), Talley (1984) and Wunsch, et al (1983).

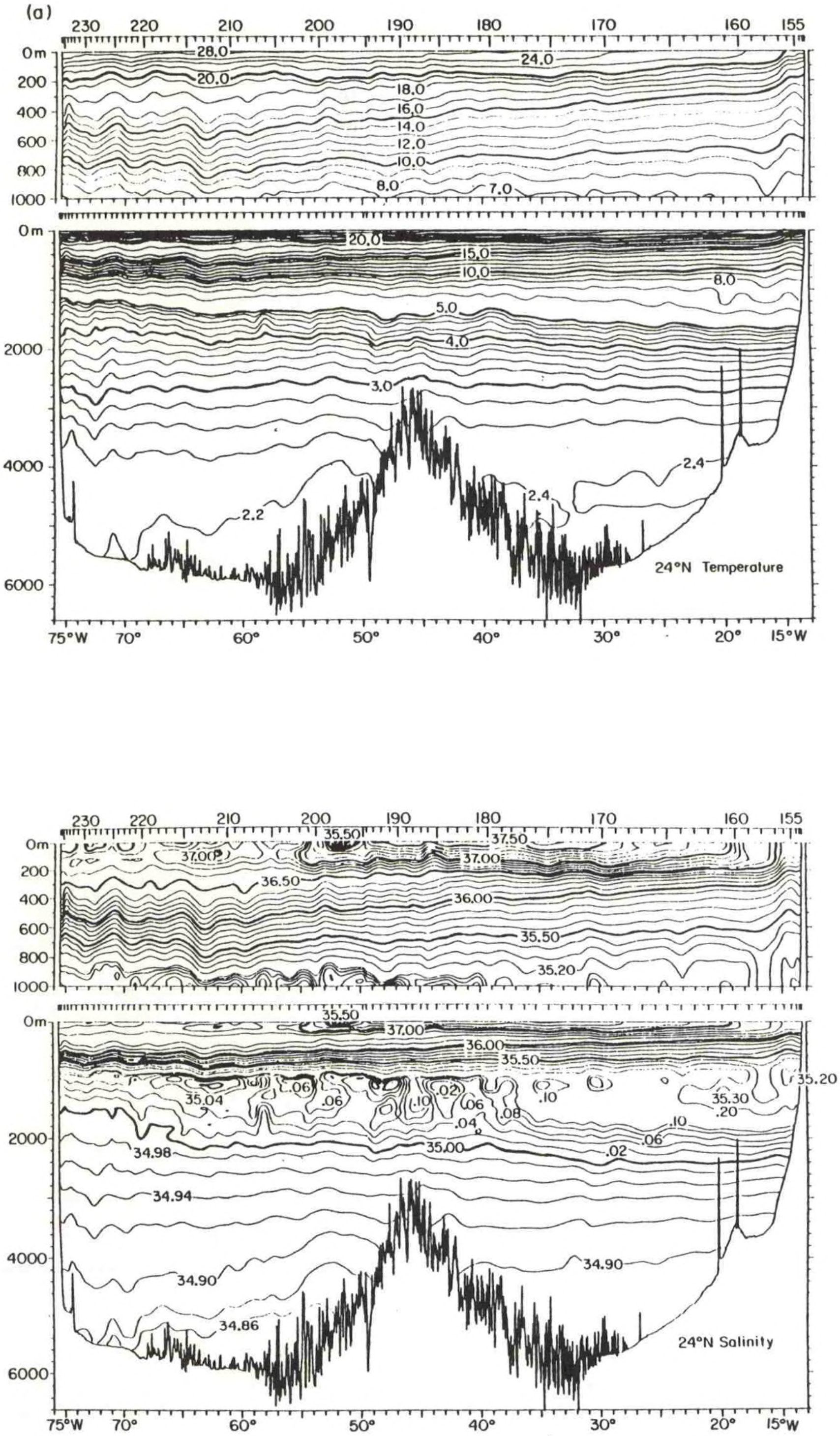

Figure 2. Temperature (a) and salinity (b) data across the North Atlantic at 24°N in 1981 (from Roemmich and Wunsch, 1985).

On a similar time scale, Dickson, et al. (1988) observe a widespread freshening of the northern North Atlantic between 500 m and 800 m in the mid-1970s. Using historical data from weather ships and repeated hydrographic sections, the salinity anomaly is traced back to the Greenland and Icelandic Seas during the 1960s where anomalous weather patterns lead to an enhanced export of fresh polar water. The analysis of Dickson, et al. (1988) suffers from the loss of the weather ship observations during the 1970s which prevents an unambiguous interpretation of the data. However, the power of long time series observations to aid our understanding of the ocean's role in climate change is shown clearly.

To understand the changes noted above, we need to determine several aspects of the the circulation of the ocean. What are the large-scale fluxes of heat and fresh water and the annual and interannual variability of these fluxes? What are the dynamical balances that control the ocean circulation and its response to changing surface fluxes? What is the variability of the ocean circulation and how does it interact with the mean ocean circulation? What are the rates and nature of the formation, ventilation and circulation of the water masses in the ocean?

Present Observational Techniques and Database

A number of techniques are presently used to describe the structure and circulation of the interior of the ocean. These techniques can be broadly grouped in three categories, direct current observations using moored current meters, neutrally buoyant floats and dropsondes, indirect current observations using hydrographic measurements of temperature, salinity and chemical constituents plus physical assumptions such as geostrophy, and acoustic and electromagnetic remote sensing.

During the Subtropical Atlantic Climate Studies (STACS) an intensive effort was mounted to determine the transport of the Florida Current and its annual variability over a three year period from April 1982 to June 1985. Three different techniques were used to estimate the transport, direct current measurements by moored current meters and by direct current measurements using Pegasus dropsonde current profiling plus hydrography and indirect transport measurements from cable voltages. The experimental layout is shown in Figure 3. Nine Pegasus stations were occupied on 96 sections during this period (Leaman, et al, 1987). From these observations it was determined that the flow through the Florida Straits is dominated by meandering of the Florida Current, which is uncorrelated with volume transport variations and the local wind stress. The current meter observations were made from 5 or 6 moorings across the Straits (Schott, et al, 1988). The current meters only sampled approximately half of the total transport with transport estimates increased using the mean shear profiles from the Pegasus observations as depicted in Figure 4. The cable voltages were converted to transport estimates using the mean Pegasus transports (Larsen and Sanford, 1985). Comparisons of the three transport estimates are shown in Figure 5 with good agreement between the different techniques. The mean transport of the Florida Current is 30.5 Sv with an asymmetrical annual cycle of 3 Sv amplitude.

The largest number of deep ocean observations are obtained from hydrographic measurements of temperature and salinity. Using these data, indirect estimates of the velocity can be obtained by assuming geostrophic flow. To obtain estimates of the absolute velocity from the geostrophic shear requires additional assumptions about the flow and its dynamics. A common assumption is the choice of a deep level of no motion. For example, early estimates of the transport through Drake Passage were calculated assuming a 3000 m level of no motion (Whitworth, et al., 1982) yielding an average transport of 103 Sv with standard deviation of 13 Sv for seven hydrographic sections between 1975 and 1980. The same authors use current meter measurements to provide a reference velocity, resulting in a higher transport estimate of 130 Sv with a standard deviation of 10 Sv for four hydrographic sections. However, no criterion for the choice of averaging period for the current measurements exists.

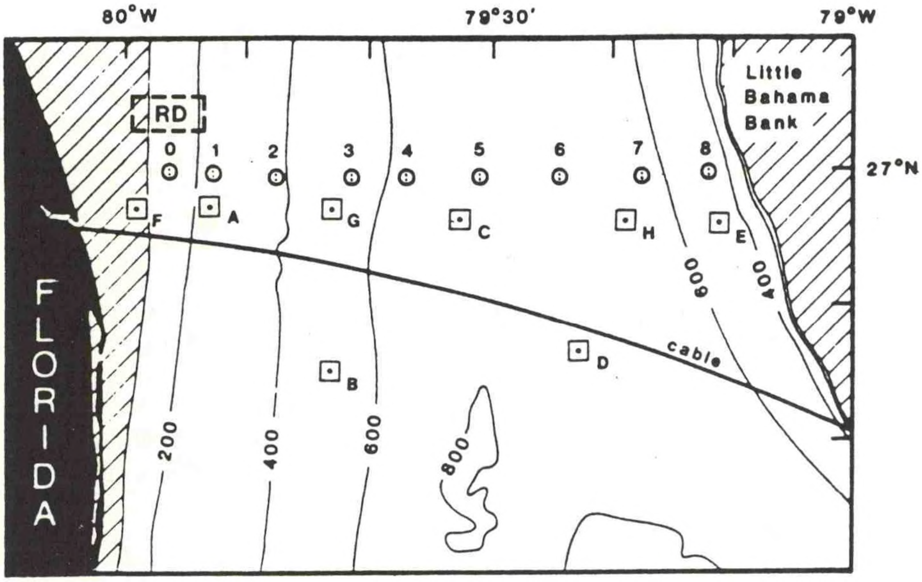

Figure 3. Topography of the Florida Straits showing the positions of the Pegasus dropsondes (circles), STACS current meter moorings (squares) and the submarine cable (solid line).

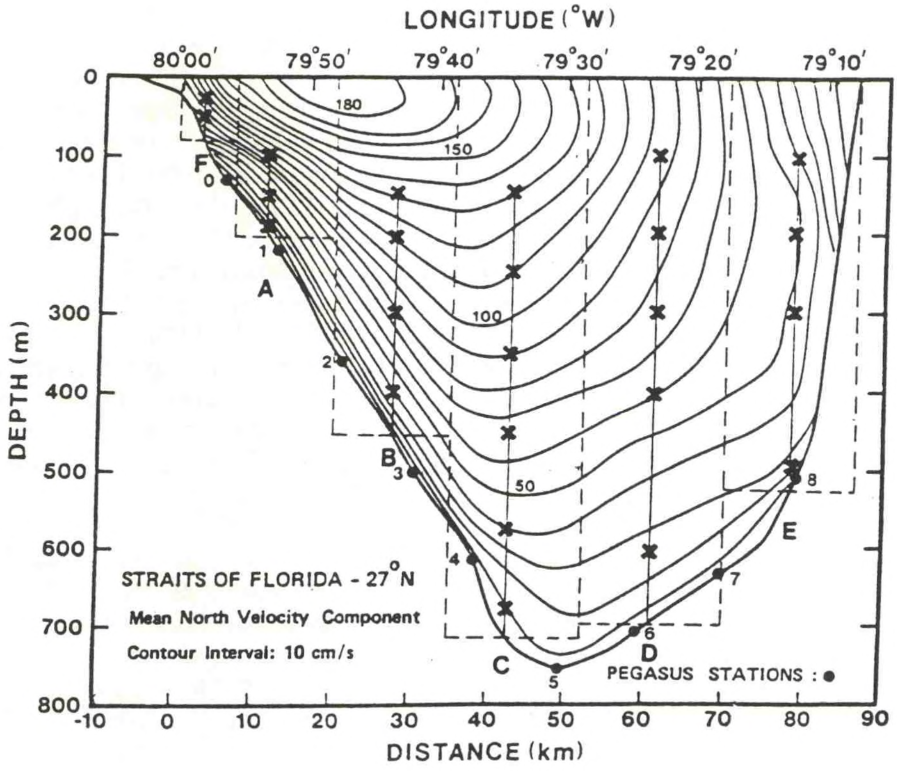

Figure 4. Moored current meter locations superimposed on the mean downstream velocity contours from Pegasus dropsonde sections (adapted from Leaman, et al, 1987).

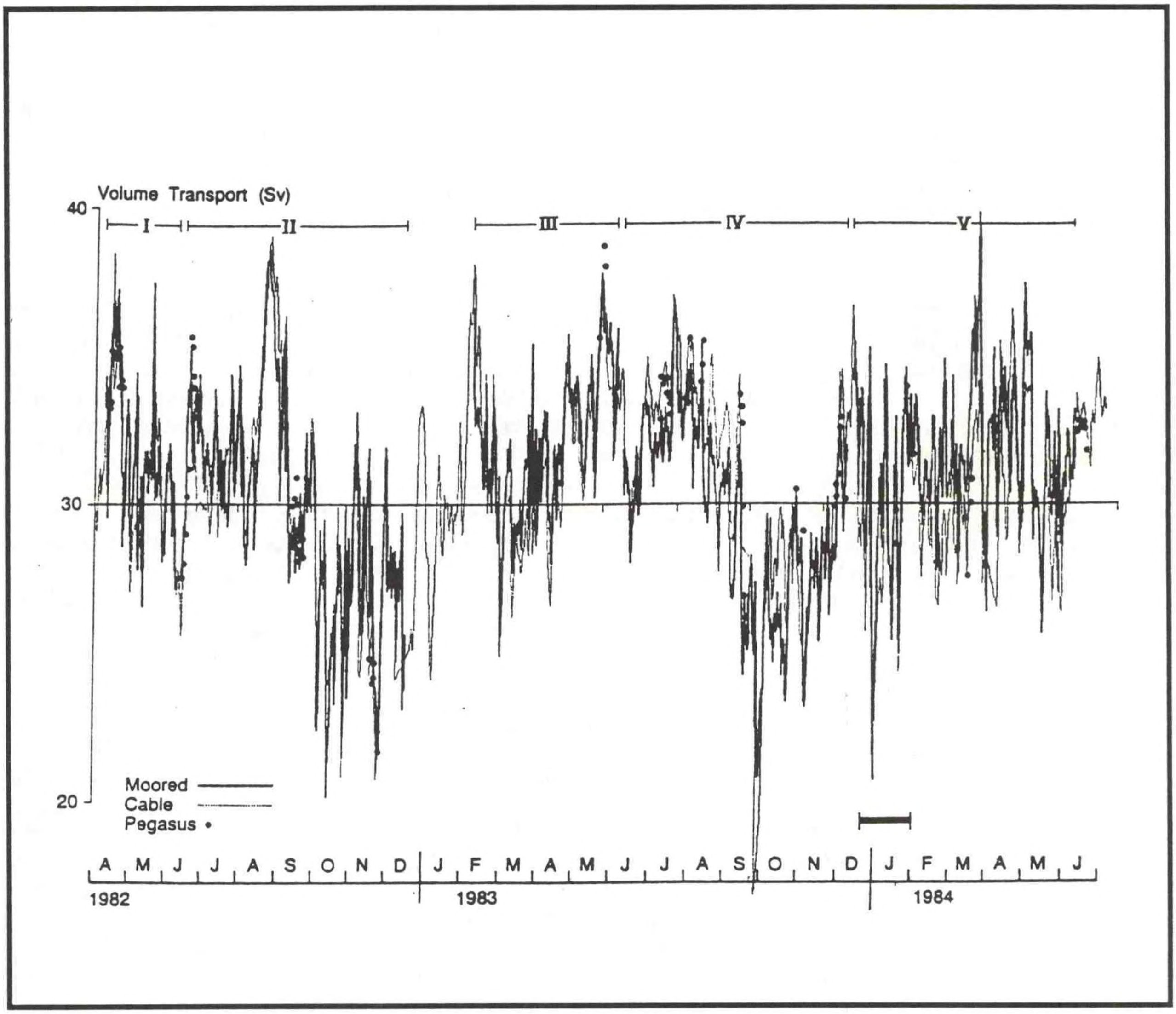

Figure 5. Time series of transport calculated from moorings, from Pegasus dropsondes sections and cable voltages for April 1982 to June 1984.

Other physical assumptions can be used to replace the level of no motion approach to obtain a reference velocity for the geostrophic transport calculation. Stommel and Schott (1977) showed that conservation of potential vorticity and the neglect of relative vorticity can be used to obtain absolute velocity from hydrographic data alone. Olbers, et al. (1985) used the b-spiral technique to infer the circulation of the North Atlantic. In Figure 6, the absolute velocity at 2000 m estimated by the b-spiral technique is shown. This depth is often taken as a level of no motion, but the b-spiral technique yields velocities of the order 1 cm/s at this depth. The resulting circulation is very different from one with an uniform depth of no motion.

Wunsch (1977) suggested that the circulation could be obtained as a constrained inverse problem to determine the reference velocity The calculated ocean circulation can be very sensitive to the choice of assumptions for the constraints. In Figure 7, meridional sections of the zonal integral of the mass transport from two inverse calculations from Wunsch (1984) are shown. The upper panel maximizes the meridional heat flux at 24° N while the lower panel minimizes the heat transport at that latitude. The resulting circulation patterns are quite different.

Direct current observations in the deep ocean have been obtained from moored current meters since the 1960s. At present, there are approximately 2,370 instrument years of long-term current meter data (Dickson, 1989). Long-term is defined here by deployments longer than six months. For the instruments below 2000 m, approximately 70% have mean currents less than 1 cm/s. Reliably estimating these weak mean currents requires multi-year deployments given the large fluctuating currents.

Lagrangian current measurements, such as those shown in Figure 8, have been obtained from SOFAR and RAFOS floats since the early 1970s. These observations are almost entirely limited to the North Atlantic. Float data provide a spatial coverage of the ocean which is not practical for moored instrumentation at the expense of temporal resolution. Schmitz, et al (1988) compared the flow statistics from a two-year mooring deployment and concurrent SOFAR float observations. The eddy statistics compared very well between the two and the mean flow estimates were roughly the same.

Levitus (1988) presents the distribution of hydrographic stations for the 75 year period beginning in 1900. The monthly time series of the number of observations at the sea surface and 1000 m are shown in Figure 9. There are almost an order of magnitude fewer observations at 1000 m compared to the surface. The distribution of the stations over the globe for the 5 year periods 1965-69 and 1970-74 are shown in Figures 10 and 11. The uneven coverage is readily apparent with the most data in the western North Pacific and North Atlantic for the entire decade and relatively little data in the southern hemisphere. In any given year, such as 1967 shown in Figure 12, the coverage can be even worse. In 1967, there is virtually no data in the Indian Ocean and few stations in the Atlantic. For much of the world, inadequate data exists to define the annual cycle of variability.

Recommendations for Continuing Observations

Recognizing climate change in the ocean and understanding the role of the ocean in climate change require systematic and long-term observations. The repeat of the IGY hydrographic sections show that internal changes in the ocean heat content are detectable on decadal time scales. However, a shown by Dickson,et al (1988) the interpretation of these sections will be greatly improved by the addition of strategically located time series observations. The weather ships provided such observations until the 1970s. At present only a few such time series, the Panulirus stations at Bermuda (Wunsch, 1972) and the Hawaii Ocean Time Series (Chiswell, et al, 1990), are being obtained. Similarly, the transport of the major ocean currents and interbasin exchanges should be monitored. Knowledge of the transports, such as the Florida Current transport, and

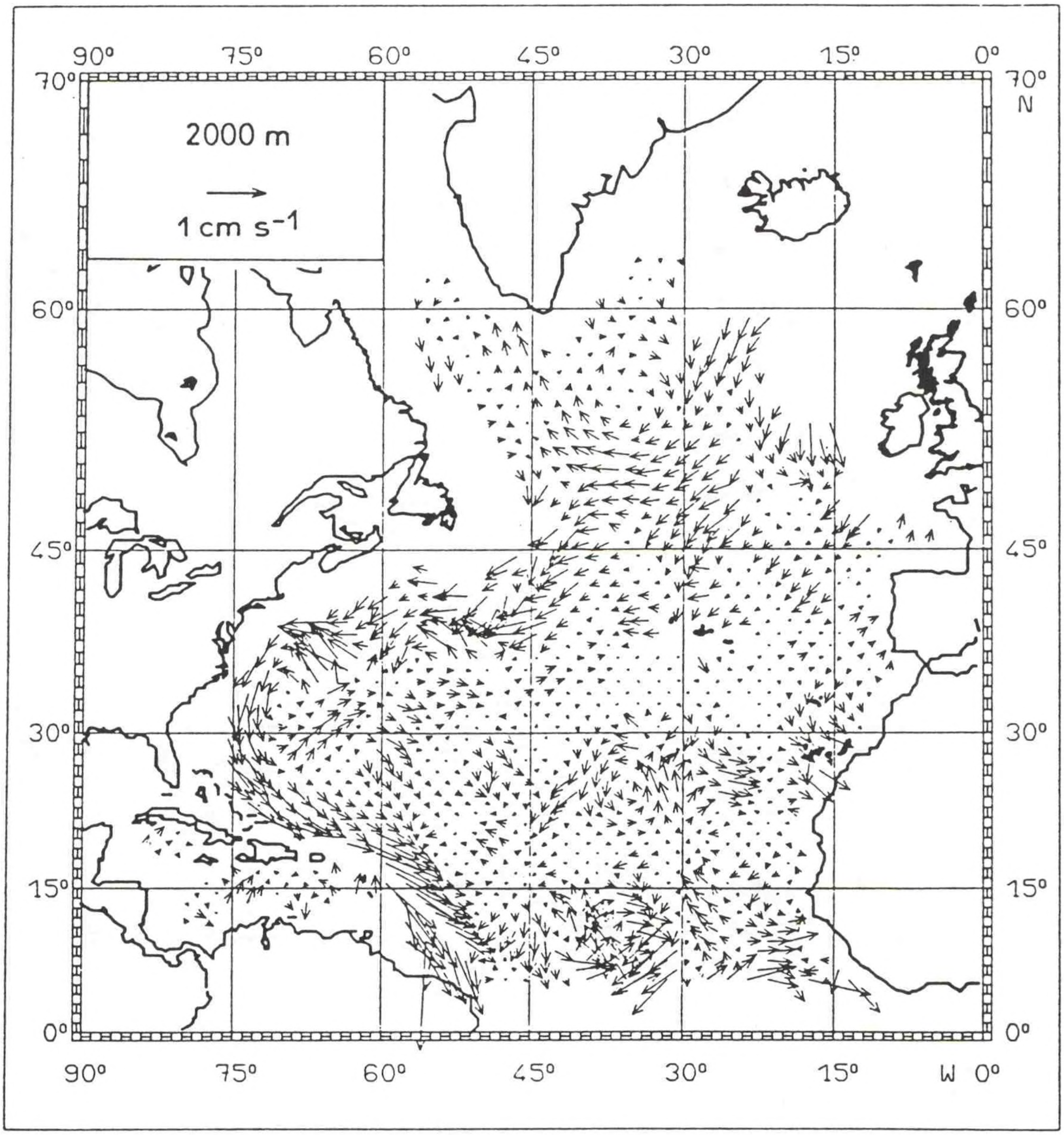

Figure 6. Absolute velocity at 2000 m in the North Atlantic calculated using the b-spiral technique from climatological hydrographic data (adapted from Olbers, et al, 1985). Note the velocities exceeding 1 cm/s in the deep western boundary current inconsistent with the idea of a constant depth level of no motion.

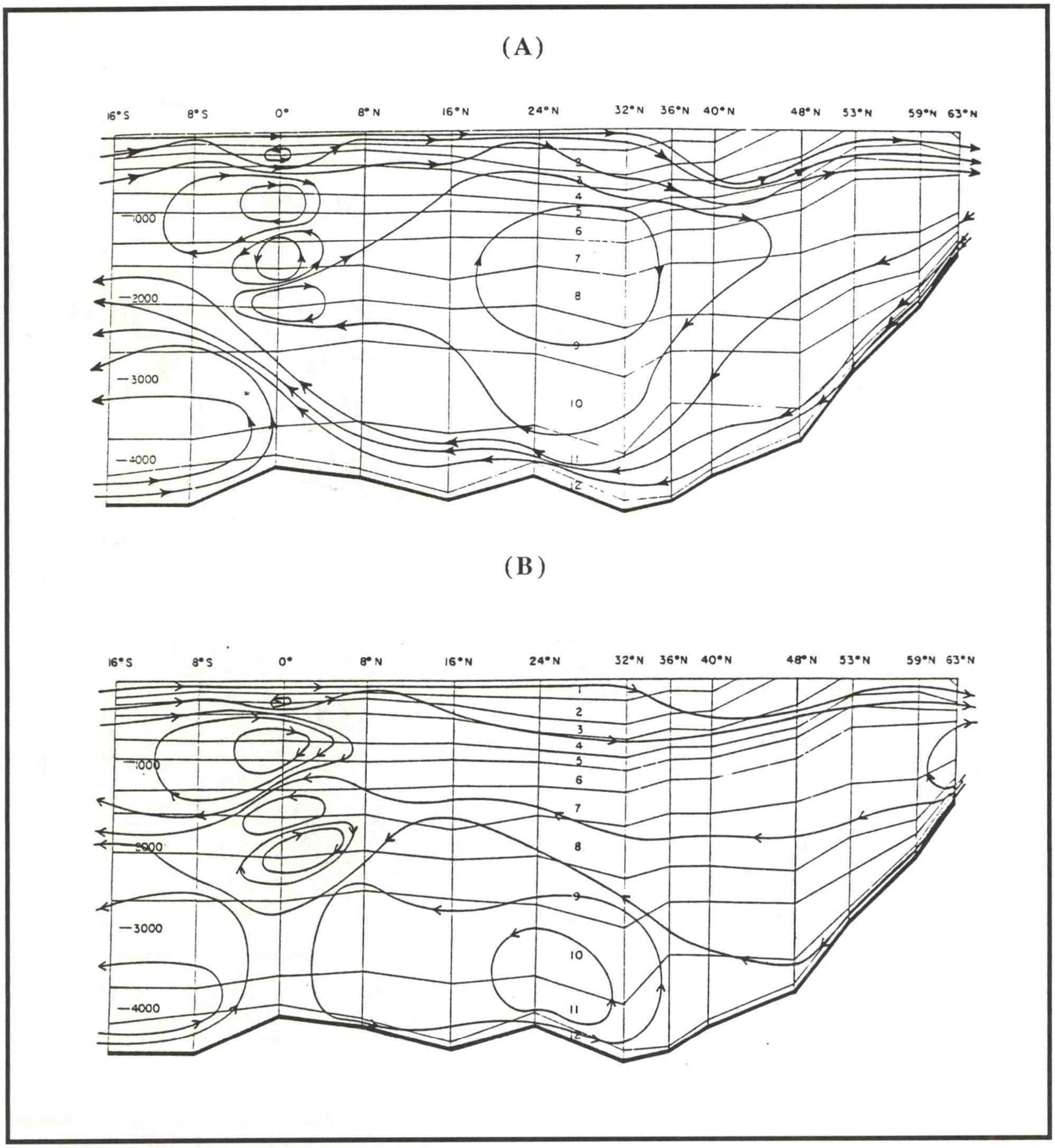

Figure 7. Meridional sections of the zonally averaged mass transport in the Atlantic Ocean (adapted from Wunsch, 1984). These sections result from two different inverse calculations. In (A) the inverse calculation is constrained to maximize the heat flux at 24°N, while in (B) the heat flux is minimized. The contour intervals are 5 Sv.

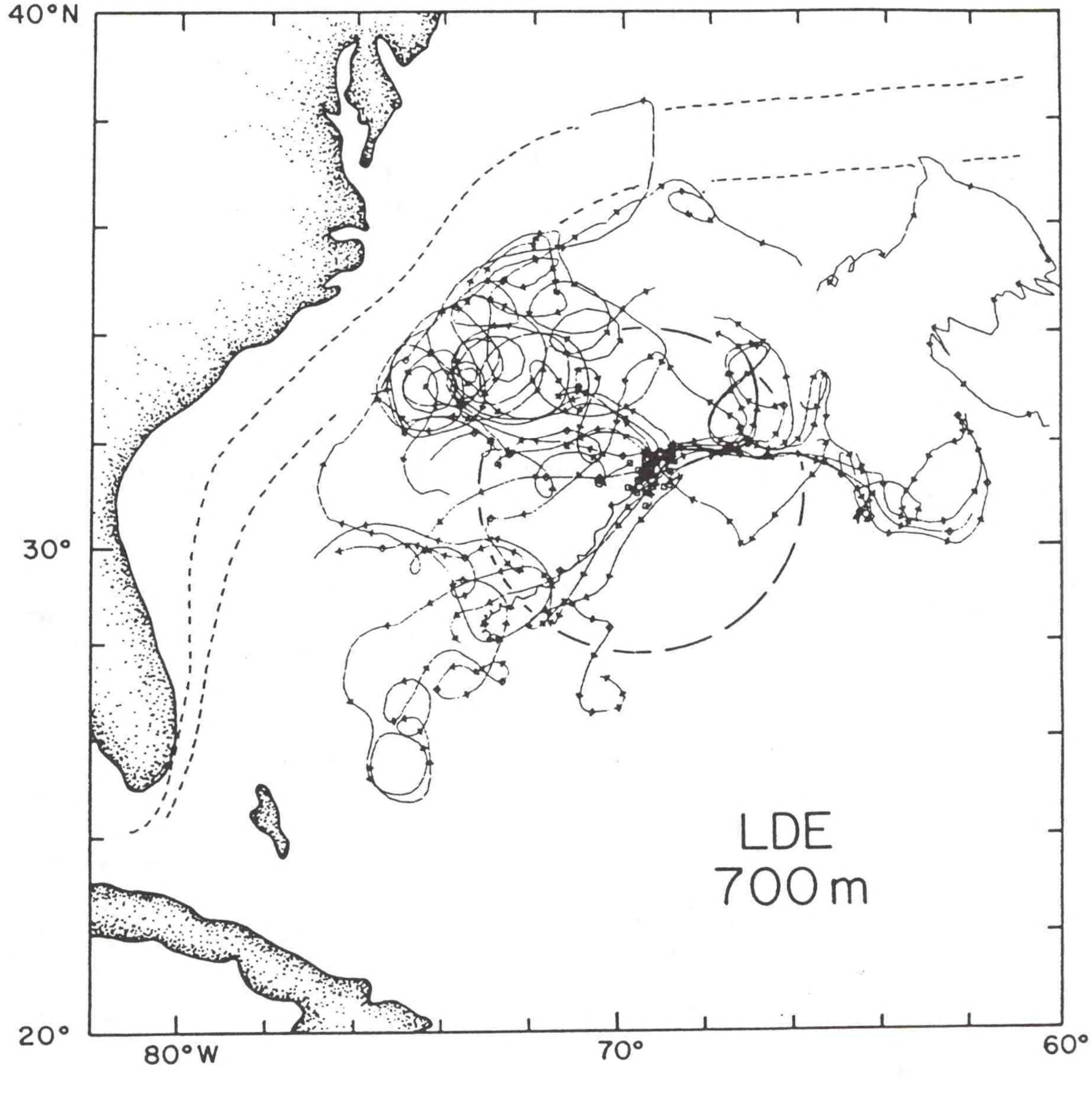

Figure 8. Trajectories of floats at a depth of about 700 m deployed during the POLYMODE Local Dynamics Experiment (adapted from Kamenkovich, et al, 1986). All floats were deployed within a 100 km radius of 31°N, 70°W. The broken circle has a radius of 400 km centered on that location. The short dashed lines are the envelope of Gulf Stream paths. The arrowheads on the tracks are placed at 10 day intervals.

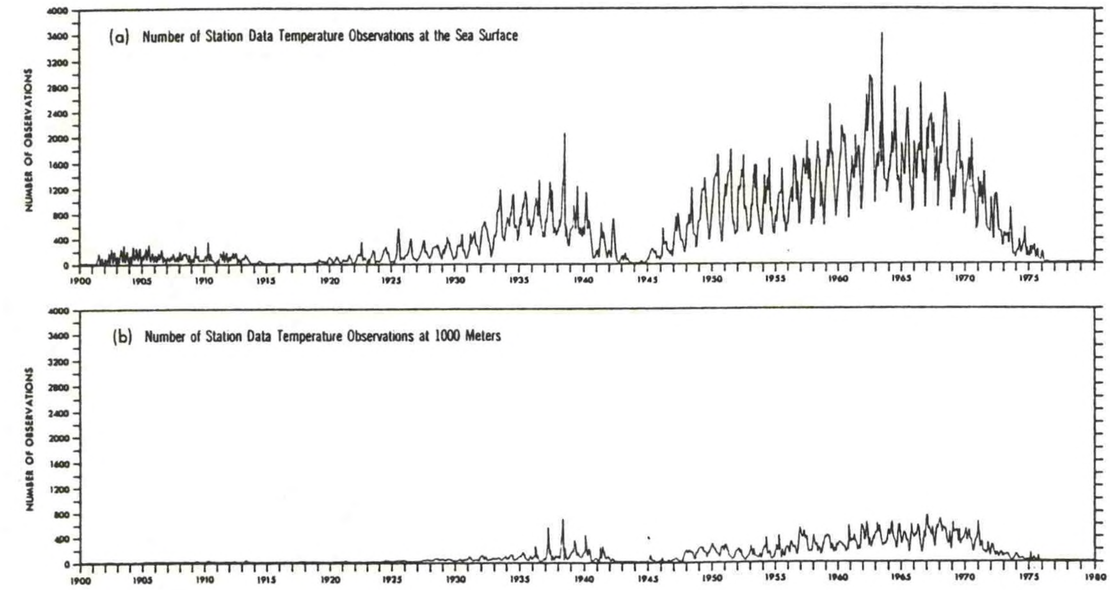

Figure 9. Monthly time series of the number of temperature observations from hydrographic stations at the sea surface (a) and at 1000 m (b) from Levitus (1982). Note the order of magnitude decrease in the number of observations at 1000 m compared to the sea surface.

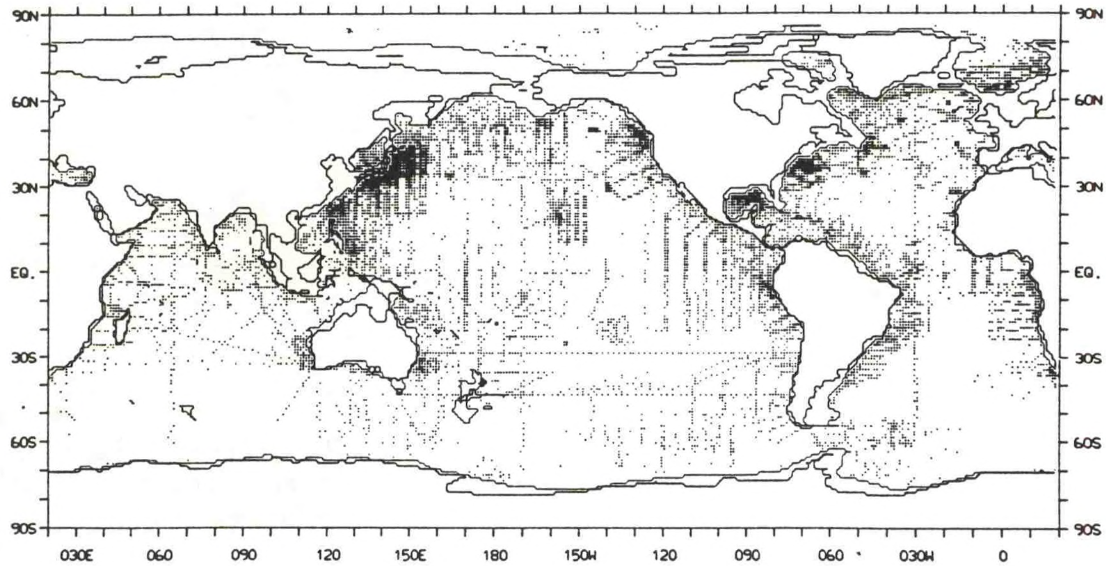

Figure 10. Distribution of temperature observations at 1000 m for the period 1965-1969 from Levitus (1982).

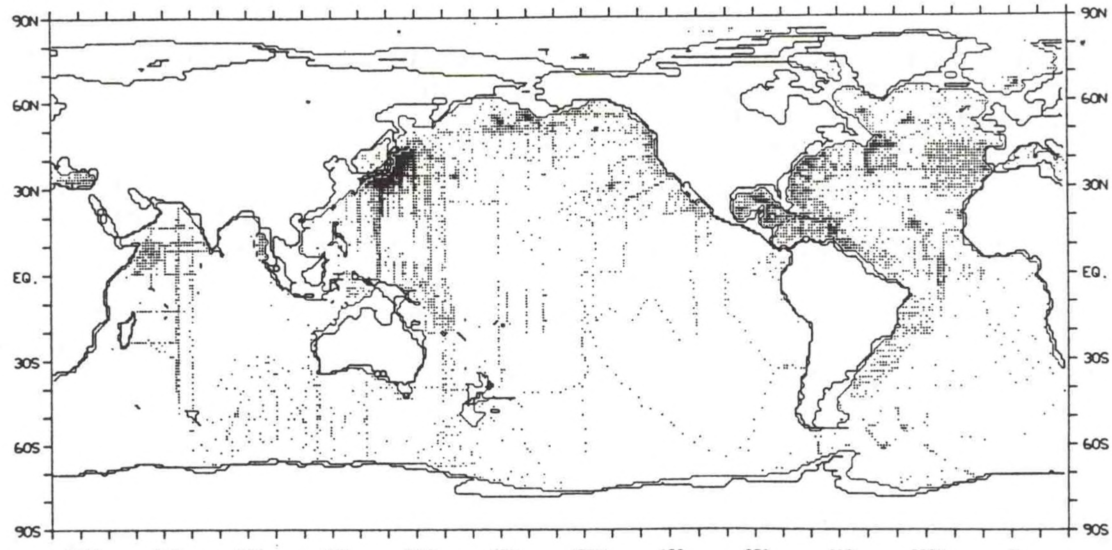

Figure 11. Distribution of temperature observations at 1000 m for the period 1970-1974 from Levitus (1982). Note the substantial decrease in observations in the southern hemisphere for this period compared to five years earlier.

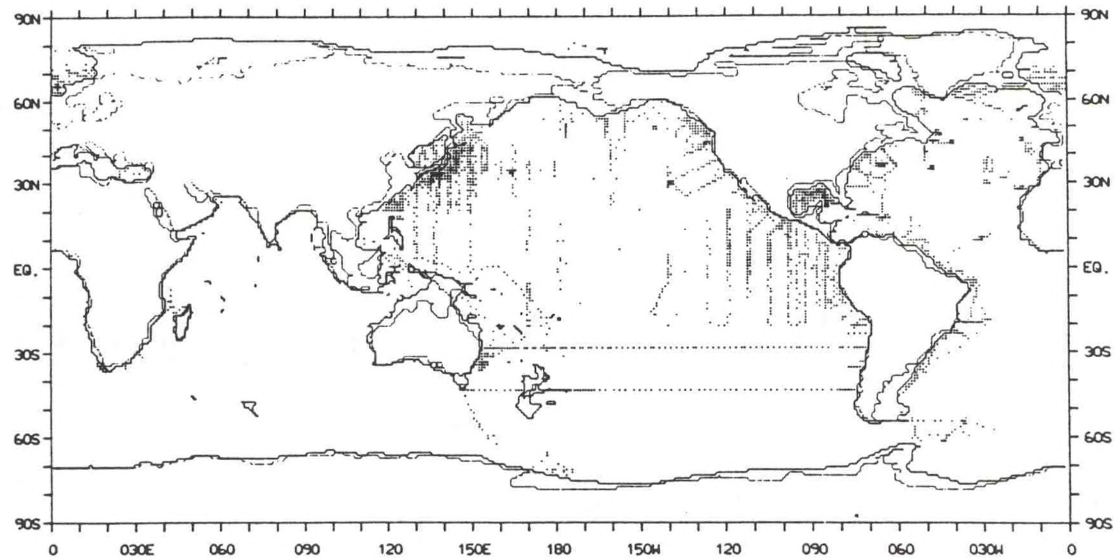

Figure 12. Distribution of temperature observations at 1000 m for the year 1967 from Levitus (1982). Note the absence of observations in the Indian Ocean and small number of observations in the Atlantic Ocean.

their variability are crucial to estimates of the meridional fluxes of heat and salt, plus provide a diagnostic for large scale changes in the strength of the circulation.

Summary

The existing database of intermediate and deep ocean observations is inadequate to provide a global description of the ocean circulation and its variability. Hydrographic coverage in the southern hemisphere is sparse with little data during the winter. Direct current measurements are limited to a few mooring locations. A significant number of neutrally buoyant float observations occurs only in the North Atlantic. Cable voltage measurements have good potential for monitoring current transports, but few such cables are available for use. A program of systematic, long-term observations is required which at a minimum should consist of repeated trans-oceanic hydrographic sections on a decadal time scale, re-establishment of single point time series observations reminiscent of the ocean weather ship observations, monitoring the transport of the major ocean currents and interbasin exchanges. The implementation of such an observing system needs to exploit present technology and look towards new and emerging technologies for an affordable implementation.

References

Baumgartner, A. and E. Reichel, 1975 The world water balance: mean annual signal, continental and maritime precipitation, evaporation and run-off. Elsevier, 179 pp.

Bennett, A. F., 1978 Poleward heat fluxes in southern hemisphere oceans. J. Phys. Oceanogr., 8, 785-798.

Bryan, K., 1962 Measurements of meridional overturning and heat transport by ocean currents. J. Geophys. Res., 67, 3403-3413.

Bunker, A. F., 1976 Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean. Mon. Wea. Rev., 104, 1122-1140.

Chiswell, S., E. Firing, D. Karl, R. Lukas, C. Winn, 1990. Hawaii Ocean Time-series, Data Report 1 1988-1989. SOEST Technical Report 1. University of Hawaii, Honolulu, HI,269 pp.

Dickson, R. R., 1989. Flow statistics from long-term current-meter moorings the global data-set in January 1989., WMO/TD - No. 337, WOCE report no. 46/90, 413 pp.

Dickson, R. R., J. Meincke, S.-A. Malmberg, and A. J. Lee, 1988. The "Great Salinity Anomaly" in the northern North Atlantic 1968-1982. Prog. in Oceanogr., 20, 102-151.

Emig, M., 1967 Heat transport by ocean currents. J. Geophys. Res., 72, 2519-2529.

Georgi, D. T. and J. M. Toole, 1982 The Antarctic Circumpolar Current and the oceanic heat and freshwater budgets. J. Mar. Res., 40 Suppl., 239-265.

Hall, M. M. and H. L. Bryden, 1982 Direct estimates and mechanisms of ocean heat transport. Deep-Sea Res., 29, 339-359.

Hastenrath, S., 1980 Heat budget of tropical ocean and atmosphere. J. Phys. Oceanogr., 10, 159-170.

Kamenkovich, V. M., A. S. Monin, and A. D. Voorhis, eds., 1986. The POLYMODE Atlas. Woods Hole Oceanographic Institution, Woods Hole, MA., 375 pp.

Larsen, J. C. and T. B. Sanford, 1985 Florida Current volume transports from voltage measurements. Science, 227, 302-304.

Leaman, K. D., R. L. Molinari and P. S. Vertes, 1987 Structure and variability of the Florida Current at 27°: April 1982-July 1984. J. Phys. Oceanogr., 17, 565-583.

Levitus, S., 1982 Climatological Atlas of the World Ocean. NOAA Prof. Paper No. 13, 173 pp.

Levitus, S., 1988 Decadal and pentadal distributions of hydrographic stations at 1000m depth for the world ocean. Prog. in Oceanogr., 20, 83-102.

Olbers, D. J., M. Wenzel, and J. Willebrand, 1985. The inference of North Atlantic circulation patterns from climatological hydrographic data. Revs. of Geophys., 23, 313-356.

Reid, J. L., 1981 On the mid-depth circulation of the world oceans. In Evolution of Physical Oceanography (ed B. Warren and C. Wunsch) MIT Press, pp. 70-111.

Roemmich, D. and C. Wunsch, 1985 Two trans-Atlantic sections: meridional circulation and heat flux in the subtropical North Atlantic Ocean. Deep-Sea Res., 32, 619-644.

Schmitz, W. J., J. F. Price, and P. L. Richardson, 1988 Recent moored current meter and SOFAR float observations in the eastern Atlantic near 32N. J. Mar. Res., 46, 301-319.

Schott, F. A., T. N. Lee, and R. Zantopp, 1988 Variability of structure and transport of the Florida Current in the period range of days to seasonal. J. Phys. Oceanogr., 18, 1209-1230.

Stommel, H., and F. Schott, 1977. The beta spiral and the determination of the absolute velocity field from hydrographic data. Deep-Sea Res., 24, 325-329.

Talley, L. D., 1984 Meridional heat transport in the Pacific Ocean. J. Phys. Oceanogr., 14, 231-241.

Whitworth, T., W. D. Nowlin, and S. J. Worley, 1982. The net transport of the Antarctic Circumpolar Current through Drake Passage. J. Phys. Oceanogr., 12, 960-971.

Wunsch, C., 1972. The spectrum from two years to two minutes of temperature fluctuations in the main thermocline at Bermuda. Deep-Sea Res., 19, 577-593.

Wunsch, C., 1977. Determining the general circulation of the oceans: A preliminary discussion. Science, 196, 871-875.

Wunsch, C. 1984 An eclectic Atlantic Ocean circulation model, Part 1. the meridional flux of heat. J. Phys. Oceanogr., 14, 1712-1733.

Wunsch, C., D. Hu, and B. Grant, 1983 Mass, heat, salt and nutrient fluxes in the Pacific Ocean. J. Phys. Oceanogr., 13, 725-753.

Wyrtki, K., 1965 The average annual heat balance of the North Pacific Ocean and its relation to ocean circulation. J. Geophys. Res., 70, 4547-4559.

Scientific Issues on the Establishment of the Long-Term Global Observing System for the Surface and Upper Ocean

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I. Observational Requirements for the Surface and Global Upper Ocean

This paper discusses some immediate issues that arise in the design of the Global Ocean Observing System, where *in situ* data will be acquired for the purpose of answering important societal questions. The *in situ* data from this system will be used in describing and modeling long-term changes of the upper oceans, the air-sea interface, and the sea ice. The network design directly follows from identification of the principal user and the objectives of the user as these factors identify the parameters to be measured and their accuracies, which, in turn, establish in logical order the measurement systems, the implementation of the data collection, quality control of these data, and analysis of these data. Because *in situ* global networks will always produce sparse data sets, their utilizations are much enhanced if the analysis can include the merging of the *in situ* observations with satellite data for the description of the phenomena near the ocean surface or modeling within the layers of the upper ocean. Both satellite data and models would, of course, be subject to verification with observations.

A. Oceanic Parameters of Interest

Long-term ocean research programs, which were established in the last decade, have the most pressing and well-stated requirements for long-term global data sets. The oceanic parameters to be measured in order to satisfy the global scientific requirements of TOGA, WOCE, JGOFS, ACC, and Climate and Global Change programs are:

- sea surface temperature
- upper ocean temperature/salinity structure
- momentum/buoyancy fluxers across the air-sea interface
- near-surface current structure
- carbon dioxide concentrations in sea water
- biological productivity and optical clarity of near-surface sea water

B. Fields of Variability

The description and prediction of climate and global change will rely heavily on statistical and numerical models of the global ocean and atmosphere. For successful operation of these models, the above specified data sources will be required. Common to them, however, is that the ocean data be represented as a uniformly distributed field in x and y (and z and t) on a global basis. **Therefore, one of the requirements for the global ocean observations is that they be adequate for resolving a global field.**

C. Timeliness of the Data

Because climate prediction and societal use is made in a timely fashion, the data from the upper ocean must be available in real time. **Therefore, the Global Ocean Observing System must operate in near-real time (i.e., with data received no more than one month delay).**

D. Measurement System Integrity

Long-term observations compete for resources with other societally-relevant activities. The recent demise of the WWW in the tropics, for example, can be directly related to the increasing costs of antiquated upper-air sounding systems. The demise of the number of TOGA southern ocean drifting barometer networks can also be directly tied to spiraling costs, since no new development of the system has occurred since 1975. The SEAS system used in the VOS-XBT network was out of data at the time of deployment and today costs four times as much as current technology can provide. **Therefore, the Global Observing System should be structured so that the measurement systems that are deployed are continually updated and improved.**

E. Measurement Quality Control

Emphasis on the Global Ocean Observing System must be concerned not only about the quantity of data returned, but its quality. Random error is not generally problematical, but unknown biases can render the entire system useless. Rigorous quality control must be practiced at the data collection level; quality control further along in the data stream (e.g., at the DAC's) is only effective in identifying erroneous data, not in correcting the cause. **Therefore, to guarantee the quality of data collected by the Global Ocean Observing System, near-real time quality control of the data needs to be conducted by the data collectors.**

F. Observational System Integrity

In TOGA and WOCE, Data Assembly Center(s) (DAC's) have been established at research institutions to conduct scientific quality control on basin-scale data sets (e.g., temperature and salinity). Scientific quality control consists, among other things, of producing basin-scale products (i.e., maps, sections, etc.) in both near-real time and delayed mode. In this way, the entire observing system can be monitored for system integrity. **Therefore, a network of Data Assembly Centers for the Global Ocean Observing System, needs to be expanded from basin-scale to global operations.**

G. Updated Observational Network Design and Development

Model/data assimilation should be employed to determine the optimum sampling densities required for each of the parameters discussed above, in order to establish the best mix of platforms to sample each parameter field over the globe to an accuracy required to address the scientific issues. In addition, this should be continually updated as a by-product of constructing global fields of selected parameters produced through model/data assimilation. The error maps associated with the products will determine where oversampling and undersampling is taking place. **Network design is a prerequisite for expansion of the observing system to a global basis.**

H. Observational Network Priority

Presently, the TOGA/WOCE ocean observing system consists of island sea-level, VOS-XBT, TOGA-TAU, and circulation measurements, confined principally in the tropical oceans. Much of these data are retrieved in real time through ARGOS. In the first five years of TOGA observing systems were implemented as envisioned at the start of TOGA, and these will produce their first complete data sets in the second half of TOGA. The ten-year data set conceived of in 1985 for TOGA will not be acquired before the year 2000 (under the umbrellas of various climate change programs). Expansion of the upper ocean observing network to the global basis should take less than five years because most of the instrumental problems have been solved in TOGA and WOCE; however, this expansion will still follow a few years behind the establishment of a stringent rationale. **The first priority of the Global Observing System is to assume responsibility for the well-developed and technologically sound existing ocean observing systems.**

I. *In Situ* Ground Truth of Satellite Data

The problem of transmitting both *in situ* and satellite observations has been solved easily within present networks of commercial, high speed, data transmission networks. These networks are fully operational in most of the TOGA/WOCE ocean observing systems. **These *in situ* data should be merged, at a few central points, with the large variety of satellite data, providing ground truth for the latter, allowing global coverage for long-term studies of the upper oceans.**

II. Institutional Structure

Careful consideration of the institutional structure of the Global Ocean Observing System is critical to the long-term success of the program. The institutional mechanisms for implementing the system must be established so the motivation and accountability are maintained over the long-term; only this will guarantee the adequacy and reliability of the system. The following presents a rationale for establishing the institutional structure of the Global Ocean Observing System which eventually relies upon a network of scientifically committed people rather than an organization to provide guarantees for the continuity of the data gathering system. The unique and highly motivational aspect of the proposed system is to make the scientific user of the data directly involved in its collection and quality control, and by recommending that international scientific teams be established to operate the system as a distribution network. Accountability is provided by the peer review process on the individual proposal level and on the system level by the National Academy of Sciences review and oversight process. The alternative is the establishment of a typical government bureaucracy that historically has not been able to meet the needs of the scientific community.

A. Expansion of Existing Regional Ocean Observing Systems

Large-scale ocean observing systems have evolved over the last two decades as much from what could be accomplished as what was scientifically or societally required. Scientists learned what parameters could be measured, with what measurement accuracy, and at what financial cost. Some measurements systems were eliminated as cost ineffective; others were found to have only regional value; while others had universal utility. Now, we wish to construct a global observing system.

RECOMMENDATION: In its inception, the long-term Global Ocean Observing System should be constructed through expansion of these regional and basin-scale ocean observing systems that have demonstrated effective operation during the

last ten years in a variety of regional climate programs (e.g., NORPAX, TOGA, WOCE).

B. End-to-End Scientific Data Management

End-to-end data management, from the data source to the scientific manuscript, has been demonstrated repeatedly in the oceanographic research community to be a necessary requirement for the assurance of reliability of the data stream. Because research scientists are the principal users of global data accruing from the Global Ocean Observing System, it follows that research scientists must take upon themselves the task of supervising the data collection and quality-control effort, as well as conducting analyses. In many ways, we expect a new breed of scientists to emerge, expert both in climate dynamics (and in the statistical analysis of global data sets) and in global observing network design and operation.

RECOMMENDATION: Mechanisms must be established in the Global Ocean Observing System allowing for hands-on control of the data collection, data quality, and data analysis, conducted by scientists actively engaged in climate research.

C. Scientific Team Approach

A most important consideration in establishing the Global Ocean Observing System is understanding that it will require international participation from scientists and government agencies around the globe. Utilizing international bodies such as IOC, WMO, and IGOSS are important for this task, but the implementation of the Global Ocean Observing System must come from ad hoc groups of scientists who will motivate these activities in each country, similar to those established for XBT's and drifting buoys in TOGA/WOCE.

RECOMMENDATION: In the past either individual or ad hoc groups of scientists have taken on the tasks of sampling regional portions of the global ocean; in the future, international scientific teams will have to be established and tasked with the responsibility of sampling the global ocean.

D. Global Ocean Observatories

Most of the existing regional ocean observing systems have been designed, implemented, and are presently operated by ocean research scientists, who have already established long-term Ocean Observatories at their respective institutions. The oceanographers who have operated these Ocean Observatories over these past years have recognized the necessity for this in order to conduct their research in the climate change discipline. The scientific community, the directors of the research institutions, and the university deans have accepted that the collection and subsequent analysis of long-term data from the ocean for the study of climate variability is a valuable intellectual activity for their institutions.

RECOMMENDATION: The long-term funding of Ocean Observatories at research institutions, directed by a chief scientist in charge of the global ocean observing project, is the backbone of the Global Ocean Observing System.

E. Motivation for Long-Term Funding

For a number of years, ocean scientist have been asked by operational agencies to design global ocean observing systems on paper, to specify the requirements for the necessary instrumentation, and recommend mechanisms for the implementation of these plans. This method of developing a Global Ocean Observing System is based on the perception that operational agencies somehow enjoy long-term support for projects that does not exist in the research environment. However, after the first five years of TOGA, we found that funds given to an operational agency for the purpose of maintaining a basin-scale ocean observing system can often disappear overnight; even the operational agencies require that a well-structured and politically strong lobby of customers exists for these ocean observations. On the basis of this experience, we learned that a well-defined research program, with a community of users that utilize the basin-scale data coverage can remain viable in the long-term, and is elemental to the success of the long-term collection system. Simply stating that the global ocean observing has entered an "operational" phase will not sustain the support for an observing system by an operational agency.

RECOMMENDATION: A well-defined, active, scientific user community, who both require the data from the Global Ocean Observation System and who have the motivation to continue to acquire the resources, is necessary for its long-term funding. Until now, ocean scientists have been vigorous in support of their own individual Ocean Observatories; this same motivation will exist when responsibility for the Global Ocean Observing System is assumed in partnership with operational agencies.

F. Global Ocean Observation System as a Distributed Network of Global Ocean Observatories

The expansion of the existing ocean observing systems to a global basis, with the same quality of data that is generated, for example, by the TOGA Program, requires that the data users (i.e., the scientists involved in the program) be directly involved in data collection, quality-control, and near-real time analysis. When more efficient observing system elements are needed, the scientist/user is usually first to identify such a requirement and implement it. The TOGA program has designed an efficient and affordable basin-scale ocean observing system through the use of *ocean observatories* providing an excellent paradigm to follow; by expanding the existing observatories, and adding new ones as they are proposed from the scientific community, the long-term Global Ocean Observing System can be established relatively quickly and maintained efficiently, with realistic and predictable costs. Using computer networking, the activities of an ocean observatory can be coordinated with other ocean observatories into a cohesive organization.

RECOMMENDATION: A distributed network of Ocean Observatories, coordinated by operational agencies in Washington, D.C., could be the focal point of a powerful grassroots organization, which would provide the scientific, technical, and political motivation required for directing and sustaining the scientific-quality long-term observation of the oceans.

Existing Bio-geochemical Time-Series

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Existing time series of ocean observations of biological and chemical systems were established for three main purposes.

1. To monitor the states of the systems;
2. To detect shared patterns of variation between different components;
3. To establish base-lines or long term means.

The reasoning behind the first objective is simply to obtain a status report on the current condition of a highly variable environment. The objective of number two is to establish a statistical basis for the description of frequency spectra. We do not now know the frequencies, amplitudes or phase relations among changes in most biological or chemical variables for any oceanic site. Cross correlations of these can give us insight as to the mechanisms of interaction between components. Number three is obviously the only basis for defining the word "change" as in "global change." From such long-term means direction, and rates of change can be determined.[1,2,3]

There are two major, long term observation systems of the biology and chemistry of oceanic areas where some space averaging of measurements is possible.

THE NORTH ATLANTIC

In the North Atlantic the Continuous Plankton Recorder (CPR) program began, in earnest shortly after the end of World War II when routes to and from Ocean Weather Stations Alfa, India, Mike, Bravo, were established for the purpose of making plankton abundance measurements.[4,5,6] This surely was extended progressively, until by 1965 a large part of the North Atlantic, north of 45°N was sampled monthly by merchant ships of opportunity and sixteen weather ships.[6] In that year 112,000 miles of continuous sampling was done: The Recorder is towed behind ships at speeds of 12-18 kts; it samples at a depth of about 10m. The mouth opening is 1/2 inch square. Plankton are collected as bands of silk mesh (285µ to 315µ mesh aperture) are passed across the throat of the recorder. In 10 nautical miles (18km) of towing about $3m^3$ water is filtered. The common, large species of phytoplankton and zooplankton species are identified and counted. Thus, the results as presented, are numbers of individuals integrated over some distance (frequently 10 nautical miles) which were living at a depth of 10 m at the time of capture. The results are generally further space averaged by sector or square where a few to many tows have taken over the course of a month. The results are presented in two general forms; as large scale spatial patterns based on long term means[7], and as time-series within sectors or squares also based on long term means.[8,9,10] These are of individual species and of total zooplankton biomass. Both time series and spatial pattern of color of tape have also been presented. The variations in color of the tapes is due to variations in phytoplankton biomass. The color intensity is estimated by eye as compared to some color standards. It is apparently a reasonably good estimator of changes in phytoplankton standing crop.

An early result of this work has been the construction of composite biogeographic maps of spatial patterns of species abundance and species diversity based on thousands of recorder observations. These clearly show biogeographic boundaries where community structure and function change from one system to another.[5] They also show rich (on average) and poor (on average) locales within regional patterns. More importantly they show how the positions of boundaries between functionally different systems vary with time. The most important frequency of these variations is interannual. While time-series and spectral analyses do show a strong seasonal signal especially in coastal zones, the interannual frequency seems always to have the largest amplitude of biological fluctuations.[8,11,12] For example, a sector in the Northeast Atlantic shows in the late 1940s an abrupt bloom of zooplankton in early May terminating in late November. This situation held until 1956 when the "bloom" began later and ended earlier.[6] This trend of shorter and shorter growing seasons held until 1981 or so when conditions reversed and the annual integrated zooplankton biomass increased. Nearby in the North Sea very similar inter-annual trends occurred although the seasonal cycle differs substantially in any one year and the annual standing stock of zooplankton is almost always less. Total phytoplankton counts showed a similar trend as did individual species of *Ceratium*. That is, there was agreement in large-scale time and space between trophic levels as to major population changes. Although the details of the causes of these changes are uncertain they are well correlated with large scale climatic variations and temperature. Both the trends in the physics and biology appeared to have reversed in unison.[8]

The "color" of the tapes is due in part to "net phytoplankton" which are the larger species retained by the mesh. But the intensity of color is also influenced by clogging of the meshes in dense phytoplankton areas. Every plankton net suffers this problem and therefore the "color" of the silk (now nylon) is some function of phytoplankton abundance. The CPR group has utilized this feature of their samples to estimate and map the seasonal change of ocean color.[7] This study is based on thousands of measurements and may be as accurate and precise as ocean color as estimated by the Coastal Zone Color Scanner. These latter CZCS patterns do not appear to agree with either the time or locale of the onset of the spring bloom in the northern North Atlantic.

Sources of Error

The earlier studies of the CPR group were impeded by the lack of physical-chemical data on commensurate scales of sampling. But as time series information accumulated it became evident that it was the larger time-space scales that showed the greatest variations and on these scales physical data were available. Interannual frequencies dominated the power spectra so that the lack of synchronous measurements on each of the recorder runs did not greatly effect these main results. But it should be pointed out that only long integrating tows averaged over months, have been thoroughly analyzed and reported so that higher frequency variations may, indeed, be of some importance in the overall picture. Clearly if we are to attempt to achieve a better understanding of functional relationships between system components by cross correlations a broader spectrum of frequencies must be measured.

Perhaps the greatest and most persistent criticism of the CPR group's work has been in the use of such a small mouth aperture sampler and a single depth of measurement (about 10 m). These two constraints arose, of course, out of necessity but they do severely limit the utility of the results in terms of ecosystem structural analyses. Further, the crude measures of phytoplankton abundance while provocative and probably at least as good as our existing satellite composites of low frequency and/or seasonal signals, are not really quantitative and do not represent water column concentrations. Neither source of data can be used for reasonably precise (i.e. within a factor of 5x) estimates of phytoplankton carbon for use in carbon balance models. Another obvious weakness of this survey is the complete lack of physical or chemical measurements on any scale of sampling. Again this was due to a simple lack of technology in the early days combined with budgetary restraints. It was not easy to get merchant seamen to operate complicated sampling devices. Finally, the design of sampling is to some extent unbalanced in the sense that some sectors were much more intensively sampled than others. The degree to which this effects composite time-series maps and their interpretation is not known. In spite of the deficiencies of the type of measurements made on this time-series it remains the best there is in the North Atlantic for providing biological insight. It is the basis in this ocean for a base line against which the word "change" can be applied.

Other North Atlantic Time Series

Other time-series of measurements in the North Atlantic are either of relatively short duration, are not biological in nature or are very near shore. The Mar Map surveys of the North Atlantic in the area of Georges Bank is a biological -- physical-chemical time-series in which space averaging is possible. It is however of fairly short duration (a few years) and the published results are, for the most part, concerned with fisheries population dynamics as indicated by larval fish abundance. Measurements of phytoplankton and, episodically, nutrients (primarily phosphate) off Plymouth are of long duration but there are good reasons to suspect that they are not particularly representative of open ocean conditions. However because of their long duration and carefully analyzed and reported data, the relationships between these very near-shore measurements and open-ocean variations should be investigated.

Time series near the island of Bermuda have a long history. However these are primarily of water column temperature and salinity. Oxygen concentration and per-cent saturation has also been measured. Oxygen concentrations in the mixed layer are affected by both physical and biological processes and therefore it is a valuable parameter if the data can be interpreted. Oxygen data from these and other measurements, taken over time, in the North Atlantic have given us new insight into the processes and the magnitude of primary production and the carbon cycle. Orthodox and traditional point measurements yield different estimates of new production than do O_2 measurements from time-series. These methods yield rates 5 to 10 times higher than accepted, traditional values of new production based on 14C or $15NO_3$ methods. The rate of new production is the key biological process affecting the role of the ocean in the global carbon cycle. The role of "new" production sets the upper bound to the amount of organic carbon that sinks or is mixed downward into the intermediate or deep ocean. Thus this new production sets the upper limit to the rate at which the "biological pump" potentially moves atmospheric CO_2 from the euphotic zone into the intermediate and deep waters, where the residence time is significantly greater than one year. Time series measurements are uniquely suited to reconcile the differences in primary production measurements. The relative roles of biology and physics in changing O_2 concentrations can be separated by determining tracer gases such as 3He and Argon.

Other biological time series in the Atlantic are either in bays or estuaries or very near shore neritic waters. They are mainly of interest because they show that there are on occasion, brief episodic outbursts of phytoplankton. That is, there is a high frequency component to the variability. It is not known if such high frequency variations occur in the open-ocean.

Finally, there have been recent attempts to monitor chlorophyll and oxygen concentrations at a few depths in the open ocean from un-manned buoys. It is not known, at present, how these instruments were calibrated nor how long they operated. However, the spacing between sensors was such that it seems dubious, at present, if such measurements can be useful for estimates of integrated water-column, plant standing crop or O_2 concentration, or the time rate of change of these.

THE NORTH PACIFIC

CalCOFI

The largest and longest time-series in the North Pacific is the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program. This 40-year study is a collaboration between a NOAA Laboratory, the State of California's Department of Fish and Game and the Scripps Institution of Oceanography, (Stanford University's Hopkins Marine Station was an original member).[13] The federal and state laboratories were interested in monitoring and studying the spawning of commercially important fishes but it was the role of Scripps Institution to study the physical and biological environment of the California Current, an area of about a million square kilometers. The first 10 years of this program consisted of a monthly sampling program throughout the entire area from San Francisco to mid-Baja, California and a distance of over 800km sea-ward. A grid sampling plan was followed with spacing of 40 nautical miles (72km) between stations on "lines" normal to the coast. These lines were spaced 40 nautical miles apart. The normal station routine consisted of a hydrographic cast of normally, 18 bottles to depths of 500m. T, S, O_2 were always measured but on many early cruises PO_4 was also estimated. Mechanical bathythermographs were taken frequently between stations as were surface temperatures and occasionally salinities. Air temperatures, relative humidities and wind speed and direction were always recorded as were wave height and direction. The main biological measurement done as a matter of routine was a meter net tow. A net of one meter mouth diameter and 5 meters in length of 505μ silk (later nylon) mesh was deployed while the ship was underway at about 1.5 kts. This net was lowered to a depth of 140m and slowly retrieved. The nets all had current meters in their mouths so that the volume of water filtered could be calculated. This averaged around 300m^3. These procedures were followed on every station of every cruise (generally about 150 stations), weather permitting. The number of cruises per year averaged somewhat over 10. In addition to the standard routine measurements a large variety of other studies both physical and bio-geochemical were done as adjuncts to the main monitoring effort. In 1960 or '61 the monthly monitoring effort could not be sustained both due to fiscal constraints and demand for other uses of the ships and personnel. Quarterly cruises were instituted and these continued as before for another 10 years. During the decade of the 1970s even greater demands for other use of resources and a conspicuous lack of appreciation for the value of time series forced an even greater restriction on the broad scale survey. Semi-monthly (six per year) cruises were now done every third year with spatial coverage and sampling design remaining the same except for the substitutions of the Bongo net for the old CalCOFI meter net. These two devices were carefully intercalibrated for over a year under all possible oceanographic conditions. Hundreds of pair-wise comparisons were made.

During the sixties and seventies when the number of wide ranging cruises was restricted, the program leaders still managed to keep a higher frequency of measurements on line 90 (ten to 15 stations) through the Southern California Bight and line 80 (10 to 12 stations) off Pt. Conception. So that these time-series are particularly good. Also by the mid to late 1960s a broader spectrum of measurements were being made. Many hydro casts to 1000m were done as were continuous T-S profiles with; first the STD and then the CTD plus rosette. Water column chlorophyll and the full spectrum of plant nutrients were also incorporated into the scheme as was micro-plankton on occasion. The decade of the 1980s saw another attempt to save on ship-time, personnel and processing costs while at the same time increasing the frequency of sampling once again to quarterly. This was accomplished by reducing the spatial coverage and hence ship and personnel time. The new CalCOFI pattern includes only those lines of stations just to the north of Pt. Conception and south to line 93 (four lines total). This however is still a grid of considerable size.

The argument for reducing the spatial coverage in order to increase frequency of sampling was based on the time-series analyses of earlier results. As in the North Atlantic it was determined that the inter-annual frequency had, by far, the largest amplitude of change[14] (much larger than seasonal). The space averaged plankton biomass, temperature, salinity and mass transport from the north all showed positive and negative standard deviations from the long term, seasonally corrected means.[15,16] This was especially true at the lower frequencies where the amplitude of the departures from the mean were greatest. Thus the entire California Current system was behaving in a very coherent way with respect to these large changes in its physics and biology. Because of this remarkable result it was now possible to sample a much smaller area with some statistical assurances that it would be representative of the larger spatial realm.

CalCOFI Data Processing & Analysis

It was recognized from the beginning in 1949 that a data management organization had to be an integral part of the CalCOFI plan. Such a team was organized called D.C.P.G., the data collection and processing group. The members of this group were both marine technicians who collected the data, at sea, and did much of the preliminary processing of the physical-chemical data on land. Thus they alternated between sea time and processing work. This had the great advantage of allowing them to see how their measurements "worked out", to review one another's work and to achieve some real understanding of the value of their work at sea. Some of these persons went on to get advanced degrees and/or publish papers in the field. Some have become administrators at S.I.O. Although the lion's share of the work was accomplished by marine techs many academics also accompanied many cruises and processed much of the data. The processing of the physical data was considered "complete" when temperature, salinity, density and oxygen data were carefully reviewed for error, tabulated at measured depths (from reversing thermometers) and interpolated to standard depths and published as cruise reports. These data and reports are considered public property and are distributed free of charge to all national and many foreign oceanographic libraries.

The basic processing of the net tow data was a simple measure of displacement volumes after the occasional large "salp" or jellyfish were removed. This displacement method was found to be a good representation of plankton biomass. It is an index of wet weight or ash-free dry weight and was not destructive to the sample. The samples were later used for species specific population studies such as the variations in abundance and spatial patterns of fish eggs, larvae, euphausiids, copepods and other organisms.[17] Some chemical analyses of these as time-series of pollutants such as DDT and lead were also done. This "library" of samples is maintained by a full-time curator and is available at all times.

Some Results of CalCOFI

In the context of global change perhaps the main result of this program is that there is no long term trend in the biomass of plankton or the abundance of total larval fish. That is to say, there has been no biomass "change" in the sense that the anomalies from the long term, space averaged mean show no systematic departures in one direction.[16] This also appears to be true of space averaged 10m temperatures, salinities and mass transport from the north.[16] However, it should be made clear that the data have been analyzed only up to 1980 and therefore the variations of the past decade have not been taken into account.

Two of the more spectacular events which occurred during this program were the California El Niños of 1958-'59[13] and 1983-'84.[18] These followed by about one year similar large scale events on the equator. Both El Niños showed very large negative anomalies from the long term mean of plankton abundance. There was a great deepening of the thermocline and chlorophyll maximum. Nutrients essentially disappeared from the euphotic zone. There were positive surface temperature anomalies of from 2 to 6° everywhere and the entire mixed layer warmed by over 2°C. However, the data particularly those from the 1983-1984 El Niño have not been completely analyzed and there is much more to be learned from this very large climatic event. Since El Niño may serve as a model of the consequences of global warming in the California Current the documentary evidence of its effects should be studied.

Another major result of this time series has to do with the degree to which coastal, wind driven, upwelling influences the "richness" of the California Current. The large positive anomalies from the long term mean in plankton abundance occur during times of negative salinity anomalies. Since the deeper coastal waters from, whence upwelling is derived, are quite salty this result is unexpected. Further the variations in plankton biomass are uncorrelated with a commonly used upwelling index at any time or space lag but are well correlated with variations in mass transport.[16]

These time series have also allowed for the essential tracking of population demographics and age structure and the relations between regular, successional seasonal events and how these vary over time. For example, the nature of the response of phytoplankton to nutrient inputs have been followed.

Although nutrients, primary productivity and chlorophyll were measured on some cruises early on and during one entire year of cruises (1969), systematic and consistent sampling of these properties did not begin until the 1980s. There have been no published time-series of these data as yet.

Overall however there have been over 800 papers published which depend all or in part on the main (40yr.) body of CalCOFI data.

Other North Pacific Studies

On the basis of the remarkable climatic events of 1958-'59 in the California Current a time series of physical-biological measurements was set up at Weather Station "P" in the Gulf of Alaska (50°N; 145°W) by Canada. This program was run from weather ships, on that station and consisted of high frequency hydrographic casts for T, S, O_2 and net tows similar to those of CalCOFI. Many or perhaps most of these were done on, at least, a weekly basis for 20 years. Later, after the measurement methodology became stabilized, chlorophyll was added to the routine. This program terminated in the 1970s. Although there have been no analyses of the high frequency biological variability, seasonal studies have yielded some remarkable results. While the physical signals showed a very strong seasonal pulse as did zooplankton biomass, the plant standing crop showed no seasonality. Apparently the grazers are in phase with plant growth so that any increment in plant biomass is transferred to animal biomass very quickly. This means, of course, that the carbon cycle cannot be modeled adequately on the basis of estimates of the time rate of change of plant carbon (as from satellites) but rather more parts of the system must be included. It is not known how many other parts of the world oceans have similar systems. These observations have led to a sizeable sea-going program (SUPER) to test hypotheses that have arisen from the time-series observations.[3]

Although a standard systematic set of measurements have been made near 28°N; 155°W in the Central Gyre of the North Pacific between 1968 and 1980 there have been large gaps, some as long as three years in the program so that only very high frequency (hourly and daily) within cruises and inter-annual between cruise results can be examined. However, a broad spectrum of water column measurements were done in almost every case. These included five plant nutrients, NH_4, NO_3, NO_2, PO_4, SiO_3 and other non-conservative compounds, primary production, chlorophyll, and phytoplankton species, micro-plankton biomass macro-plankton biomass and copepod species, small fish and squid by mid-water trawl and acoustics, continuous traces of T, S, and bottle O_2. In addition, dissolved and particulate organic carbon, inert trace gases, other phytoplankton pigments and 15N uptake were often done as were temperature micro-structure studies.

There have been two major results of this time-series. It was observed early on that a sharp sub-pycnocline oxygen maximum developed in summers. This was well within the photic zone but far above the nutricline. Calculations showed the oxygen increment was far greater (5 to 10x) than could be accounted for by new production. Tracer gas studies (argon) showed that the oxygen super-saturation was due to biological activity. Thus an independent study from that (done later) in the Atlantic reached a similar conclusion i.e. previous work with 14C and 15N to estimate primary production were gross under-estimates. Further, since the nutricline was always much deeper than the productivity there must be some serious flaws in our understanding of vertical eddy diffusivity. The other main result has to do with tests of the theories of diversity maintenance via competitive interactions. These theories have been falsified in a series of four papers published in leading ecological journals. This could not have been done without time series information.

Although the central gyre time-series has large gaps it did span about 20 years with comparable sampling routines. These data have shown that a long-term trend in the mean concentration of chlorophyll in the deep chlorophyll maximum layer has occurred. A doubling of the plant bio-mass but only at depths of about 100m in the chlorophyll maximum seems certain. This was accompanied by a trend in the mean winds in the winter months.[19]

There must exist long-term biological and chemical measurements in the Kuroshio since there are many marine laboratories along the coast of Japan. However, few of these results appear in the English language scientific literature except by reference.

Near Shore Studies

A shore station time-series of daily measurements of temperature and salinity from ocean piers has been maintained at a series of locales from La Jolla to British Columbia for over 70 years. In the years 1919 to 1939 daily samples of phytoplankton were taken and the species identified and counted at two locations, S.I.O. and Port Hueneme. These data have been used recently in an application of chaos theory. Essentially this study uses time-series data for predictive purposes. Recently (since 1983), twice a week replicate samples of chlorophyll have been made from S.I.O. Pier and even more recently (since 1987) nutrients have also been taken. This time series also shows high frequency, episodic outbursts.

OVERVIEW

The Atlantic and Pacific time-series, particularly those of the CPR and CalCOFI programs provide us with long-term space averaged means of physical and biological variables.[4,5,6,7,13,16] From these means, the word "change" can be quantitatively defined. That is, the direction, amplitude and time rate of departures of anomalies from the long term average can be derived. Further frequency spectra can also be calculated and cross spectral correlations be made. These can provide strong inference as to the linkages between climate, the physics of water movement and the response of biogeochemical systems. The word "change" can only be defined by comparison to some standard such as these.

Although only a limited number of basic variables were measured, they have provided us with much new, unexpected insight. These series have been successful and can serve as the basis for the design of new and better time series with the addition of new and better instrumentation and a broader array of environmental variables and site selection. However, the extant data base should be extended and not supplemented by incompatible new data sets. In particular the CPR and CalCOFI data as yet unanalyzed should be utilized in the development of new programs. A way should be found to calibrate the CPR color and zooplankton data so that they be made more quantitative in terms of ordinary units such as mass per unit volume.

Although one of the chief goals of new time series should be to provide regional-long term means and confidence limits for the major components of the carbon cycle for use in models, there are other important objectives as well. For example, it is generally felt that the biogeochemical systems respond to physical events, but we really do not know what types of atmospheric or hydrographic perturbations affect these systems and which do not. There are many kinds of perturbations ranging from microscale turbulence to El Niño phenomena. Although almost all of them have been implicated one way or another some of them seem to have large effects, others do not. Which ones then are which? If various components of physical-biological-chemical systems interact to influence each others magnitude and if this happens in a consistent patterned way, there should be detectable statistical relationships between them in spite of a large amount of noise. There should be what ecologists call "succession". A dense data set will be necessary in detecting these relationships. Cross correlation between time series must be the first step in such a study. Such information is essential for us to be able to understand the consequences of climatic change.

Finally, oceanic time-series at several critically chosen locales can, especially after a few years experience, monitor the state of our ocean environment. Although we are lacking in long term data for many critical variables we should begin now to measure them.

REFERENCES

1. Haury, L.R., McGowan, J.A. and Wiebe, P.H. (1978) in Spatial Patterns in Plankton Communities (Steele, J.H.,ed.), pp.277-327, Plenum Press.
2. Stommel, H. (1963) Science 139, 572-576.
3. Wiebe, P.H., Miller, C.B., McGowan, J.A. and Knox, R.A. (1987) EOS 68, 1178-1190.
4. Hardy, Sir Alister (1956) The Open Sea-Its Natural History-The World of Plankton, Collins St. James's Place, London.
5. Oceanographic Laboratory, Edinburgh (1973) Bull. Mar. Ecol. 7, 1-174.
6. Glover, R.S. (1967) Symp. Zool. Soc. Lond. 19, 189-210.
7. Colebrook, J.M. (1982) J. Plankton Res. 4, 435-462.
8. Dickson, R.R., Kelly, P.M., Colebrook, J.M., Wooster, W.S. and Cushing, D.H. (1988) J. Plankton Res. 10, 151-169.
9. Colebrook, J.M., Robinson, G.A., Hunt, H.G., Roskell, J., John, A.W.G., Botrell, H.H., Lindley, J.A., Collins, N.R. and Halliday, N.C. (1984) J. Cons. Int. Explor. Mer 41, 304-306.
10. Colebrook, J.M. and Taylor, A.H. (1984) Rapp. P.-V. Reun. Cons. Int. Explor. Mer 183, 20-26.
11. Colebrook, J.M. (1982) Oceanologia Acta. 5, 473-480.

12. Radach, G. (1984) Rapp. P.-V. Reun. Cons. Int. Explor. Mer 185, 234-254.

13. Sette, O.E. and Isaccs, J.D. (1960) Calif. Coop. Oceanic Fish. Invest. Rept. 7, 1-217.

14. Bernal, P.A. (1979) Calif. Coop. Oceanic Fish. Invest. Rept. 20, 89-101.

15. Chelton, D.B. (1981) Calif. Coop. Oceanic Fish. Invest. Rept. 22, 34-48.

16. Chelton, D.B., Bernal, P.A. and McGowen, J.A. (1982) J. Mar. Res. 40, 1095-1125.

17. Brinton, E. (1976) Fish. Bull. 74, 733-762.

18. McGowan, J.A. (1985) in El Niño North (Wooster, W.S. and Fluharty, D.L., eds) pp. 166-184, Univ. Washington, Seattle.

19. Venrick, E.L., McGowan, J.A., Cayan, D.R. and Hayward, T.L., (1987) Science v. 23: pp 70-72.

APPENDIX

Proposed List of Core Time Series Measurements

High Frequency Suites

Physics (atmosphere)

- Outgoing long-wave radiation
- Wind speed and direction
- Relative humidity
- Barometric pressure
- Surface air temperature
- Light 0.3 to 3μm

Physics (ocean)

- Wave conditions
- Sea surface temperature
- Conductivity, temperature, depth (0-1000 m)
- Currents (0-200 m; acoustic profiling of ocean currents, or APOC)
- Currents (greater than 200 m; moorings)
- Submarine light to less than 0.1% of surface illumination

Chemistry

- Dissolved nutrients (NO_3, NO_2, NH_4, UREA, SIO_4, PO_4: 0-500m)
- Total CO_2, alkalinity, pCO_2
- O_2

Biology

- Microbial carbon (in euphotic zone)
- Phytoplankton carbon (in euphotic zone)

- Chlorophyll profile (plus phaeopigments)
- Microzooplankton carbon (euphotic zone plus integrated 0-1000m)
- Macrozooplankton carbon (euphotic zone plus integrated 0-1000m)
- Micronekton by acoustics
- Size frequency distributions of living matter (euphotic zone)
- Primary production (to 0.1% light)

Lower Frequency Suites

Physics (ocean)

- Lagrangian currents (drifters)
- Deep conductivity-temperature-depth (CTD) casts (0-2000m)
- Deep Currents (moorings)

Chemistry

- 3HE
- Particulate organic (POC), nitrogen (PON), phosphorous (POP), and silicon (PSI), (0-2000m)
- Dissolved organic carbon (DOC), nitrogen (DON), and phosphorous (DOP)
- Dissolved nutrients (0-2000m)
- Deep total CO_2, alkalinity, pCO_2
- Sinking particles (traps -- upper 2000m)

Biology

- Depth stratified sampling for all size categories (day/night to 1000m)
- Replicate water column primary production (three to four per depth per day bi-weekly)

A Basic Ocean Observing System for Climate Forecasting

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Introduction

A routine system of global ocean observations is needed to address many issues for understanding the climatic variability of the oceans. Many of these have been addressed in either the preceding discussions for this workshop or various international reports. Rather than reiterating these, the important components of an ocean observing system in the context of developing a seasonal predictive capability using coupled models will be discussed. The discussion will be based on what has been learned in the past five years in taking steps to set up a coupled forecast system for the El Niño/Southern Oscillation (ENSO) phenomena at the Climate Analysis Center of the National Meteorological Center (CAC/NMC).

A system for making long time forecasts consists not only of an atmospheric model but also an ocean model. The latter is required because the long term memory of the climate system is thought to reside in the ocean. A project was started at the CAC to develop model-based analysis system for the tropical Pacific Ocean in 1985 for the purposes of documenting oceanic climatic change, allowing climate diagnostics, and providing initial conditions for a coupled forecast system. Even in meteorology, the observing system cannot by itself provide sufficiently accurate descriptions of the state of the atmosphere either for diagnoses or initializing forecasts. Over the years meteorologist have developed techniques to combine observations with dynamical model fields through the techniques of four dimensional data assimilation. The model fields provide a means of dynamically interpreting the observations in space and time to fill the data gaps. The operational systems have evolved to the point that they in fact can be used to identify poor observations. Few meteorologists, who are interested in studying the variability of the atmosphere, resort to looking at the observations. Instead they use these model-based analyses.

In the past this approach was not possible for oceanography. There was little real-time information about the ocean. The models and techniques for combining the data with the model fields were not developed. Slowly the situation is changing. Through the efforts of IGOSS and a number of climate programs, considerable real-time in situ data is available. Also computer technology and ocean modeling has progressed to the point that model-based analyses for the ocean are feasible. At the CAC routine weekly analyses are performed for the ocean using both a Pacific basin and global model. These combine all the real-time thermal data, e.g. satellite, ship, buoy, mooring, and XBT, with model fields from a primitive equation ocean model. The development of a seasonal forecasting system by coupling the Pacific basin model with a medium resolution atmospheric model has just started.

We created a sea surface temperature (SST) field in the tropical Pacific from our first six month coupled simulation. Overall the SST field looked quite reasonable. This would be especially the case if 1990 turned out to be an El Niño year! Compared to "normal" October conditions, the SST in the equatorial zone was anomalously warm. However, much more development work is required in order to gain confidence in such forecasts. The ability to make documentable forecasts such as this is of great economic and social benefit. Much of the justification for a permanent ocean observing system will come from its relevance towards enabling such forecasts to be made.

The linkage of the observations to such a forecast system comes in two ways. Observations are needed to develop physically correct numerical models and to be used in the model-based analysis system for providing the analyses of the ocean and atmospheric fields which will be used for initializing and verifying the forecasts. The atmosphere primarily feels the influence of the ocean through the SST and upper ocean heat content. The ocean is forced by the fluxes of momentum, heat, and fresh water from the atmosphere. At a minimum the ocean observing system must allow documentation and verification of these exchanges. Specifically it must enable a correct documentation of the global SST variability and the causes for this variability using the observation by themselves or in combination with models. Routine observations of the air-sea fluxes are not possible. Consequently sufficient information must be collected about variables that can be used to verify basic model fields, e.g. surface winds, or those which are needed to infer the fluxes. The following discussion will more fully address these points.

SST and Upper Ocean Thermal Measurements

A routine observational program already exists for SST which provides almost global coverage. However, this needs to be improved. A variety of measurement types are used to infer SST. These include remotely sensed data, shipboard measurement, and measurements from research instruments such as XBTs and moored and drifting buoys. These measurements sample the near surface temperature in different ways. Satellite estimates measure the skin temperature, i.e. the upper millimeters of the ocean, in cloud free areas. Ships and buoys use a variety of techniques and can sample at different depths (but not right at the ocean surface). The satellite-in situ differences are minimized by calibrating the satellite SST retrievals by regression against measurements from drifting buoys, i.e. resulting in a satellite estimate of a bulk measurement. There is a fundamental question about what is meant by an analysis of SST. Considerable natural variability exists on space and time scales that are not adequately sampled by the measurements. The amplitude of this can be larger than the time and space averaged quantities that are required for climate quality analyses. Diurnal variability in light wind areas with strong isolation can be several degrees Centigrade. What is desired in a SST analysis depends on the application. Forecast models require an estimate of the average temperature in the upper tens of meters of the water column, i.e. a mixed layer temperature which can be used as a representative value for energy exchanges with the atmosphere over a period of a day or so.

Measurements must be available sufficiently densely in space so that representative estimates of the spatial structure of the thermal field can be made. A year ago in the western Pacific day time temperatures estimated from satellites were a degree colder than the nighttime ones. This was clearly an algorithm problem. Even at present it is possible to find regions in the Pacific and globally where the daytime estimates are persistently colder than the nighttime ones. Although remotely sensed estimates give wonderful temporal and spatial sampling, the risk in using these measurements is that large scale biases can exist. These can be of the same amplitude as the climatic signal. However, without satellite estimates, global coverage is difficult.

Higher accuracy measurements can be provided by XBTs and drifting buoys. However, each of these measurements types can also have problems. SST is difficult to estimate from XBTs. Drifting buoys can have diurnal heating problems or sensor failures. A major problem for both of these systems, which is illustrated by this figure, is that the spatial sampling provided by these measurements is inadequate to accurately define spatial means even in this region which is heavily sampled by the TOGA measurement program. The Volunteer Observing Ships (VOS) measurements are the only in situ measurements which come close to providing spatial coverage on the same scale as the satellites. Unfortunately VOS SST estimates are of very mixed quality. In our quality control procedures at CAC we routinely throw out about a quarter of the reports because of temperature bias problems. Even the remaining observations are less reliable than those from the other platforms.

Our analyses at CAC combine all these different types of observations using the techniques of optimal interpolation. In such a technique individual error characteristics are applied to each measurement type (or platform) as well as to a first guess analysis field (if one is used). At present we do two types of analyses. One class uses a primitive equation ocean model to provide the first guess field; the other uses the previous analysis. Over the years in working with these analyses, the experience suggests the following as a minimal observational network for SST. Satellite estimates provide the necessary spatial and temporal coverage. A global network of drifting buoys is needed to provide basic calibration point for the satellite. However, probably the coverage provided by the drifting buoys will not be adequate to define the possible spatial biases of the satellite fields. Hence the quality and quantity of the shipboard measurements needs to be improved since it is shipboard sampling which measures on the same global scale as satellites. Ice limits are needed in polar latitudes to limit the SST in those regions. Such a satellite, ship, drifting buoy observing network has some built in redundancy. In case one of the three components fails, the other two are still sufficient to provide global coverage. Furthermore, both the shipboard and drifting buoy systems can provide observations of other in situ parameters.

For sustained air-sea interactions a knowledge of the upper ocean heat content is vital. It is believed that the climate memory for the ENSO variability is in low frequency variations of this quantity. Most of what has been inferred observationally about this has historically been learned from XBT and sea level measurements. More recently moored thermistor chain technology has developed to the point that routine real-time observations are available from the tropical Pacific. Over the next several years studies have to be undertaken to determine the direct level of T(z) sampling which is required to provide initialization for the coupled forecast models. This is a complex question which depends directly on the quality of the ocean models, how well known the stress fields are, and availability, quality, and quantity of sea level information.

Much of the ocean variability in low latitudes is wind forced. Hence it is possible that with good models and well known stresses in the tropics little or no subsurface thermal data will be required. Indeed the only existing dynamical coupled forecast system (Cane and Zebiak, 1987) uses only a knowledge of the past history of the wind field to initialize its forecasts. Currently, because of various uncertainties both with the models and the forcing fields, direct measurements must continue to be made. As was the case in the determination of SST, XBT sampling by itself is inadequate to accurately define the variability of the subsurface thermal field. Fortunately, current modeling and data assimilation technology has progressed to the point that interannual variability of the subsurface thermal structure can now be documented. Without use of the ocean model based analysis system this would not be possible. Much of the information about the subsurface thermal variability is contained in the wind variability.

Subsurface thermal measurements are central to helping verify model simulations and to evaluate forcing fields. A temperature bias of the order of 1 degree Centigrade is a depth error of about 5-10 meters. This example illustrates that arrays that routinely produce measurements at fixed locations are invaluable in the evaluation and development of models and forcing fields. Moored information is much more useful in this context because it allows for comparisons to be made over long periods of time at regular locations. Although similar analyses can be done with XBTs the results are much more difficult to interpret. Moored measurements can also serve as platforms to make research quality low level atmospheric measurements which can be used to directly evaluate the fields from atmospheric models.

Flux Fields

Direct measurement of air-sea flux fields over the global ocean to absolute accuracies that are adequate for climate purposes is an impossible endeavor. For example, current studies indicate that from routine observations the error in the estimation of the net heat flux is of the order of 40 watts/m^2. Uncertainties of this magnitude lead to r.m.s. SST simulations error of the order of 1 degree Centigrade per month. Such errors, especially if they are systematic would cripple attempts at seasonal forecasts. Longer climate simulations will require flux imbalances between the ocean and atmosphere to be a watt/m^2 or less. Similar obstacles face evaluation of the fresh water and momentum fluxes.

An additional complication exists in that it is likely that the ocean and atmospheric model that will be used for forecasting will themselves have model bias problems resulting from inadequate physical and numerical approximations. Hence a coupled forecast system will have to be "tuned" to perform properly. The resulting fluxes, which are internal to such a system, can differ from the best observational estimates. Global flux fields will only be available from operational atmospheric models and from some satellite estimates. Consequently there is a need for a program of direct measurements to validate these various fields. For practical reasons this will not be global in extent.

Observations of ocean fields and their evolution serve as strong constraints on the fluxes. One could in principal have estimates based on satellite data, drifting buoy data, and from the surface marine data available from the VOS. The ocean analysis system computes on a weekly basis the advective, diffusive, and storage changes in the heat content. From the sum of this is inferred the surface heat flux that must have produced these changes. The ocean is forced during this time with a net surface heat flux which is set to zero. The quality of the ocean analysis system estimate is directly determined by the ability to accurately estimate the upper ocean temperature structure (primarily the SST). An error here of .25 degrees Centigrade results in a heat flux error of 40 watts/m^2. We think the ocean analysis system is producing SST estimates to close to this accuracy; these flux estimates confirm this. The implication from this study is that a good monitoring and analysis system for SST goes a long way towards helping determine the net surface heat flux.

The fresh water flux between the ocean and the atmosphere is a key component of the global hydrological cycle. This is a combination of the precipitation and evaporation. At present this can only be estimated globally by using indirect estimates from remotely sensed fields and by using the output of operational atmospheric models. There are also a few climatological estimates. Our studies in the tropical Pacific indicates that in that region all three rainfall estimates agree within reasonable uncertainties. However, direct rainfall and evaporative estimates will be needed to more carefully evaluate the present estimates. We have started to use the ocean model simulations to examine if the model circulation properly redistributes the fresh water flux implied by these estimates. It is disconcerting that there is so little surface salinity information available even on a historical basis that most aspects cannot be verified. Without surface salinity information there is little hope of accurately defining the global hydrologic cycle. If salinity information were as widely available as SST information, ocean analyses could strongly constrain the net fresh water flux as it does the heat flux. Obviously it would be desirable to have global measurements of the upper ocean salinity structure. The only way this can be achieved is through the use of XCTDs and salinity measurements from research vessels. The TOGA experience has shown that it is difficult to regularly define the upper thermal structure on the basin scale using such techniques. Thus it is unlikely that the global near-surface salinity field can be monitored in this manner. Surface salinity measurements from VOS are much more feasible and would provide partial global coverage. This has to be a first step in setting up a system to monitor the global fresh water flux.

The upper ocean budgets for heat and fresh water are primarily determined by local storage and advective changes. To assess the validity of flux estimates using ocean analyses, the model current needs to be evaluated. Without getting into details, this is a complicated task. (A side benefit of having routine surface current information is that it allows for indirect evaluation of the momentum flux.) The largest collection of near surface ocean current estimates is available form the Pan Pacific Drifter program in the tropical Pacific. These drifting buoy estimates of currents can be directly compared against the ocean model produced estimates. The overall model-buoy intercomparisons are quite good and indicate that the model simulations produce realistic currents. In building a global ocean observing system, it is desirable to have such routine current estimates available not only for their own sake but also for helping evaluate the model fields.

Summary

The focus in this discussion has been on those components of a global ocean observing system which are of central importance primarily in the context of coupled forecast systems. However, little practical experience exists in this area and these conclusions might have to be modified in the future. The discussion also highlighted the central role that ocean analyses, specifically dynamical model-based analyses, must play in synthesizing the observations and in providing estimates of the ocean fields to fill in the gaps in the observational network or provide estimates of fields which will be difficult to directly observe, e.g. the fluxes. Furthermore, such an analysis systems can providing state-of-the-art observational quality control and a centralized data management system. These later issues, although central to setting up a climate monitoring system for the ocean are not discussed herein.

The primary oceanic variable of interest in this context is SST. To insure that climate quality analyses are available the following steps have to be undertaken. Day and nighttime estimates by satellites need to continue to be made, possible biases identified, and improvements made where possible. A regular in situ monitoring system needs enhancement and improvement. This consists of a global network of drifting buoys and improved VOS estimates of SST. A global system of VOS measurements of surface salinity also has to be established. Analyses made using these basic measurements could be used to infer the net surface heat flux, and constrain the fresh water and momentum fluxes.

Routine information about the subsurface thermal structure from moorings and XBTs is necessary. How much of this will routinely be necessary in the future, presently cannot be addressed. However, it is clear that documentation of oceanic variability, and model and forcing field evaluation is best done in the context of regular arrays of moored measurements. Moored measurements also allow research quality measurements to be made at low level atmospheric variables that can be used to evaluate the output of the operational models. At present, the largest documented component of climatic variability for which there is also some prospect of developing a forecast capability, is the ENSO cycle. Hence a continued focus for subsurface thermal measurements in this region has strong rationale. Hopefully studies over the next several years will establish the requirements for a subsurface thermal measurement program in this region and globally.

A monitoring system for sea level has not been discussed. An island and land-based system is already being established by GLOSS. Altimetric estimates have been shown to provide excellent estimates of the global variability on a variety of space and time scales which span those of climatic interest. The sea level signal can be directly proportional to the oceanic heat content. Hence one can anticipate that future research will establish that this information can be used as a surrogate for subsurface thermal information. Hence the question of a sufficient direct subsurface thermal monitoring program and the availability of altimetric sea level estimates are intimately related. Even at present, model simulations of sea level variability, especially in the tropical Pacific and along the western boundary of the U.S. are capable of describing much of the observed variability. One anticipates that a model-based analysis system will play a central role in the utilization of such data.

Other observing systems such as moored current meter and flux mooring clearly play a role in understanding and documenting climatic variability and in model verifications. Since these however will by in large remain research efforts, they are not appropriately considered in this discussion of a global observing system.

References

Cane, M., and S. E. Zebiak, 1987. Prediction of El Niño events using a physical model. In *Atmospheric and Oceanic Variability*. H. Cattle (ed.) Royal Meteorological Society Press, pp. 153-182.

Data Management for Global Ocean Observing Systems

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Summary

Operational ocean data collection and management is proceeding internationally with the Integrated Global Ocean Service System (IGOSS). International data exchange is carried out under guidelines established by the International Oceanographic Data Exchange (IODE). In cooperation with these operational programs, a number of large-scale ocean research programs have a key role in developing the scientific basis for managing global ocean data.

The major ocean climate research programs (TOGA, WOCE, JGOFS) are making data management arrangements in terms of their own needs. At the moment there are few arrangements for overall coordination between programs to develop common standards, to reduce duplication, and to integrate their data collection management procedures into the operational systems. The OOSDP, with the eventual aim of designing an ocean monitoring system, will need to plan for integrating the data management elements of the above and other components into a global system.

This paper focuses on the current status of data management arrangements within some of the large-scale ocean research programs.

Introduction

Data management in support of a global ocean observing system should take an evolutionary approach. Some of the basic questions for an ocean observing system have yet to be answered: what kind of ocean data is needed? How should the measurements be distributed? How should ocean measurements be analyzed and processed to meet the needs of a global ocean observing system?

There is as yet no overall effective model on which to base a data management system for ocean data. Many components do exist. The international programs IGOSS and IODE are making an effort to develop the kind of data management and distribution system that would meet the needs of a global ocean observing system, but they do not yet have a set of effective end-to-end procedures.

The large-scale ocean research programs, particularly those directed to climate studies are developing procedures for processing and managing their own datasets. The scientific use of the datasets constitutes the best means for developing data processing procedures and quality control guidelines. Because such scientific involvement is widely dispersed in many laboratories and countries, some kind of distributed international data system is called for.

Data input is a problem. A significant proportion of the data which are collected never arrive in the IGOSS system. This is a special problem with oceanographic research data. Because of its quality, it's particularly important to collect as much of these data as possible. Policies are needed to encourage and reward the submission of dataset to an international data system, such as IGOSS. The large-scale ocean research programs have or are developing data sharing policies. I have summarized these policies here for TOGA. WOCE, and JGOFS.

I also give details on the distribution of TOGA and WOCE data centers, to show the diversity and to give some flavor of a distributed scientific network involved with developing a global ocean observing system.

Existing Data Management Elements

Current activities in managing global ocean monitoring data include operational elements under the IOC and WMO as well as major ocean research programs. The Ocean Observing System Development Program (OOSDP) plan for ocean monitoring includes interactions between the operational programs and oceanographic research programs.

Data management activities in the international operational ocean programs and in the large-scale ocean research programs show a wide range of diversity:

IGOSS, operated by the Intergovernmental Oceanographic Commission (IOC) and the World Meteorological Organization (WMO), is coordinating the collection and distribution of real-time ocean data. The large-scale ocean research programs are stimulating system improvements.

IODE, a program of the IOC, is developing new procedures to respond to the challenge of international data distribution and archiving imposed by the large-scale research programs. Together with IGOSS, IODE is developing a Global Temperature and Salinity Pilot Project as a prototype climate data system.

TOGA is an international research program that is both atmospheric and oceanic. The observational program has been underway for five years. There is no standing TOGA data management group.

WOCE will collect primarily physical oceanographic data. The WOCE field program has been underway since the beginning of this year. WOCE has a data committee and an active program underway to deal with data issues and to carry out systems tests.

JGOFS collects datasets that deal primarily with marine biogeochemical processes. The program has a data working group who are developing plans for a pilot experiment.

The operational data programs (IGOSS and IODE) have been responding strongly to the stimulus of meeting the needs of the ocean climate research programs. The following sections review some recent activities of the ocean climate research programs. I reproduce the Data Sharing policies for TOGA, WOCE, and JGOFS, since the issue of data sharing is a critical one in developing a global ocean observing system.

IGOSS

The IOC/WMO Integrated Global Ocean Service System coordinates a world-wide operational ocean service system. It manages the collection and distribution of real-time oceanic data and products derived from ocean datasets. A principal component is the IGOSS data system. Its effective operation will be critical to some elements of climate research programs.

IGOSS relies on the activities of the participating nations to carry out operations. The WMO and IOC carry out a role that is purely coordinating. Thus, the national programs are critical to the success of IGOSS.

IGOSS World Oceanographic Centers are maintained at Moscow and Washington. Specialized Oceanographic Centers (SOCs) are located in Argentina (for the South Atlantic), in

Australia (for the Indian Ocean and Pacific Ocean south of 20°N), in France (for drifting buoy data), in Japan (for the Pacific Ocean) and in Hawaii (for the Pacific sea-level program).

IODE and IGOSS are cooperating in the development of a Global Temperature Salinity Pilot Project (GTSPP). The aim is to create a timely global ocean temperature and salinity dataset of know quality in support of TOGA, WOCE, and JGOFS. The GTSPP is seen as the first step toward modernization of data management practices and techniques.

IGOSS suffers from a low data rate. The amount of data received by IGOSS is growing from year to year, but is not enough for preparing global ocean products and services. In 1989 the number of IGOSS BT transmissions was less than 40,000. This works out to about 100 observations per day, distributed over the globe. Since the observations tend to be concentrated in areas of intensive ship traffic, the available data is generally insufficient for preparing effective global products.

A high priority for IGOSS is to increase the percentage of observations that are submitted. This is particularly true for research observations, which tend to be of high quality and are most useful to improving the system.

IODE

The IOC's International Oceanographic Data Exchange (IODE) coordinates international exchange and archiving of oceanographic data. IODE establishes codes and standards, sponsors the creation of data catalogs and aids in the development of national oceanographic data centers. It will be a key component of a global ocean observing system.

IODE has put increasing emphasis on modernizing its system to meet the challenge of support to climate research and monitoring programs. Among other actions IODE has established a group on *Responsible Oceanographic Data Centers and Climate Data Services*. The group is planning an Ocean Climate Data Workshop, hosted by the USA, to be held possibly in autumn 1991.

More than forty countries have established national oceanographic data centers or have designated a national agency for oceanographic data matters. The backbone of the IODE system is the system of World Data Centers for Oceanography. World Data Center A (WDC-A) is in Washington, WDC-B in Obninsk, USSR, and WDC-D is in Tianjin, China.

In addition to the WDCs, many national data centers have accepted the responsibility for specific oceanographic datasets. Among these "Responsible National Oceanographic Data Centers" are:

Argentina	Southern ocean
Canada	Drifting buoy data
ICES	Data formats
Japan	Acoustic doppler current profiling data
Japan	WESTPAC program data
Japan, USA	Marine pollution monitoring
Japan, USA, USSR	IGOSS
UK	Wave data
USSR	MEDALPEX program data

IODE has been striving to improve the international system to meet the data challenge of the large-scale climate research programs. New technologies are being adopted for data collection, tracking, storage, and dissemination.

Just as with IGOSS, IODE depends on national contributions. The IOC's role is that of coordination.

IODE is putting the highest priority on changes to meet ocean climate research and monitoring programs. National data centers recognize this as an opportunity for improvement in their capability and credibility. Though the international oceanographic data system has been slow to change, evolution is now more rapid under the climate research stimulus. Change is being helped by new technology.

Though the World Data Center system and the IODE are still being improved, the oceanographic data system is a model that many other scientific disciplines would like to emulate.

TOGA Data Management

The Tropical Ocean Global Atmosphere Research Program (TOGA) data management approach is set out in the TOGA *International Implementation Plan* (available as Report No. 1 of the International TOGA Program Office [ITPO], Third Edition, February, 1990). The data issues in TOGA are not strictly oceanographic: both oceanic and atmospheric datasets are involved.

TOGA has a mature data management system built around a number of operational international data centers. Most of the TOGA datasets are obtained through operational, rather than research programs. In this regard TOGA contrasts with WOCE and JGOFS where a large proportion of the datasets will be collected by research programs. Most TOGA data is collected in real time and transmitted on the Global Telecommunications System (GTS). Products and datasets are sent to the relevant World Data Centers (WDCs) for archiving and further distribution.

The Level II-A Data Center, Bracknell, UK, produces daily optimal global analyses of meteorological fields and derived first-guess surface fluxes.

The TOGA Marine Climatology Data Center, Bracknell, UK, collects ship marine meteorological data from Global Telecommunications System real-time data and from ship logs in a delayed mode. It provides a quality-controlled dataset to the WDCs for meteorology.

The Global Sea Surface Temperature Data Center, Washington, USA, collects ship and buoy data as well as satellite radiances. The center produces global sea-surface temperature products and datasets for archiving by the WDCs for oceanography and meteorology.

The Tropical Sea Level Data Center, Honolulu, USA, collects hourly and daily sea-level values from coastal, island, and ocean tide gauges as well as monthly mean sea-level values from stations outside the tropics that deliver data to IGOSS. The Center delivers products to the Permanent Service for Mean Sea Level, Bidston, UK and to the WDCs for oceanography.

The Tropical Ocean Subsurface Data Center, Brest, France, collects observations over the tropical oceans from the IGOSS network. Datasets include those from XBTs, drifting buoys, moored thermistor chains, hydrocasts, and other sub-surface ocean temperature and salinity measurements. It provides datasets and products to the WDCs for oceanography.

The Tropical Upper-air Data Assembly Center, is supposed to begin operations later this year in New Delhi, India. The Center will collect in-situ upper-air measurements over the TOGA tropical area and provide a Level II-B dataset to the WDCs for meteorology.

The ITPO in Geneva monitors TOGA data management activities. Though the TOGA program has no formal data committee, ad hoc meetings of experts on data issues are arranged as appropriate.

TOGA CD-ROM Pilot Project

The NASA Ocean Data System (NODS), Pasadena, USA, is preparing a TOGA CD-ROM as a pilot project. TOGA data from 1985 to 1988 will be included. The bulk of the data will be ECMWF analyzed surface parameters and model-derived fluxes. Other data include monthly averaged fields of global SST, wind stress, subsurface ocean-model fields, hourly and daily sea level, moored buoy and island data, drifting buoy data, and ship observations. Thanks to support from the US National Aeronautics and Space Administration, the CD-ROM should be available to the scientific community free of charge.

Reanalysis

The TOGA Scientific Steering Group has set the goal of producing a homogeneous and consistent set of analyses for the tropical oceans and global atmosphere over the full TOGA period. The SSG is thus arguing for a re-analysis of the TOGA dataset. A two-stage process is being considered. First, a Level II-B dataset will be constructed to be used as input to a data assimilation scheme. Second, assimilation and model forecast programs will produce the Level II-B analysis and diagnostic fields.

As part of the first stage activities, Level II-B datasets are being prepared as follows:

Global subsurface dataset	NODC, USA
Drifting buoy dataset	MEDS, Canada
Ship dataset	Met Office, UK
Sea-level dataset	Univ of Hawaii, USA

TOGA Data Sharing Policy

As far as I can tell, there is no formal TOGA data sharing policy. To quote the TOGA *Implementation Plan*:

"Research data are frequently most readily and quickly available through scientist to scientist and/or institution to institution contacts. These arrangement are considered beyond the purview of International TOGA."

WOCE Data Management

The World Ocean Circulation Experiment (WOCE) will collect mostly physical oceanographic data. The data management approach is set out in the *WOCE Implementation Plan*. The WOCE Data Management Committee (DMC) guides the development of the WOCE data system. A number of WOCE Data Assembly Centers (DACs) are in operation, as is one Special Analysis Center (SAC). The WOCE Data Information Unit is in operation. Plans to set up other centers are underway in a number of countries.

Unlike TOGA, WOCE is developing a data system with a high degree of scientific participation. The plans for handling each data type are being developed in cooperation with the appropriate WOCE planning committee. A data-sharing policy has been adopted by the WOCE

SSG but specific details such as confidentiality and publications rights are being addressed with each element of WOCE.

WOCE Data Sharing Policy

The WOCE data sharing policy included in the Implementation Plan has yet to be tested but there are occasional indications that exceptions will be taken. The DMC is concerned that principal investigator concerns about proprietary rights tend to get cited more than the data sharing policy. The DMC, therefore, requested that SSG ensure that National agencies remind principal investigators of the over-riding criteria for data sharing.

There is a fundamental tradeoff-on the one hand, protecting the intellectual effort and time of the originating investigators (those who plan an experiment, collect, calibrate, and process a dataset to answer questions about the ocean). On the other hand is the need to compare various datasets and data types to check their consistency, to better understand the ocean processes involved, and to see how well the numerical models describe the real ocean. The WOCE data-sharing policy is a tradeoff between these conflicting needs.

"Any data collected as part of WOCE should be made publicly available no later than 2 years (the publication rights period) from collection[1] , unless specifically waived by the SSG and funding agencies."

"Individual WOCE programs (hydrography, surface velocity, etc.) may require all participating investigators to submit (usually within a few months after collection) data collected as part of WOCE to a DAC for the purposes of quality control and data synthesis during the public rights period. In that case the recipient (DAC) may not redistribute such data, or a derivative containing most of the information unless specifically approved by the originating principal investigator, and should use the data for the stated purpose only."

"Originating investigators are strongly encouraged to share their data before the end of the publication rights period. The receiving investigator should not publish any paper during that period based predominantly on the received data, should co-author results with the originating investigator, and should not redistribute the data."

To assist the WOCE International Project Office (IPO) in keeping WOCE participants informed of progress, scientists should submit inventories of data collected to the IPO. This should be done within one month after a cruise or at regular intervals (less than 6 months) in the case of continuing data such as sea level and satellites.

The early submission of inventories to the WOCE IPO is encouraged so that information on observational programs could be shared with interested principal investigators to facilitate their cooperation. The Data Information Unit will be the primary means by which the inventories would be made available. According to the *Implementation Plan*:

"To assist the WOCE IPO in keeping WOCE participants informed of progress, scientists should submit inventories of data collected to the IPO. This should be done within one month after a cruise or at regular intervals (less than 6 months) in the case of continuing observations such as of sea-level and from satellites."

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1 Implies completion of the determination of the value of the particular parameter. Thus, for example, tritium/helium collection may not be complete for over a year after return to shore/laboratory

WOCE Hydrographic Program Data Assembly Center

Location:	Woods Hole, USA	Contact:	Terry Joyce

The WHP DAC has been in operation since September 1989. The Center is giving priority to quality control procedures, operations manuals, preparations to receive data from early WOCE cruises, and acquiring pre-WOCE datasets.

WOCE Hydrographic Program Special Analysis Center

Location:	Hamburg, Germany	Contact:	Jens Meinke

Established in November 1989, the Center is collecting "good quality" historical datasets and installing GF3 transfer routines. A meeting of SAC and DAC members was held in January 1990 to discuss interactions, responsibilities, and objectives of the centers.

Drifter Data Assembly Center

Location:	Ottawa, Canada	Contact:	Ron Wilson
Location:	Miami, USA	Contact:	Donald Hansen
Location:	La Jolla, USA	Contact:	Peter Niiler

Scripps (Niiler) will coordinate deployments, render technical assistance, and evaluate drifter performance. AOML (Hansen) will carry out quality control functions and distribute data to the Marine Environmental Data Service (MEDS) in Ottawa, Canada. MEDS has the DAC GTS responsibilities and will act as the distribution center. MEDS (Wilson) is taking the lead for a test of the drifter data flow to be carried out over the next several months using the TOGA Pan-Pacific dataset.

Sea-Level Data Assembly Center

Location:	Bidston, U.K.	Contact:	Meirion Jones
Location:	Hawaii, USA	Contact:	Klaus Wyrtki

The United Kingdom will operate the "slow" or "final" component of the DAC at the British Oceanographic Data Center. This center is responsible for producing the final quality-controlled sea-level dataset within 2 years. "The fast center" will be operated by the USA at the University of Hawaii. It will receive and redistribute data transmitted over satellite or other fast links. Their quality-controlled data will be available approximately 6 months after reception, a time scale comparable to satellite data processing.

Upper Ocean Thermal Data Assembly Center

Location:	Brest, France (Global)	Contact:	Jean-Paul Rebert
Location:	La Jolla, USA (Pacific Ocean)	Contact:	Warren White
Location:	Miami, USA (Atlantic Ocean)	Contact:	Bob Molinari
Location:	Hobart Australia (Indian Ocean)	Contact:	Garry Meyers

This DAC activity will be a collaboration between a Global Center at Brest and the three regional centers. These centers will be supported by the IGOSS/IODE Global Temperature Salinity Pilot Project (GTSPP). Representatives of each component, including the GTSPP, met in February 1990 to begin the process of defining operational details related to quality control, exchange formats, collection and dissemination procedures, exchange and processing schedules, and standard product (analysis) generation.

Current Data Assembly Center

Location: Corvallis, USA Contact: Dale Pillsbury

A pilot program has been founded in the USA with the anticipation that the center will be operational in early 1991 at Oregon State University. The center in the US will possibly be supported by the UK.

Float Data Assembly Center

No steps have been taken to establish a Float DAC. A Float DAC is called for in the *WOCE Implementation Plan* but the DMC deferred setting up an infrastructure until the nature of the data collection and sharing problems were better understood. However, data from recent non-WOCE float deployments, particularly in the Atlantic, would be of value to WOCE. The DMC and Float Program Planning Committee will review the available data and determine whether and how they could be made available.

Acoustic Doppler Current Profiler Data Assembly Center

Location: Tokyo, Japan Contact: Shin Tani

No steps have been taken to establish an ADCP DAC but Japan has accepted responsibility for operating an ADCP center within the IOC's International Oceanographic Data Exchange program. The DMC is monitoring that activity and will advise if the establishment of an ADCP DAC is warranted.

Data Information Unit

Location: Lewes, USA Contact: Ferris Webster

The WOCE DIU is in operation. With the beginning of the WOCE Field Program, the activities have become more intense. The DIU is seeking cooperation with national committees and the IPO to obtain accurate program information. The IOS Deacon Laboratory (UK) has hired a DIU coordinator at the IPO.

JGOFS Data Management

The Joint Global Ocean Flux Study (JGOFS) will collect biogeochemical data. Such data have not heretofore been catalogued or exchanged easily, because of the labor-intensive nature of the analysis process, differences in analysis protocols, and lack of confidence in the data product. The JGOFS approach is based on a distributed international system that requires rapid, easy sharing of data, models, analyses, and observation system.

The international JGOFS data management system is a group of interacting national centers. There is no central entity. Each nation has a JGOFS data coordinator responsible for assembling and exchanging national JGOFS datasets and analyses with other nations. Individual scientists will interact with their nation JGOFS coordinator. Eventually each participating nation should have a comprehensive JGOFS data set.

The structure and scope of the national centers will be driven by national requirements. On receipt of a final data set, a Center would forward that data set (fully documented) to the other Centers in the network. In this context, the Atlantic Bloom data set will be assembled simultaneously at all five Centers. The plan is being treated as a prototype in dealing with a diverse suite of observations/variables. Its effectiveness should be reassessed in a year.

Although the JGOFS data format (Meirion Jones and Glenn Flierl) and GF3 are the approved formats, in fact most JGOFS scientists have their own data on personal computers in their favorite spreadsheet data base. Most of these spreadsheets are *Lotus 1-2-3* compatible and hence *Lotus 1-2-3* has become a defacto exchange format.

JGOFS Data Sharing Policy

The JGOFS Committee consider that free exchange of information is essential for the success of JGOFS and at its 1989 meeting adopted the following policy:

"Recognizing that science is best served by free and open communication of findings, including data in raw form; and

In view of the enormous value of uncorrupted datasets as input to models useful in the design of field projects and in hypothesis testing; and

Noting that JGOFS will produce, at public expense, high-quality datasets of extreme value to ocean biogeochemistry;

The JGOFS Committee believes that reading access to the JGOFS data base(s) should be without restriction for any interested user. The information in the data base(s) will be labelled as to its originator and it is expected that readers would obey the normal scientific obligation to contact the originator for permission to make further use of those elements of interest to them.

The JGOFS Committee hopes that every national committee for JGOFS will endorse this policy on data access."

Conclusions

A effective data management system for a global ocean observing system should involve a transfer of knowledge and technology between the scientific procedures being developed in the large-scale ocean research programs and the operational ocean observing programs. The scientific community should be encouraged to play a greater role in this exchange.

There is a lot of room for joint exploitation of common data management technologies, such as data catalogs, international communications networks, and information interchange standards. The simultaneous growth in technology, in oceanographic research, and in ocean observing system programs presents an exciting opportunity.

Navy Concept of Operations and Advanced Technology

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Abstract

This paper describes the NAVOCEANCOM "Concept of Operations" and relates our strategy for providing operational environmental support to the realities of high-tech and increasing fiscal pressures. The Concept of Operations is the strategy through which the Commander, Naval Oceanography Command will provide operational environmental support to Navy forces operating throughout the globe. The current architecture of the Naval Oceanography System is discussed and compared with that planned for the mid to late 1990s. Significant elements of the environmental support infrastructure are in place and are providing oceanographic, acoustic, and meteorological guidance at resolutions in time and space that were unheard of 5 years ago.

Technological advancement is providing improved remote sensing systems, both *in situ* and space based, super computing, high resolution dynamic data bases, and advanced numerical prediction models for the oceans and atmosphere. As examples, the Navy implemented the first dynamic oceanographic forecast model, developed by researchers at Harvard University, for the Gulf Stream in December 1989. As the Navy Operational Gulf Stream Forecast System (NOGUFS) 1.0., this first model only slightly beat seven-day persistence forecasts by about 15 percent. Within two months of the acceptance of NOGUFS 1.0, and largely due to lessons learned with the first model, a second model developed by the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) was shown to beat 14-day persistence forecasts by 17 percent. This model is now being implemented at the Naval Oceanographic Office and Fleet Numerical Oceanography Center. The Naval Oceanography Command's first large-scale Class VII supercomputer will be installed at NAVOCEANO in October 1990 and a second will come on line at FLENUMOCEANCEN by 1992. These computers will provide the oceanographic community with the computing power required to develop, implement and operate global scale, coupled, ocean-atmosphere numerical prediction systems.

Today, in response to climate change and other factors, a global operational Ocean Observing System (OOS) is seriously being considered by the Navy and the National Oceanic and Atmospheric Administration (NOAA). The vast expanse of the oceans and high cost associated with conventional data gathering techniques prevented the oceanographic community from planning and implementing a "synoptic" observing system until the development of low-cost, multiple-sensing, satellite-reporting buoys. The first use of these instruments was to survey the Arctic in the mid 70's. Initially the cost to procure and deploy the buoys was prohibitive for operational applications. However, substantial research and development has now resulted in a generation of low-cost and logistically simple expendable instruments. On-going work will, within two years, yield sophisticated environmental surveillance sonobuoys capable of making a host of oceanographic and meteorological observations that include: atmospheric pressure, subsurface temperature, wind speed/direction, precipitation, and broad-band ambient noise.

Likewise, improved satellite-borne sensors such as the microwave imager, altimeter and scatterometer are adding a new dimension to the classic "visual" photographs of the past. Satellite sensors, satellite communication (SATCOM) and automated sensing devices of all types promise to

restructure the classic view of oceanography as slow-paced and populated by sea-going researchers. These new and emerging technologies have rapidly brought oceanography to a cross-road similar to that faced by the meteorological community of 10-20 years ago. New demands for high resolution (time/space) oceanographic analyses, forecasts, and guidance dynamically coupled with the atmosphere requires that the oceanographic community step back and plan to meet the challenges of the 21st Century.

Polar Oceanography: Its Role in a Global Ocean Observing System

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Introduction

The Polar Regions have a pivotal role in the earth's climate. They serve as heat sinks for the energy radiated from the lower latitudes, providing the necessary climatic balance. They are places of water mass formation that are fundamental to the thermohaline-driven circulation of the world's oceans. There are areas in the Polar Regions that experience levels of biological productivity that are not matched in the lower latitudes, and hence, are important components of the earth's carbon cycle. Interests in the Polar Regions that justify their incorporation in a global ocean observing systems are: economic (non-renewable (oil) and renewable (fisheries) resources), environmental, national defense, and global climate change detection, assessment and monitoring). Science elements encompass physical dynamics, ecosystem and biogeochemical dynamics and geodynamics.

The initial research objectives of a polar component of a global ocean observing system are the characterization of budgets for carbon, ice, kinetic energy, heat, salt, and sediment. Operational objectives include improved weather forecasting, environmental protection, assistance of economic development, and support for government operations including defense-related activities. Unique aspects of the Polar Regions are the seasonal sea ice cover, alternating periods of prolonged light and darkness, and their remoteness from population and industrial centers. All of these, along with the intense cold, add a premium to the acquisition of environmental data and justify taking a regional view to designing a polar component for a global ocean observing system.

Incorporating the requirements of the Polar Regions into a global ocean observing system will be a challenge. However, this challenge cannot be dismissed as too difficult because of the importance of polar observations in meeting the overall objectives of the global system. What follows is a brief discussion of the existing observing systems, how these might be enhanced, and mention of new technologies and techniques that may be applied to the problem of developing a polar component to a global ocean observing system.

Existing Systems

With the exception of a few scattered drifting buoys, ice islands, shore stations and oil rigs on the arctic periphery, and coastal antarctic research stations there are precious few routine meteorological and even scarcer oceanographic observations emanating from, on, or near, the polar seas. Coupled with observations from occasional ice-breaking and other ice-going vessels they constitute the universe of surface-based geophysical data that are available to research and operational analysts and forecasters. Presently available space-borne remote sensors consist of the NOAA polar orbiters' AVHRR visible and infrared instruments and the passive microwave imager SSM/I aboard the DMSP satellites. Until its recent demise (January 1990) the Geosat altimeter had been applied to locating the sea ice edge and measuring the height of the Greenland ice sheet. Visible data from the AVHRR are not available during the darkness of the long polar night.

Enhancing Existing Systems

Because of the paucity of platforms for taking routine observations in the high latitudes, there is little that can be done to substantially improve the responsiveness of existing systems without a major expansion at currently prohibitive costs. New approaches are needed, and these will be discussed later. Nevertheless, there is room for improving the existing systems.

- Sustain and optimize the Arctic Drifting Buoy Network.
  - Establish a long term interagency and international mechanism for maintaining, funding and deploying a coordinated Arctic Drifting Buoy Network.
  - Develop low cost, air-deployable arctic buoys that will accurately and reliably measure water column properties and expand meteorological observations (e.g., wind speed).
- Continue research into utilization of satellite imagery and algorithms for automated analysis.
  - Develop synergistic methods for blending/merging diverse data sets (e.g., SAR and passive microwave imagery).
  - Develop automated analysis techniques for mapping ice features (leads, polynyas, ridges), quantifying ice dynamics (flow, rotation, divergence/convergence), and classifying ice types and concentrations.

Polar Component of an Observing System

Space-Based Component

The remote, hostile, and unpopulated nature of the Polar Regions lend support to the notion that remote sensing is the most effective means of obtaining a fundamental understanding of the biogeophysical distributions and variabilities necessary to the unraveling of climate cycles and for the continuous analysis and forecasting of environmental conditions in support of polar operations. The following outlines the space-based contribution to the Polar Regions requirement.

- Synthetic Aperture Radar (SAR): This high resolution, active microwave sensor has demonstrated capacities of varying degree for mapping sea ice extent, concentration, type, and features (ridges, leads, polynyas), as well as for providing ice field motion vectors. Its high resolution, all-weather, day/night features lend themselves especially effective to meeting operational requirements, but have also been identified as important to such global climate studies as air-sea heat flux and biological productivity.

- Special Sensor Microwave Imager (SSM/I). These sensors flown aboard current and future versions of the DMSP satellites, along with their predecessors, the Nimbus Scanning Multifrequency Microwave Radiometers (SSMR) dating back to 1976, are compiling an historic record of low resolution (25-30 km) distributions of sea ice extent and concentration. These data are particularly valuable for determining the interannual variability of seasonal ice coverage, but because of their low resolution do not generally provide information on features of a scale important to most operational and many research applications.

- Altimeter (ALT). The radar altimeter has been applied to sea ice edge detection and measurements of glacial ice sheet elevations. Surface roughness from altimetry for estimating air-ice stress values as input to ice motion models is still in the research mode.

- Advanced Very High Resolution Radiometer (AVHRR). The AVHRR which has been the mainstay of polar ice observation is limited in its application by cloud cover and darkness. Nevertheless, what we know about variations in the earth's sea ice cover over the past two decades owe mainly to the long term continuity and success of this sensor and its predecessors.

- Coastal Zone Color Scanner (CZCS). The CZCS that was operating from the Nimbus-7 spacecraft in the late 1970s to early 1980s had wide-swath imaging capability that provided valuable insight to the seasonal and geographic distributions of biological productivity of the world's oceans. This sensor documented the relationship between ice cover and productivity in the polar seas, and revealed the unexpected richness of the peripheral seas in the Arctic. A follow-on ocean color scanner, SeaWIFS is expected to continue with the mapping of oceanic productivity.

All of these sensors date their heritage to Seasat in 1978 or Nimbus-6 in 1976 and Nimbus-7 in 1978. Since then one or another of these sensors, except for the SAR, have been flown on succeeding earth observing satellites, some even simultaneously, but not on a single spacecraft. The future holds promise for incorporating several of these sensors on single spacecraft to allow concurrent, and hopefully, synergistic monitoring of the polar environment. Approved programs such as ERS-1, JERS-1 and Radarsat all include SARs. ERS-1, EOS and SeaWIFS, collectively, include all of the above-mentioned sensors.

Earth-based Component

Regardless how successful we are in establishing a comprehensive space-borne remote sensing capability for the Polar Regions, there will remain a requirement for a complementary earth-based component to calibrate and validate the space-based component, as well as to take the measurements that cannot be made from space -- ice thickness, surface winds over ice, water column properties, and sea floor characteristics, etc. A variety of platforms, some existing, others in need of development, in addition to new observing techniques are required for a wide-area, fine-scale ocean observing system in the Polar Regions for what is indisputably the most challenging segment of a global system.

Icebreakers, Ice-capable Vessels, and Ice Camps

Multidisciplinary research conducted from icebreakers, ice-capable vessels, and ice camps provides the insight into time and space scales of ocean variability and the engineering data necessary for designing and optimizing a polar ocean observing system. Multi-icebreaker, multinational trans-arctic and high latitude expeditions planned for the early and mid-1990s which are expected to coincide with the flights of such earth-observing satellites as ERS-1, JERS-1, Radarsat and Geosat Follow-on provide excellent opportunities for testing and evaluating new instrumentation and techniques for both *in situ* and remotely sensed measurements. Ice camps such as those planned for the Lead Dynamics Experiment support the essential process oriented studies that are needed for the development of analytical and forecast models. Nevertheless, the small number of these vessels and ice camps, their occasional nature, and the seasonal and geographic limitations imposed by ice cover, will necessarily circumscribe their usefulness to a global ocean observing system to the applications just discussed.

Moored and Drifting Buoys

Arctic drifting buoys have given us the general circulation of sea ice in the Arctic Ocean, defined current velocities in the Southern Ocean, and provided barometric pressure readings for calculating atmospheric flow in both regions. Continued deployment of a drifting buoy network is an essential component of an earth-based remote sensing system which provides basic input to analytic and predictive models. International coordination is needed to ensure that the buoy array is adequately maintained and optimally deployed. Efforts are underway in the U.S. to provide that coordination on a national level and through the WMO on an international level.

The potential of buoys -- both moored and drifting -- has not been fully explored. Surface buoys acting as telecommunications relays may someday collect data acoustically from the bottom and intermediate moorings from transfer ashore via a satellite communications link, and in turn command the underwater sensors to change mode or perform housekeeping duties. Other innovative buoy applications include their use as homing devices, command modules, power sources, and data storage for autonomous underwater vehicles that may be employed in conducting detailed repetitive regional surveys under the ice. Additional R&D is needed to expand the sensor suite on drifting buoys to include such parameters as water velocity, ice thickness, volume scattering, optical transmission, bottom depth, etc. New types of buoys are needed to measure ice stress, snow/ice moisture, insolation, etc.

Autonomous Underwater Vehicles

Autonomous Underwater Vehicles (AUV) may be thought of as the oceanographic analog of the unmanned space vehicles that have and are being used to explore the planets of our solar system and their satellites. Capable of carrying sensors, once deployed, AUVs can conduct systematic under ice surveys on a regional scale limited only by the range of communication with their command module and their energy supply. Ice penetrating buoys would serve the function of command and control for the AUVs as well as a satellite communications link for retrieving data from the AUVs and providing them with new instructions. These buoys might even recharge the AUVs power supplies. Once fully-developed and tested, AUVs employed under the ice in Polar Regions have the potential for becoming a major aspect of the earth-based component of a global ocean observing system.

Arctic Research Submarine

Not a new idea, the concept of outfitting a retiring nuclear submarine for a comprehensive survey of the Arctic Ocean continues to merit serious consideration. The size of the craft support a large and varied selection of sensors. Powering the sensors is not a problem, nor is endurance for providing areal coverage in the course of a single survey. Repetitive surveys every two to three years over a decade or more would be invaluable in climate change research.

Acoustic Tomography

A multi-agency effort is planned in 1991 to determine the feasibility of detecting and precisely measuring the arrival times of acoustic signals propagated over transoceanic distances. For the time and space scales involved, changes in the sound travel time over specific ray paths would be the result of changes in sea temperature. If successful, the Heard Island Experiment, as it is called, is expected to continue, and over time, will be capable of determining trends in the bulk sea temperature of the worlds oceans. In theory, global warming from a rise in greenhouse gases as predicted by some researchers would be observed by this method. It has been hypothesized that global climate change is intensified in the polar regions, thus offering a locale for the earliest detection of the signal. Such an investigation of the feasibility of using acoustic measurements to detect warming in the Arctic Ocean has been proposed. In addition, more complex tomographic arrays may also yield information on the location of fronts and eddies in the Polar Regions.

Communications

Ice cover and the polar night do not present the only unique challenges of the Polar Regions to the global ocean observing system. The use of geostationary communications satellites for relaying data from earth-based remote sensors is denied most of the Polar Regions. There are no commercial polar-orbiting communications satellites. Researchers have so far depended on the limited capacity of the store-and forward capabilities aboard the NOAA and the (one-of-a-kind) ATS satellites. There remains an unsatisfied requirement to develop a capacity for the near-real time high data rate transmission from the high latitudes.

Summary

A global ocean observing system is incomplete if it does not encompass the Polar Regions. It is currently hypothesized that climate change signals are intensified toward the Poles. The existing observing system is extremely limited, and consists almost entirely of low-resolution visual, infrared, and passive microwave images from polar-orbiting satellites and ad hoc deployments of drifting buoys. Near-term improvements depend upon the successful launch of several planned U.S. and foreign earth observing satellites featuring all-weather, day/night sensors. Also, efforts are being made to expand and sustain the current Arctic Drifting Buoy network.

These efforts alone will not be sufficient to provide the necessary baseline data for routine operational forecasts to the resolution and accuracy required, nor will they be adequate for the assessment and monitoring of global climate change. New technologies and techniques, especially for the earth-based component, are needed. Some of these already in the R&D stage (e.g., acoustic tomography, advanced data buoys, AUVs) show promise for meeting some of those requirements. New institutional relationships, new partnerships will be necessary to meet the funding, technological, and managerial challenges of a global ocean observing system. This is especially true for the Polar Regions where logistical costs traditionally run much higher than the lower latitudes. What is important at the moment is to ensure that the polar component is properly integrated into the global ocean observing system plan and to review existing polar research for its ability to contribute to the definition and design of that component.

On the Coastal Ocean[1] Subsystem to a Global Ocean Observing System

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Introduction

When we consider time scales associated with interannual variability and longer, we must take into account the strong interactions between the coastal ocean, coastal atmosphere, and coastal land, i.e., the "coastal zone," a term which will be defined further below. The coastal zone might well be called the "pollutiondom," where most earthlings attempt to function. The understandable societal preoccupation with pollution serves to explain why the term 'coastal monitoring' is so often focused on problems created by so-called point and non-point sources of noxious materials and toxic substances. Without ignoring these bona fide concerns, we must raise our sights to consider a broader set of issues in the coastal zone in general, and in the coastal ocean in particular. Presumably, a well-designed global ocean observing system (GOOS) and a well-designed coastal zone (ocean) monitoring system (though seemingly focused on short-term transients) would be highly complementary; in fact, they would share many elements, the classic example being coastal tide gauges, which are also global sea level gauges. Because the coastal ocean is highly impacted by global processes--e.g., sea level rises and falls--all those earthlings may eventually be convinced to have a vested interest in the GOOS. (Not to be overlooked are the impacts of those earthlings and their activities, and the other coastal zone processes, on global change itself.) One consequence is that there is a very serious "signal-to-noise" ratio problem in the coastal ocean, which is particularly poignant when it is time to fix blame for a coastal environmental disaster that could be attributed to natural variability, often of an interannual nature, just as well as to anthropogenic suspects. If the coastal ocean has been poorly monitored, there is then an underdetermined problem to be faced in fixing the blame.

Coastal Ocean Processes[3]

The coastal ocean is rich in variability, period. The good news is that coastal ocean variability tends to be structured and ordered by scale and forcing. The predominant forcing functions of the coastal ocean are

- atmospheric forcing, especially by transient winds on synoptic time scales of days to weeks, of circulation and stratification;
- tidal forcing of elevation and currents;

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1 The term 'coastal ocean' is used here in the NOAA-sense, i.e., the EEZ plus the estuaries and the Great Lakes.

2 Presently at the University of Miami, Rosenstiel School of Marine and Atmospheric Sciences

3 Brink, K.H., et al. (1990), Coastal Ocean Processes (CoOP), results of an interdisciplinary workshop, WHOI Contr. No. 7584, 51 pp., offers a broad overview

- meandering boundary currents and impinging open ocean eddies on time scales of weeks to months;
- river run-off with strong storm and seasonal cycles;
- wind waves;
- tsunamis;
- storm surge; and
- mean sea level change.

Topographic features (e.g., coastal capes and embayments, submarine canyons and capes, and banks and basins) have major kinematical and dynamical effects on coastal ocean circulation and mixing. In part because the coastal ocean is a transition zone between the continents and the open sea, oceanic fronts of various origins tend to be particularly prevalent. For example, fronts are generally associated with river run-off plumes, the turbulent coastal boundary layer (where the wind-driven surface turbulent mixed layer merges with the tide-and-wind-wave-driven bottom turbulent mixed layer), the shelfbreak (where fronts form between shelf and oceanic water masses), coastal upwelling, tidal flows around capes, and so forth. Of course, the fronts are very important both for concentrating materials and as mixing centers. Because the continental shelf portion of the coastal ocean is basically all "upper ocean," it is not only extremely responsive to atmospheric storm cycles, but also subject to strong seasonality in stratification and circulation associated with large scale, seasonal atmospheric forcing. Alongshore jets are highly characteristic features of the coastal ocean. Some are surface currents, others are undercurrents; some are persistent and linked to the larger scale oceanic circulation, others are transient and local and possibly recurrent. At least some of these jets become unstable and shed eddies. Coastal upwelling and storm surge are very significant wind-driven, vertical-motion processes. In addition to the positively buoyant inputs associated with river run-off plumes, there are negatively buoyant inputs (and sinking motions) associated with cooling, brine rejection with freezing, evaporation, and high suspended sediment concentrations. Cross-shore circulation must be important, but it is difficult to determine and has short alongshore length scales, which complicates estimation of cross-shore exchanges. In high latitudes, cooling, freezing, brine formation, ice formation, ice pack evolution, and melting are important processes. In low latitudes, heating and evaporation are important processes. All these, and other, physical phenomena, processes, features, and factors provide the physical milieu in which coastal ocean biological and chemical systems function, including the reigning physical transport and exchange processes which help to support the rich coastal ecosystems and fisheries, and to provide for the exchange of nutrients and pollutants between the land and the open sea. The importance of coastal ocean air-sea interaction for chemical and biological transfers should not be neglected. Due to the proximity of urban centers, coastal oceans receive major inputs of particles, pollutants, etc., via aeolian transport. Conversely, because the coastal ecosystems are so rich, there can be major outgassings of DMS, etc., which affect critical atmospheric processes--e.g., cloud formation. Similarly, the biological processes and biogeochemical transports in the benthic boundary layer are under the strong influence of currents, turbulent mixing, and sediment transport, and influence the overall coastal ecosystem and carbon and other cycles. The seaward reaches of the EEZ are generally dominated by the seaward edges of boundary currents and ocean eddies in full ocean depth regimes. We know very little about the upper ocean circulation, let alone the deep circulation, there.

The above discussion emphasized physical processes almost to the total exclusion of chemical and biological processes, a deficiency which is partially redressed in the following. Due to the increased use of fertilizers in agriculture and increased urbanization, and thus sewage, nutrient loading of coastal ocean waters is a serious issue of growing dimensions. In some instances, the loading is high enough to produce eutrophication which can lead to hypoxia or even anoxia of coastal waters. While much is yet to be learned about normal algal blooms in the coastal waters, there is a growing concern with the increased prevalence and impact of toxic algal blooms, which constitute a threat to important fisheries and human health. Hence, there is a recognizable need to monitor the coastal ocean for the purpose of tracking the evolution of toxic algal blooms, and eutrophication, hypoxia, and anoxia events.

The coastal ocean is very vulnerable to global climate change. Many of the coastal ocean processes outlined above could be impacted. The most obvious impact is coastal flooding, beach erosion, and related effects, associated with sea level rise due to global warming. An example of an easily overlooked "related effect" is that of increased storm frequency and intensity due to increased SST in the coastal ocean. If there are changes in the hydrological cycle, there could be quantitative and qualitative changes in river run-off, with large effects on estuarine and shelf waters and biota. If there are major changes in large scale atmospheric and oceanic circulation, the coastal ocean circulation can be altered to the disadvantage of coastal biota; the El Niño-Southern Oscillation phenomenon is a classic case in point. If there are major changes in water mass properties, the quality (nutrients, DO, etc.) of oceanic waters upwelled and onwelled onto shelves could be fundamentally altered, possibly to the detriment of coastal ecosystems. Conversely, changes in shelf water properties and biota could have strong effects on open ocean conditions due to affected properties of exchanged waters. Changes in atmospheric forcing (e.g., alongshore wind stress, evaporation and precipitation, and freezing and melting of sea water) could lead to changes in the properties of shelf waters or even the general nature of shelf stratification and circulation.

Unique Aspects of the Coastal Ocean Vis-a-vis GOOS

Generally, the observing system requirements of the coastal ocean are similar to those of the open ocean: for example, long time and space series of T, S, and V(z); satellite altimeter sea heights, ocean color imager chlorophylls, and scatterometer winds; and satellite-tracked drifters. There are, however, several unique and important aspects of the coastal ocean to be considered in the GOOS context, such as,

1) the river input of fresh water, nutrients, trace elements, sediments, etc., should be determined for major rivers;

2) smaller space and time scales of variability due to the propensity of frontal formation and responsiveness to synoptic atmospheric forcing present high demands for observing and modeling systems;

3) logistical opportunities exist to use coastal Bragg-scatter radars (e.g., CODAR) for surface currents, over-the-horizon (OTH) radars for surface winds, airborne remote sensors, and air-deployable sensing systems, and they should be evaluated as potential monitoring system elements;

4) tide gauges, plus temperature, salinity, nutrient, and chlorophyll samplers, located at coastal sites exposed to ocean processes are excellent (and inexpensive) for detecting large-scale, long-term physical and biological variability; long time series already exist at some coastal sites, including piers, and should be maintained;

5) surface gravity wave dynamics are crucial to nearshore circulation dynamics and beach erosion and deposition; thus, surface gravity wave observing systems (spectral wave analyzers on buoys, aircraft, and/or satellites) need special consideration for the coastal ocean;

6) the richly productive coastal ocean ecosystems support large fisheries, which need monitoring system/strategy studies;

7) several oceanographic grids have been established for several years to several decades, and they should be supported, after a review of their adequacy, to develop long time series;

8) piers and sewage outfalls can be useful locations for sensors;

9) the extreme sensitivity, and vulnerability, of the coastal ocean to global changes (which lends importance to (6)) can be used for climate change detection by monitoring sea level, coastal water quality, and ecosystems; and

10) partly as a consequence of (6), many ("tactical") civil and naval activities and operations require real-time data-acquisition systems and model products as a high priority.

Overall, the coastal ocean observing system needs must be met, as in the open ocean, by the combination of real-time observations and numerical models through data-assimilation.[4]

Since broad international participation is vital for GOOS to succeed, it is also useful to remark that most coastal nations, for understandable reasons, have a stronger interest in the coastal ocean than in the interior ocean; some are more interested in operational than climate change issues and, thus, need a real-time observational capability. Hence, to enlist their enthusiastic participation, it may be essential to ensure that GOOS has a strong coastal component which operates in a real-time mode.

Discussion of General Strategy

The topical element of "coastal zone" conveys the notion that we are dealing with the coastal ocean, coastal atmosphere, and coastal land, which are rich in interactive physical, chemical, and biological processes. Given the competing considerations of the high-intensity natural and societal activities located very near the coastline and the broader natural and societal activities associated with the EEZ, on the one hand, and the estuaries, wetlands, and watershed, on the other hand, it seems useful to define an inner zone and an outer zone for the coastal zone. This structuring of the coastal zone is intended to reflect the boundary layer nature of this realm. For the sake of discussion, the "inner coastal zone" is taken to include +/- 20 km of the shoreline and the planetary boundary layer above (ca. 0.5 km altitude), and the "outer coastal zone" is taken to include +/- 300 km of the shoreline and the lower troposphere above (ca. 5 km altitude). It is anticipated that the monitoring strategy will differ between the inner and outer zones. The topical element of "monitoring" can be defined to include observing systems, models, communication networks, data base management systems, and decision aids for environmental and governmental managers. Our concern is with operational monitoring; however, we must also consider the research aspects. We should consider biological as well as physical components, and, by implication, relevant chemical and geological components. We should focus on requirements for designing a monitoring system which can detect the response of the coastal zone to global climate

4 Mooers, C.N.K., Convenor (1990), The Coastal Ocean Prediction Systems Program: Understanding and Managing Our Coastal Ocean, Vol. I: Strategic Summary, 116 pp.; Vol. II: Overview and Invited Papers, 354 pp.: Synopsis, 20pp.; Report of a Planning Workshop held 31 October to 2 November 1989 at the University of New Orleans, Joint Oceanographic Institutions Inc., Washington, DC provides a source document with conceptual and technical details.

change. (Such a system should also be sufficient for monitoring the coastal zone impact of global change in general.)

It is appropriate to dwell on the "global coastal" topical element for a moment. (It is viewed, at first glance, as an oxymoron by most informed, but uninitiated scientists, which only reflects its largely underdeveloped nature.) Certainly, if there is a global climate change, it will affect the coastal zone on a global basis, albeit possibly with a great deal of local and regional nonuniformity. Second, modern technology, e.g., satellite remote sensing, provides information on the state of the coastal zone on a global basis, whether we like it (or use it) or not. Third, political leaders in the various power centers of the global village can be anticipated to demand current knowledge of the global coastal zone because rapid degradation of a local or regional coastal zone is likely to lead to economic, social, and political dislocations, which they must know about in order to be in a position to attempt to ameliorate the assorted deleterious effects. (Finally, there is in turn the possibility that the coastal zone, as a ca. 300,000 km x 600 km x 5 km globe-girdling strip with intense physical, ecological, and human activity, may have major influences on global change.)

It is useful to recognize that there are aspects of the coastal zone which can be organized by scale: local; subnational regional; national; supranational regional; global. It seems important to focus on the supranational regional and global scales, and to recognize that the local, subnational regional, and national scales are the province of individual national governments. Realistically, however, it should be anticipated that the Third World countries will expect the First World countries to provide technical advice and, probably, even technical assistance with their monitoring needs.

In approaching the supranational regional scale coastal zone issues, the regional programs of IOC, WMO, UNEP, UNESCO-Marine Sciences, IGBP, etc., should be viewed as useful coordinating entities. They could potentially provide for the regional needs for telecommunication networks and data bases. Airborne remote sensing of the ocean-atmosphere-land elements of the coastal zone on this scale may provide a very useful supplement to satellite remote sensing.

In approaching the global scale coastal zone issues, maximum utilization of satellite remote sensing systems must be incorporated. The adequacy of existing and planned research and operational satellite remote sensing systems should be examined. It is conceivable that new requirements for remote sensing satellites to cover the global-coastal domain may be identified. The satellite remote sensing systems provide an incredibly rich and valuable flow of data which must be "anchored" with key in situ observing networks--in some cases to control the quality of the satellite data, in others to provide subsurface ocean, biological, etc., information which is not otherwise available.

In structuring the monitoring strategy, sensitivity must be shown to the existence of physical and biological (biomes) zones. Physical zones include eastern boundary current, western boundary current, subpolar gyre and subtropical gyre regimes. Biological zones include coral reef, mangrove swamp, and coastal upwelling regimes. Fortunately, there is considerable correlation between the physical and biological regimes. A successful monitoring strategy would be certain to ensure that representatives of each major category of zonation were monitored to some degree.

In designing the monitoring strategy, it would be wise to recognize that there is a triad of subsystems which must be considered: physical, ecological, and management. The physical subsystem consists of several elements: physical (and some elements of chemical and biological) coastal oceanography, coastal meteorology, and coastal hydrology. These elements lend themselves to automated, electronic, in situ, real-time telemetry observing systems and numerical modeling. The ecological subsystem also consists of several elements: biological oceanography, limnology, botany, zoology, and ecology; they are generally enormously more complex spatially and have many trophic levels but, fortunately, are more slowly varying temporally. To a significant degree, these elements will depend upon labor-intensive, delayed-time laboratory analyses of samples. Consequently, bulk measures or indices of the coastal ecosystem will be valuable commodities. The management subsystem consists of scientific (network design, modeling, assessments) management of the monitoring program, its technical (sensors, computers, telecommunications, graphics, etc.) management, and intergovernmental (protocols and budgets) management. It also consists of decision aids (GIS-style computer graphics) for the environmental and governmental managers.

In approaching a task of this magnitude, it would be wise to take as many lessons as possible from the successful experience of the operational meteorologists. First, establish international standards and plans early in the effort. Second, coordinate closely with major research efforts to mutual benefit. Third, establish a hierarchy of observing stations: primary, secondary, tertiary, etc., which are progressively less well equipped with sensors, sample less frequently or accurately, etc.

The relationship between research and operational monitoring is worth mentioning at this juncture. "Operational monitoring" implies observing and modeling conducted according to established standards on a long-term official (i.e., governmental) basis. The long time series produced by monitoring, if well documented, are invaluable to research. In turn, research is needed to create new sensors, models, observing system network design, and, most importantly, process studies to better understand the relationships among the various variables and processes. Hence, we must note where we think research is needed to support the goals of this program.

Through large, international cooperative research programs--e.g., TOGA, WOCE, JGOFS, etc.--the global ocean is probably destined to become better sampled over the next decade. A general community objective is to establish an initial, operational global ocean observing system by the turn of the century. The emphasis has been in the open ocean except for some hydrographic stations and boundary current studies which fall into the coastal ocean and, most notably, the IGLOSS sealevel network. (However, there is a UNESCO study in progress which is narrowly focused on the impact of a possible climatic sea level rise on the coastal ocean. That study has found that the IGLOSS network is somewhat useful but inadequate for their purposes, which are often quite concerned with acute local problems: e.g., those of Bangkok, New Orleans, Venice, etc.) Of course, the coastal zone monitoring program should be linked to all such efforts and make full use of the information they provide.

The IGBP is considering a program for the coastal zone which would be concerned with the interaction of coastal land and ocean processes and the flux of materials between the continents and the oceans. The research results from this program could be influential in the design of the coastal zone observing system.

Currently, there is a great deal of activity in U.S. agencies initiating or modifying programs in coastal zone monitoring. Canadian agencies are busy, too, applying new technologies: e.g., real-time airborne SAR to remote, ice-covered coastal zones. However, in neither the U.S. nor Canada is there yet a comprehensive approach to coastal zone monitoring. Based on the discernable sense of societal priority and technical opportunity, good, concrete examples of successful strategies may be available within a few years.

Towards a Coastal Ocean Monitoring System

The present discussion is leading to a scoping of the topic entitled "global coastal zone monitoring program (GCZMP)to detect global climate change." In the course of its development, many agencies and people on a global scale will be made aware of the topic's existence and importance. A number of relevant and promising activities, technologies, and methodologies will be identified.

A phased approach to the development of the GCZMP should be considered. Inevitably, it will need to make use of regional and international workshops and committees. It must build upon a fruitful collaboration between the research and operational communities. Several experimental observing system elements should be attempted in the near term: it is vital to start some additional, and novel, time series soon! A few supranational regional monitoring programs should be undertaken in an R&D fashion: e.g., for the Black Sea, Caribbean Sea, Baltic Sea, North Sea, Bering Sea, Japan Sea, Gulf of Maine, etc.

It would be extremely useful to gain some experience with the combined use of satellite and airborne remote sensing, plus vastly upgraded NDBC buoys, on a regional scale of monitoring. The upgraded NDBC buoys could employ acoustic Doppler current profilers for current profiles plus zooplankton biomass estimates. The buoys could also be equipped with conductivity/temperature chains, fluorometers, transmissometers, and other sensors which would make them more broadly useful for biological and chemical studies and monitoring. While vertical acoustic remote sensing from ships and moored buoys has proven highly successful in the coastal ocean, very little work has been done on lateral acoustic remote sensing systems, ala acoustic tomography, for the coastal ocean, and these systems should be considered as a research priority for some of the physics and biology.

To gain full benefit of the monitoring effort, and to produce full 4-D field estimates, coastal ocean observing systems should be linked to the coastal ocean prediction systems through 4-D data-assimilative models. These predictive systems can provide approaches to both the short-term societal problems caused by pollution and the long-term climate change monitoring function. The enhanced data sets and modeling activity will also provide a fertile basis for the development and evaluation of coastal ocean simulation models designed to explore the response of the coastal ocean to various conceivable climate scenarios.

Appendix B

I. WORKSHOP STEERING COMMITTEE

D. James Baker
Richard Hayes
Ants Leetmaa
Christopher N.K. Mooers
Ray Partridge
John A. McGowan
Peter Niiler
James G. Richman
Ronald C. Tipper
Ferris Webster
Peter Wiebe
William Woodward

II. NOAA/NAVY GLOBAL OCEAN OBSERVING SYSTEMS WORKSHOP

September 10-12, 1990

Attendees

D. James Baker	Joint Oceanographic Institutions Inc.
Charles Bookman	NAS, Marine Board
Melbourne G. Briscoe	Office of Naval Research
Kirk Bryan	NOAA/Geophysical Fluid Dynamics Laboratory
John Calder	NOAA/National Ocean Service
John Carey	NOAA/National Ocean Service
Muriel Cole	NOAA/National Ocean Service
Peter Cornillon	University of Rhode Island
Webb Dewitt	Fleet Naval Oceanographic Center
Frank Eden	Joint Oceanographic Institutions Inc.
Ray Godin	IOC/CCCO
David Goodrich	NOAA/Office of Global Programs
J. Michael Hall	NOAA/Office of Climatic & Atmospheric Research
Donald Hanson	NOAA/AOML
Richard Hayes	Office of the Oceanographer of the Navy
Donald Heinrichs	National Science Foundation
Geoffrey L. Holland	Canadian Physical & Chemical Sciences Directorate
Terry Howell	Office of Naval Research
Bob Jacobson	NWS/Office of Meteorology
Terrence M. Joyce	Woods Hole Oceanographic Institution

Mary Hope Katsouros	Ocean Studies Board/National Research Council
Dana Kester	NOAA/National Ocean Service
Ronald Lavoie	NWS/Office of Meteorology
Ants Leetmaa	NOAA/Climate Analysis Center
Sidney Levitus	NOAA/NODC
Marlon Lewis	NASA Headquarters
John McGowan	Scripps Institution of Oceanography
Hugh Milburn	Pacific Marine Environmental Laboratory
Bob Molinari	NOAA/AOML
Christopher N. K. Mooers	University of New Hampshire
Marvin Moss	Scripps Institution of Oceanography
Robin Muench	SAIC
Walter Munk	Scripps Institution of Oceanography
George Needler	WOCE International Project Office
Regina Nichols	NWS/Office of Meteorology
Peter Niiler	Scripps Institution of Oceanography
Worth Nowlin	U.S. Planning Office for WOCE
James J. O'Brien	Florida State University
Ray Partridge	Naval Oceanography Command
RADM Richard F. Pittenger	Office of the Oceanographer of the Navy
Judi Powell	The Oceanography Society
James G. Richman	Oregon State University
James Rigney	Stennis Space Center
H. Thomas Rossby	University of Rhode Island
Thomas B. Sanford	APL/UW
Neville Smith	Australian Bureau of Meteorology Research Center
Sharon Smith	Brookhaven National Laboratory
Tom Spence	National Science Foundation
Peter Tatro	Science Applications International Corporation
Peter Taylor	Institute of Ocean Sciences
J. Dana Thompson	NORDA
Ron Tipper	Joint Oceanographic Institutions Inc.
Virginia Tippie	NOAA/National Ocean Service
Grace Torres	Joint Oceanographic Institutions Inc.
Ferris Webster	University of Delaware
Robert A. Weller	Woods Hole Oceanographic Institution
Warren B. White	Scripps Institution of Oceanography
Peter Wiebe	Woods Hole Oceanographic Institution
Robert Winokur	US Naval Observatory
Greg Withee	NOAA/NESDIS
William E. Woodward	NOAA/Office of Ocean Services
Klaus Wyrtki	University of Hawaii
Jim Yoder	University of Rhode Island

III. NOAA/NAVY GLOBAL OCEAN OBSERVING SYSTEMS WORKSHOP

Agenda

Day 1
September 10

Plenary Session (all day)

0830 Welcome, The International Context	J. Baker
NOAA Background and Requirements	V. Tippie
NAVY Background and Requirements	RADM R. Pittenger
U.S. Global Change Research Program	M. Hall
Coffee	
Overview of Requirements	
TOGA	P. Niiler
WOCE	J. Richman
JGOFS	M. Lewis
Lunch	
Plenary Session (continues)	
Existing Systems and Technology	
Upper Ocean and Atmosphere	P. Niiler
Intermediate and Deep Ocean	J. Richman
Chemical and Biological Systems	J. McGowan/P. Wiebe
Coastal Processes	C. Mooers
Coffee	
Polar Oceanography	R. Hayes
Data Management	F. Webster
Use of Modeling	A. Leetmaa
Advanced Technology	R. Partridge
Introduction of Working Groups	J. Baker
Reception	
Dinner	

Day 2
September 11

0830 Working Group Sessions (all day)

Working Group I - Air/Sea Interaction and Upper Ocean
Working Group II - Intermediate and Deep Ocean
Working Group III - Biogeochemcial Measurements

During the morning, all groups should also consider the following cross-cutting issues as pertinent to their area:

- Enhancement of Present Measurements
- Data Management
- Impact of New Technology
- Modeling
- Coastal Processes
- Polar Oceanography

Luncheon - Guest Speakers W. Nowlin/G.Holland

During the afternoon, all groups should also consider the following cross-cuts as pertinent to their area:

- Linkages between Measurements
- Required Instrumentation, Equipment and Facilities
- Interaction with Existing Programs
- Interaction with International Programs
- Interaction with Satellite Systems

Dinner

During the evening, all working groups will continue discussions and write-up of documents

Day 3
September 12

0830 Plenary Session

Reports by Working Group Chairs

Open Discussion with a panel of working group chairs W. Woodward, moderator

Closing Remarks J. Baker

1200 Workshop Adjourns

IV. LIST OF ACRONYMS

ACC	Antarctic Circumpolar Current
ACCP	Atlantic Climate Change Program
ADCP	Acoustic Doppler Current Profiler
ADEOS	Advanced Earth Observation Satellite
ALACE	Autonomous Lagrangian Circulation Explorer
AOML	Atlantic Oceanographic and Meteorological Laboratory (NOAA)
ARCSS	Arctic System Science
ARGOS	Satellite Data Collection and Platform Location System
AUV	Autonomous Underwater Vehicles
AVHRR	Advanced Very High Resolution Radiometer
CAC/NMC	Climate Analysis Center/National Meteorological Center
CalCOFI	California Cooperative Oceanic Fisheries Investigations
CCCO	Committee on Climatic Changes and the Ocean
CEES	Committee on Earth and Environmental Science
CLIMAP	Climatic Long-Range Investigation, Mapping and Prediction Project
CPR	Continuous Plankton Recorder
CZCS	Coastal Zone Color Scanner
DAC	Data Assembly Center
DIC	Dissolved Inorganic Carbon
DMC	Data Management Committee (WOCE)
DMSP	Defense Meteorological Satellite Program
DOC	Dissolved Organic Carbon
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of Interior
DOS	Department of State
DOT	Department of Transportation
ECMWF	European Center for Medium-Range Weather Forecasting
EEZ	Exclusive Economic Zone
ENSO	El Niño/Southern Oscillation
EOS	Earth Observing System
EOSDIS	EOS Data and Information System
EPA	Environmental Protection Agency
ERS-1	Earth Remote Sensing Satellite
GCM	General Circulation Model
GEOSAT	Geodetic Satellite Mission
GEOSECS	Geochemical Ocean Sections Study
GIS	Geographic Information System
GLOBEC	Global Ocean Ecosystems Dynamics
GLOSS	Global Sea-Level Observing System (IOC)
GOOS	Global Ocean Observing System
GPS	Global Positioning System
GTS	Global Telecommunications System (WMO)
GTSPP	Global Temperature Salinity Pilot Project
HOTS	Hawaii Ocean Tim-Series
ICCP	Interagency Committee on Coastal Processes
IGBP	International Geosphere-Biosphere Programme (ICSU)
IGOSS	Integrated Global Ocean Service System (IOC/WMO)
INMARSAT	International Marine Satellite Communications System
IOC	Intergovernmental Oceanographic Commission (UNESCO)
IODE	International Oceanographic Data Exchange (IOC)

IPO	International Project Office (WOCE)
ISCU	International Scientific Council of Unions
ITPO	International TOGA Program Office
JERS-1	Japanese Earth Resources Satellite
JGOFS	Joint Global Ocean Flux Study
JOI	Joint Oceanographic Institutions Incorporated
JSC	Joint Scientific Committee
LANDSAT	Land Remote Sensing Satellite
MEDS	Marine Environmental Data Service
METSAT	Meteorological Satellite
MMS	Minerals Management Service
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
NOARL	Naval Oceanographic and Atmospheric Research Laboratory
NOGUFS	Navy Operational Gulf Stream Forecast System
NODC	National Oceanographic Data Center
NODS	NASA Ocean Data System
NOS	National Ocean Service (NOAA)
NSF	National Science Foundation
OMB	Office of Management and Budget
ONR	Office of Naval Research
OPC	Ocean Processes and Climate (IOC)
OOSDP	Ocean Observing System Development Panel
OSB	Ocean Studies Board
OTH	Over The Horizon
SAC	Special Analysis Center
SATCOM	Satellite Communications System
SCOR	Scientific Committee for Ocean Research (ICSU)
SEAS	Shipboard Environmental (Data) Acquisition System (NOAA)
SeaWIFS	Sea-Viewing Wide Field-of-View Sensors (Ocean Color)
SMMR	Scanning Multichannel Microwave Radiometer
SOC	Specialized Oceanographic Center
SOFAR	Sound Fixing and Ranging
SSM/I	Special Sensor Microwave Imager (DMSP)
SST	Sea Surface Temperature
STACS	Subtropical Atlantic Climate Study
SVP	Surface Velocity Program
OPC	Ocean Processes and Climate
TAO	Thermal Atmosphere-Ocean (TOGA)
TOGA	Tropical Ocean and Global Atmosphere
TOPEX/Poseidon	Ocean Topography Experiment
UNEP	United Nations Environmental Program
UNESCO	United Nations Educational, Scientific and Cultural Organization
USCG	United States Coast Guard
USGRP	United States Global Change Research Program
USGS	United States Geological Survey
VOS	Volunteer Observing Ships
VLBI	Very Long Baseline Interferometry
WCRP	World Climate Research Programme
WDC	World Data Center
WESTPAC	Program Group for the Western Pacific
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment