IMPLEMENTING US CLIVAR 2001—2015

THE U.S. CLIVAR SCIENTIFIC STEERING COMMITTEE

DRAFT VERSION

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The Origins of US CLIVAR

Planning for the international Climate Variability and Predictability (CLIVAR) program began in 1993 when the Joint Scientific Committee (JSC), recognizing the contributions to understanding of the world ocean and the links between the ocean and atmosphere provided through the WOCE and TOGA programs, commissioned a follow-on program emphasizing cross-disciplinary perspectives in exploring the dynamics of the coupled atmosphere, land, and ocean climate system. International science plans (WCRP, 1995) and initial implementation (ICPO, 1998) established an approach through a collective framework of Principal Research Areas (PRAs), discretized by time scale. In parallel with international planning, US planning was initiated through the Global Ocean-Atmosphere-Land System (GOALS) and Natural Climate Variability on Decadel-to-Centennial Time Scales (DECCEN) panels established by the National Research Council. A number of US meetings and workshops resulted in preliminary US science and implementation strategy documents (e.g. NRC, 1998).

In 1998 program managers from NASA, NOAA, NSF, and DOE began meeting as an interagency group (IAG) to promote and coordinate national interest in CLIVAR. The IAG appointed a Scientific Steering Committee (SSC) to provide overall scientific guidance, to recommend priorities and effective sequencing of US CLIVAR activities, and to ensure balance within the various elements of the program. Based on US inputs to international plans and national research interests, the SSC assembled a US position paper (USCO, 1998) in preparation for the International CLIVAR Conference (ICPO, 1999). This position paper emphasized US priorities in improving seasonal-to-interannual predictions, especially the decadal modulation of ENSO variability, as well as decadal variability in the Pacific; expansion of studies of the American monsoon system; continued investigations of Atlantic climate variability; including emphases on northern and tropical regions; and developing climate models for use in evaluating and predicting climate changes and variability. It also indicated, in contrast to the time-oriented framework of the international CLIVAR plans, the intent to proceed with a strategy of regional program development, whereby each region would address a wide range of time scales.

Since the international conference, the SSC has used the position paper as an initial guide, but recognized more input was required to develop comprehensive plans, programmatic priorities, and a balanced implementation strategy. Three regional implementation panels (Atlantic, Pacific, and Pan-American) were appointed by the SSC for regions where scientific rationale, as well as planning and organization, were relatively mature. Additionally, a working group focusing on seasonal-to-interannual modeling and predictions was formed to provide guidance and suitable plans for focused activities in this program-wide element. The resulting implementation plans described herein, reflect this evolutionary process of developing US plans for the CLIVAR program. These plans will continue to change as US CLIVAR matures.

Comments on the plans are welcomed. They may be submitted to the US CLIVAR program via our web page (www.usclivar.org), email (comments@usclivar.org), or through any of the members of the US CLIVAR SSC or Interagency Group (IAG).

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1. INTRODUCTION

1.1 WHAT IS US CLIVAR?

The Climate Variability and Predictability (CLIVAR) program is an internationally coordinated World Climate Research Program (WCRP) initiative that is aimed at improving scientists understanding of and skill in predicting physical climate variability, from time scales of seasons to decades. US CLIVAR is the scientific program designed and implemented by US scientists and agencies to carry out the parts of the international CLIVAR plan that are most important to the United States and to which we can contribute the most. This document describes the initial implementation strategy for US CLIVAR developed at the end of the year 2000.

The scientific basis for this plan is the international CLIVAR Science Plan (WCRP 1995). The science goals in that plan that motivate US implementation are as follows:

- Describe and understand the physical processes responsible for climate variability and predictability on seasonal, interannual, decadal and centennial time scales, through the collection and analysis of observations and development and application of models of the coupled climate system, in co-operation with other relevant climate research and observing programmes;
- Extend the range and accuracy of seasonal to interannual climate prediction through the development of global predictive models;
- Understand and predict the response of the climate system to increases of radiatively active gases and aerosols and to compare these predictions to the observed climate record in order to detect the anthropogenic modification of the natural climate signal.

The US CLIVAR science objectives are a subset of these comprehensive goals; the US CLIVAR objectives reflect the US community s scientific judgment regarding the importance of the larger effort s goals, our readiness to make progress, and the way the US could help build the best possible overall CLIVAR program. The US CLIVAR goals are to

- identify and understand the major patterns of climate variability on seasonal and longer time scales and evaluate their predictability;
- expand our capacity to predict short-term (seasonal to interannual) climate variability and search for ways to predict decadal variability;
- better document the record of rapid climate changes in the past, as well as the mechanisms for these events, and evaluate the potential for abrupt climate changes in the future;
- evaluate and enhance the reliability of models used to project climate change resulting from human activity, including anthropogenic changes in atmospheric composition; and
- detect and describe any global climate changes that may occur.

US CLIVAR is concerned primarily with natural climate variability. Various aspects of this work will either be approached globally or regionally, including

- improvements in the instrumental record and observing system to document ongoing and future climate fluctuations, to better elucidate their structures and mechanisms, and to provide initial conditions for model data assimilation and forecasting;
- model application and experimentation to develop long-term model data sets to study climate variability, assess inadequacies and improve the capabilities of models to simulate and predict climate variability, explore mechanisms of climate variability, and develop dynamical hypotheses to help focus observational requirements;
- empirical studies of the climate record from instruments, satellites and proxy records, and climate model simulations, to define patterns of climate variability and to develop and test hypotheses; and
- regional and process field studies to quantify specific processes that must be included in successful climate models and for which present treatment is inadequate.

1.2 Scientific Rationale

As a result of significant scientific advances at the end of the 20th century, worldwide seasonally averaged climate anomalies associated with the El Niño/Southern Oscillation (ENSO) are now predicted with useful skill Although improving scientists understanding of and prediction skill for ENSO will be a primary objective of CLIVAR, climate anomalies outside the tropical Pacific and on longer time scales will receive increasing attention. Climate records that are long enough to describe climate variability to decadal time scales have been constructed with existing instrumental data, proxy records, and results from numerical climate models that include representations of the circulating ocean. In addition to ENSO, several other patterns of climate variability have large impacts, from interannual to decadal time scales. Over the Atlantic, these patterns include the North Atlantic Oscillation (NAO) and Tropical Atlantic Variability (TAV). Together, these patterns orchestrate large, coherent fluctuations in ocean and land temperature, rainfall, and surface pressure with myriad impacts on society and the environment. Likewise, the North Pacific rim area is affected by anomaly patterns on interannual to decadal time scales the Pacific North American Pattern (PNA) and the Pacific Decadal Oscillation (PDO) that control much of the wintertime climate variability over the western US.

Continental regions are affected by precipitation anomalies during growing seasons (summer in extratropical regions and rainy seasons in subtropical regions). In particular, the TAV largely determines the occurrence of rainfall over the Nordeste Brazil and contributes to long cycles of droughts in the Sahel region of Africa. In general, there is substantial interannual variability in the summer precipitation systems of both Americas. Variations in the summertime monsoon in the southwestern US and northern Mexico are related to the state of the tropical Atlantic and Pacific, as well as local land-atmosphere interactions. This system also is strongly connected to precipitation elsewhere in the western and central US, especially over the Great Plains.

Anomalies in ocean temperatures affect fish populations in all oceans. Frequencies of damage by storms and provision of hydrological resources also depend on climate variability. Loss of agricultural productivity from drought in semiarid regions is substantial; summers of severe wildfires are visible manifestations of climate variability.

The 1930s drought in the United States was especially notable because of its severity, extended duration, devastation of the local economy, and impact on the psyche of a whole generation. What are the odds that a drought of this duration will happen again in the next 50 years? The instrumental record of climate over the United States is extremely limited for periods prior to the 20th century. Indeed, there are only a handful of instrumental records from anywhere around the globe prior to 1850. A variety of proxy data, however, now provides a reasonable record of drought in the continental United States over the past millennium including several occurrences of severe drought that were much longer in duration than the Dust Bowl of the 1930s. The paleoclimate record not only provides evidence for past climate changes that were much larger than any in the instrumental record; it also demonstrates that during glacial times the global climate system routinely exhibited extreme and abrupt changes probably related to changes of the thermohaline circulation.

How will human activity affect global and regional climate, and what must be done to mitigate these effects? The answers to these questions have very large implications for future US and world economies. Therefore, improving our ability to predict these effects is very desirable. The increasing concentration of atmospheric carbon dioxide results mainly from burning of fossil fuels. Carbon dioxide traps outgoing long-wave radiation, which warms the globe. Short-wave scattering by increasing aerosol particles (also from fossil fuel combustion) cools the planet, however, and therefore at least partially compensates for fossil fuel-induced warming. The net effect on the atmospheric radiative budget also depends strongly on changes in atmospheric water vapor and clouds. Such radiative effects on climate are fully coupled with the dynamics of the atmosphere-ocean-cryosphere system through that system s ability to transport heat and water. Accurate predictions of the impact of human activity require comprehensive numerical models of the global climate system to simulate this complex coupling. Separating the observed warming of global surface temperatures into natural versus anthropogenic effects is difficult; models of global change must simulate both aspects of climate variability.

The great similarity of the scales and processes of natural and anthropogenic climate change complicates attribution of observed changes to natural or anthropogenic sources. It also complicates verification of climate models through comparison of simple observed indices (e.g., average global temperature) with those predicted from models that include anthropogenic forcing. Consequently, simulations of natural variability by these models provide the best perhaps the only way to verify climate models. US CLIVAR will use the increasing base of knowledge about the temporal and spatial structure of natural variability phenomena to test and improve climate models that are used to project climate change.

More extensive summaries of the current state of knowledge concerning climate variability are available in numerous documents, including the CLIVAR Science Plan (WCRP 1995), the National Research Council s (NRC) natural climate variability on decadal time scales (NRC 1995), and NRC s report on the Tropical Ocean Global Atmosphere (TOGA) program (NRC 1996).

1.3 Strategy and Priorities

CLIVAR will enhance our knowledge of the climate system, advance our ability to predict the future state of the climate, and transform our conduct of climate science. At the core of CLIVAR is a set of wholly new climate observations, especially in and over the oceans. Investment in these observations will pay off doubly: by directly improving our knowledge of the climate system and by driving improvements in the models we use to assimilate climate data and forecast the future state of the climate system. At the same time, improved models when used as assimilation tools will add to the value of our observations. This synergistic interaction between observations and models represents a truly new approach to climate science under CLIVAR.

Fifteen years from now, when CLIVAR has been completed, scientists anywhere in the world will have electronic access to a synoptic, self-consistent depiction of the state of the climate system atmosphere, ocean, cryosphere, and land surface throughout the CLIVAR period as a consequence of assimilation of large volumes of data with much improved coupled models. The ocean, atmosphere, land surface, and cryosphere are coupled by boundary fluxes. The representation of these fluxes in models will be improved through observational studies. Furthermore, these improved coupled models will be used to generate coupled reanalyses that will provide internally consistent depictions of the entire climate system extended back in time, perhaps to 1970 or even earlier. Thus, at the end of CLIVAR we will have a dynamically and energetically consistent picture of the climate system spanning half a century or longer and a detailed quantitative understanding of how the ocean moves energy through the climate system. Assimilated and reanalyzed data will provide a consistent picture of how the ocean, the cryosphere, and the land surface contribute to fluctuations in surface temperatures and precipitation the climate variables that are most tangible to humans.

Improved models will produce improved climate forecasts. Perhaps more important, improved models will generate credible depictions of climate variability on time scales that are longer than those represented in the observational record. These models will then be used to address questions that bear directly on our ability to provide the public with useful climate forecasts and reliable estimates of climate-related risk:

- What is the predictability of the climate system? In particular, how do the different components of the system contribute to enhanced predictability of the tangible climate, beyond the limits of atmospheric predictability alone?
- Which parts of the system, over which regions, must we observe to exploit this enhanced predictability?
- Which climate features are most predictable, and how should forecasting systems for these features be designed?
- Beyond the limits of deterministic predictability, what is the likelihood of extreme or persistent events, such as large-scale floods and droughts?

In addressing the probability of extreme climate events, we will use the extended and more detailed paleoclimatic records that CLIVAR will produce in collaboration with paleoclimate research programs to validate our models. Again, enhanced paleoclimate data will benefit model development, and more credible climate models will greatly enhance the use and interpretation of paleoclimate data.

US CLIVAR will give high priority to improving the scientific basis for enhancing scientists skill in predicting climate variability associated with ENSO, NAO, TAV, and PDO. A concentrated and systematic program will improve the coupled numerical models that are used for climate forecasts, knowledge of the initial conditions for these models, and assimilation procedures by which data are incorporated into the forecast models.

Improving the Instrumental Record and Observing System

CLIVAR will take coordinated steps to improve the instrumentally based record of the climate system on the scale of the patterns of climate variability. Special emphasis will be placed on designing and implementing a climate observing system and on developing analysis and model-assimilated data products for the atmosphere, upper ocean, and hydrological state of the land surface on the scale of continents and oceans. Much of the required atmospheric data already are available through existing activities, but a substantial focus on expanding oceanic observing capabilities is essential.

In the ocean, the array of existing satellite and *in situ* observations is inadequate for accurate state estimation with today s procedures. Consequently, sustained *in situ* ocean measurements will be implemented to augment the present ocean climate observing system and, in cooperation with the Global Ocean Data Assimilation Experiment (GODAE), to improve ocean-data assimilation procedures. In addition, new ocean analyses will be used to examine climate dynamics. Success in developing regular analyses of the global ocean is expected to revolutionize climate research and prediction the way that global atmospheric analyses revolutionized meteorology in the 1970s.

CLIVAR also will focus on combining satellite observations, routine surface reports, and new research-quality measurements to improve the accuracy of global analyses of air-sea fluxes of heat, water, and momentum. The atmospheric component will include improvements in climate observations, where needed, and reanalysis activities that are based on continually improving numerical weather models that will incorporate an expanding suite of *in situ* and satellite observations. Required land data can be divided into prescribed boundary conditions and dynamically varying (prognostic) variables. Both of these kinds of data are provided by the inversion of various satellite sensors. Because of the indirect nature of their inference, model assimilation and reanalysis procedures are of major importance for obtaining prognostic land variables that are consistent with the coupled model.

Model Application and Experimentation

Comprehensive climate models are central to many aspects of today s climate science. Through reanalysis, they provide the most comprehensive picture of the instrumental record of climate variability. Through multi-century integrations, they provide realizations of full-system climate variability on time scales that are too long to be observed except through fragmentary paleoclimate proxies. Experimentation with such models facilitates the dynamic diagnosis that is necessary for understanding and successfully predicting the various phenomena of climate variability. These models will provide the most successful predictions of natural variability and anthropogenic change.

The technical challenges of improving and exercising comprehensive climate models require substantial allocation of resources and development of large teams of scientists and programmers associated with each model. This concentrated model work in a few major institutions has limited the contributions by the larger research community to improving these models. New research structures will be devised to accelerate community involvement in the main national models used for reanalysis, operational climate prediction, and global change projections.

Seasonal climate predictions focus on utilizing the relationships between the slower components of the climate system and seasonally averaged atmospheric quantities (e.g., sea surface temperature in the tropical Pacific affects the seasonally averaged temperature and precipitation in the southwestern United States). Recent research suggests that seasonally averaged changes in the frequency of extreme events also may be predictable. Models used to forecast ENSO do not have high enough resolution to resolve hurricanes, but they do predict environmental changes that are important for hurricane growth and intensity. Hence, forecasts of ENSO can be used to predict, in a statistical sense, seasonal changes in hurricane paths, intensities, and frequency.

Empirical Studies

US CLIVAR will include efforts to mine the observational record and results from comprehensive model runs for evidence of strong relationships between predictable large-scale, low-frequency patterns of climate variability and the probability of extreme events.

1.4 Structure of US CLIVAR

US CLIVAR is a national contribution to the international CLIVAR program. US CLIVAR is overseen by the Climate Research Committee of the NRC. Scientific leadership for US CLIVAR is provided by a Science Steering Committee (SSC). An Interagency Group with members from the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the Department of Energy (DOE) initially appointed the SSC. The SSC has established several standing working groups for specific tasks and three panels with oversight of all US CLIVAR concerns in the three regions of its primary interest. The Atlantic, Pan American, and Pacific Sector Implementation Panels report to the SSC, which appointed their members. The working groups are the Seasonal-to-Interannual Modeling and Prediction (SIMAP), the Asian-Australian Monsoon, a joint Past Global Changes (PAGES) and CLIVAR working group, and a joint Study of Environmental Arctic Change (SEARCH) and CLIVAR working group. The working groups and sector panels report to the SSC, which is the main line of communication to the international CLIVAR program and the Interagency Group.

The functions of the elements of US CLIVAR are explained more fully in Section 4.2.

1.5 Relation to Other Programs

Climate involves a complex web of phenomena that affect most aspects of life on earth. Many coordinated activities other than CLIVAR are addressing aspects of the climate problem. US CLIVAR must collaborate effectively with several related research programs at the national and international level.

The Intergovernmental Panel on Climate Change (IPCC) process effectively marshals scientists to assess the effect of human activity on climate change (see IPCC 1996). A US community is involved in the IPCC process, and a vigorous program of model development and experimentation supports these activities. Therefore, US CLIVAR will not seek to directly address anthropogenic climate change. Instead, it will facilitate US activities under the IPCC process by using existing and new knowledge of the record and mechanisms of primarily natural climate variability to improve the models that are the basis for projecting climate change and by assisting in the development of methods to separate natural and anthropogenic changes. A high level of cooperation will be required between the academic community and the few national centers that are capable of supporting the comprehensive climate models that are needed to study climate change.

The hydrological cycle is central to the atmosphere s climate engine, climate variability, and its impacts on human activity. This key topic is the focus of another WCRP program the Global Energy and Water Cycle Experiment (GEWEX). Efficiency of the US science effort requires that CLIVAR and GEWEX coordinate their activities in the overlapping areas of climate variability, the water cycle, and energy transfer. Joint analyses, modeling activities, and process experiments are envisioned.

The US Carbon Cycle Program is developing plans for atmospheric, land-based, ocean-surface, and ocean-interior observations to enable scientists to better understand sources and sinks of carbon (Sarmiento and Wofsy 2000). This program also is considering data-assimilative and prognostic models. Although the processes involved in the transport and transformation of carbon may be more complex than those affecting heat and water, they are strongly coupled, and there are strong similarities in the underlying physics and methodologies of climate and carbon research. Consequently, significant synergy between the Carbon Cycle Program and CLIVAR should be anticipated and encouraged. The two programs observing strategies (which involve many of the same platforms), their common need to assimilate relatively sparse ocean data, and their desire to better understand ocean transport and mixing all provide a basis for significant cooperation.

US CLIVAR will be attempting to improve the accuracy and completeness of the instrumental climate record. At best, however, these improvements can add only an increment to the length of the record that is available for studies of climate variability. Consequently, US CLIVAR will actively support work to understand the implications of the proxy climate record through joint work with PAGES. The joint PAGES/CLIVAR working group will foster this research, although CLIVAR will not directly address efforts to extend the record of proxy data backward in time.

Other activities that are at the scientific heart of CLIVAR research but are organized separately include significant improvement of the ocean climate observing system through the use of profiling floats by the ARGO program and necessary improvement of the analysis of sustained ocean observations to be carried out in GODAE. In addition, coordination with the Global Climate Observing System (GCOS) will help to ensure that the components put in place by CLIVAR are fully integrated into the global climate observing system. Links to development and application activities within forecast centers (e.g., National Center for Environmental Prediction [NCEP], International Research Institute for Climate Prediction (IRI) will be central in establishing developmental pipelines between the research community and the climate forecasters who implement and utilize the climate models that CLIVAR will improve (see Section 2.3.3).

Effective links to other WCRP research programs such as Stratospheric Processes and their Role in Climate (SPARC; <http://www.aero.jussieu.fr/~sparc/>) and Climate and Cryosphere Initiative (CLIC; <http://www.npolar.no/acsys/CLIC/clicindex.htm>) will ensure that a global perspective is maintained and results from the entire climate system are incorporated into CLIVAR.

1.6 STRUCTURE OF THIS PLAN

US CLIVAR is a global program of sustained observations, empirical studies, modeling, and process experiments. Its strategy addresses various climate phenomena that involve the earth s atmosphere, oceans, and land surface. Although the strategy and much of the activity is global, the tactics for achieving the effort s global goals require many studies to be tailored to specific phenomena or regions. This implementation plan first presents the global aspects of the program, focusing on the general application of specific methodologies. It then describes regional foci in which several methodologies are applied to the phenomena that dominate a certain region.

This document is based on many detailed studies by US CLIVAR panels and working groups, as well as other groups outside US CLIVAR. The plan s objective is to provide a perspective on and description of the entire program. Several reports explain the rationale and scientific basis for the studies described here. The US plan follows from the international CLIVAR implementation plan (WCRP 1998) as interpreted by several US meetings, panels, and working groups. In the following sections of this plan, we provide brief summaries with references to more extensive discussions on which the plan is based. The most important sources are as follows:

- Prospectus for a Pacific Basinwide Extended Climate Study (Lukas et al. 1998) (hereafter the PBECS Prospectus)
- Atlantic Climate Variability Experiment (ACVE): Science and Draft Implementation Plan (Visbeck et al. 1998) (ACVE Prospectus)
- Implementation Plan for the Atlantic Climate Variability Experiment: Summary and Recommendations (Joyce and Marshall, 2000) (ACVE Plan)
- Implementing the Pacific Basin Extended Climate Study (PBECS) (Davis et al., 2000) (PBECS Plan)
- US CLIVAR Pan American Implementation Panel, 2001: US CLIVAR Pan American Research: A Science Prospectus and Implementation Plan (Pan American Plan)
- US CLIVAR Atlantic Implementation Plan (Atlantic Plan)
- US CLIVAR Pacific Implementation Plan (Pacific Plan)
- Seasonal to Interannual Modeling and Prediction (SIMAP) Panel of US CLIVAR (SIMAP Plan)
- Proceedings of the International Conference on the Ocean Observing System for Climate, Saint Raphael France, October 18—22, 1999 (OceanObs99)

All of the foregoing documents except OceanObs99 are available from US CLIVAR and at its Office s Web site, <http://www.usclivar.org>.

This implementation plan is a living document that will evolve as new things are learned, new technology becomes available, and new questions are asked. The plan will be updated periodically and maintained at the US CLIVAR Web site.

2. GLOBAL STUDIES

2.1 IMPROVE DATA RECORD THROUGH ANALYSES

Key objectives of CLIVAR include improvements in the predictability of phenomena that vary on seasonal to decadal time scales and evaluation of hypotheses about the mechanisms of climate variability. The phenomena under investigation are dynamically complex; many involve interaction among the ocean, atmosphere, and land. Realizable *in situ* observing systems are too sparse to observe all important processes directly, and satellites alone are insufficient for testing many hypotheses. Numerical models have been used with great success to diagnose mechanisms in process-oriented studies. An important element of US CLIVAR will be extension of this process-oriented methodology to regional-scale climate phenomena by using models to combine diverse sets of data and reliable dynamical constraints to test dynamic hypotheses.

2.1.1 Atmospheric Analyses

Physically consistent synthesis of diverse ocean, atmosphere, and land observations is provided through rigorous data assimilation. This new paradigm for ocean and land research follows the production of global analyses for weather forecasting purposes over roughly the past two decades by operational centers such as the NCEP and the European Centre for Medium Range Weather Forecasts (ECMWF). Operational analyses, however, are not well-suited for climate purposes; in particular, changes implemented to improve weather forecasts (e.g., changes in numerical weather prediction models, data handling techniques, initialization, and so forth) disrupt the continuity of the analyses. Reanalyses of atmospheric observations, using fixed, state-of-the-art data assimilation systems, yield much-improved estimates of the global atmosphere that are free from such discontinuities. Moreover, they are not produced under operational (e.g., time) constraints so that, for instance, observations from all sources can be gathered, and the analysis at a particular time can also potentially take account of "future" observations (true four-dimensional data assimilation).

Three major global atmospheric reanalyses have been carried out to date, and a fourth is underway at ECMWF (ERA-40). These products have been of considerable value to an impressive range of scientific studies and applications (as evidenced by two international conferences sponsored by WCRP). Moreover, reanalyses will improve as CLIVAR-coordinated climate observing systems are implemented, as the science and technology of data assimilation improves, and as competition between different approaches increases. Global reanalysis should be regarded, therefore, as an ongoing program of data integration.

Within the United States, there are no firm plans to perform the next generation of global reanalyses. This issue was addressed at a workshop at the University of Maryland in June 2000 (see <http://www.usclivar.org/Mtg_US_Reanaly_WS_0600.html>). A principal conclusion of the workshop was that global reanalyses of atmospheric (as well as land and oceanic) data should be institutionalized. With several groups undertaking reanalyses, these efforts should be staggered, and each group should undertake reanalyses roughly every 10 years. This is the time scale during which major improvements in models and data assimilation aggregate, making previous reanalyses obsolete. The core of such a program is not the production effort itself but the necessary scientific analysis and technology development, as well as the continual organization and archival of observations, that will drive such production activities. CLIVAR will focus on these supportive activities as part of an ongoing, iterative process to improve climate data sets.

CLIVAR is especially challenged to develop new technologies that address climate-specific issues better and thus yield better estimates of longer-term climate variations—as opposed to those of most relevance to numerical weather prediction. Climate model biases, observing system biases and inhomogeneities, handling of changes in observing systems, physical consistency of budgets, and improved estimates of physical processes are examples. The goal of ERA-40, for instance, is to produce the best analyses of the atmosphere given available observations; therefore, it will suffer from continuity problems as observing systems change. The approach toward reanalysis of historical atmospheric observations, therefore, must be re-thought. Are state-of-the-art operational analysis systems that focus on the use of high-resolution, high-accuracy, space-based observing systems best to reanalyze historical atmospheric observations? Satellite observations must be included to provide the best estimate of the system state. For a long-term climate record, however, providing an analysis that includes only conventional historical data may be desirable, to assess the impact of satellite data on the analyses. The next-generation reanalysis could be divided into at least two separate but closely connected analyses—one aiming at a long period (going back in time to at least the 1940s), perhaps using fixed observation systems (over 5- to 10-year segments, with ample overlap in time) to improve estimates of low-frequency climate variability, and the other focusing on the post-satellite period, when the observational coverage is more comprehensive but of a different character. Both analyses should be continued to the present to serve users with different needs.

In addition to improved estimates of decadal and longer-term changes, deficiences in modeled precipitation and the radiative effects of clouds are shortcomings that should be highlighted because they have limited the utility of current reanalysis products. Precipitation biases over summer continents (especially in the diurnal cycle) limit the utility of reanalysis data for driving land surface models and other land hydrology studies. Poor surface fluxes (see Section 2.1.3), particularly cloud deficiencies, also make current products poorly suited for many ocean-modeling applications. Better estimates of the hydrological cycle are needed for studies of the global water and energy budgets, as well as for understanding global change and its impacts. Other issues, such as improved gravity-wave parameterization schemes (see Section 3.1.4) and increased spatial resolution, are important for several applications; these issues are discussed in more detail in the aforementioned reanalysis workshop report.

One of the largest activities in reanalysis is the organization of the input data base. Assembly and organization of the data are extremely valuable activities for climate studies. These data, as well as the analysis products and the information on the acceptability and possible biases in the observations, should be freely and openly available and easily accessible to all researchers, to encourage scientific analyses and thus contribute significantly to the success of CLIVAR.

A reanalysis program that has an ultimate goal of including all relevant components of the earth system requires substantial national and international resources. Numerous government, academic, and private institutions must be tapped to provide the necessary data, personnel, and program infrastructure to produce and analyze the reanalysis products. Efforts to date have been concentrated at operational centers, preventing the larger research community from becoming involved in improving the reanalysis models. US CLIVAR will facilitate community involvement in reanalysis programs.

2.1.2 Ocean Analyses

Testing of hypotheses about the ocean s role in climate with models is limited by uncertainties in surface forcing and initial fields, as well as the scarcity of and errors in verification data. Separating the effects of erroneous data from errors in model physics and numerical approximations requires the formal process of data assimilation. Data assimilation uses observations and numerical models to produce state estimates that are as close as possible to the real state of the system. In data assimilation, solutions from a numerical model are made to agree with data within *a priori* specified errors by minimizing the mismatch between the state estimate and observations and between estimated and observed surface forcing and initial conditions. The result is a dynamically consistent representation of the data with the data error reduced and gaps filled by interpolation/extrapolation. Otherwise, the model is in error. In addition to testing the underlying model dynamics and providing accurate products to elucidate climate phenomena and physical processes, data assimilation supports evaluation of the impact of given data in constraining the analysis, the relative impacts of different data types, rational parameter estimation, estimating uncertainties in processes such as mixing, improving air-sea fluxes, and the design of observing networks.

US CLIVAR recognizes the critical importance of ocean data assimilation to the study of climate variability and climate change as discussed in the ACVE and PBECS prospectuses. Without improved data assimilation, determining the dynamics of climate variations that involve the ocean will remain difficult and optimizing predictions of these phenomena or diagnosing coupled climate models will be impossible. Assimilation of *in situ* and satellite ocean data into ocean general circulation models (OGCMs) is a new and rapidly developing field. Advanced methods have been demonstrated on basin to near-global scales (see OceanObs99), and assimilation of ocean and atmospheric data into intermediate coupled models has been attempted for the tropical Pacific. For several years NCEP has used rudimentary but effective methods to initialize comprehensive OGCMs for coupled forecasts of interannual variations in the tropical Pacific.

CLIVAR and GODAE

The goal of GODAE, to be conducted from 2003 to 2007, is to elevate global ocean state estimation from its current experimental status to a quasi-operational tool for climate research and prediction that will help to integrate the modeling and observational communities. GODAE accepts CLIVAR objectives as some of its own (OceanObs99; GODAE Strategic Plan). There is substantial overlap in the two communities, and GODAE provides an appropriate venue for discussion of the technicalities and goals of the ocean data assimilation that CLIVAR needs.

To address the needs of CLIVAR and GODAE, two data assimilation consortia are being supported under the National Ocean Partnership Program (NOPP; described in a 2000 special issue of *Oceanography*). One scientific goal of the NOPP effort is to describe and understand the global general circulation of the oceans and its role in climate by combining modern large-scale data sets with state-of-the-art OGCMs. The central technical goal is a complete global-scale ocean state estimate from 1985 to 2003 at the highest possible resolution and quality, along with a complete error description. Just as having more than one group produce historical atmospheric analyses is recognized as beneficial to atmospheric diagnostics, having several ocean data assimilation efforts that use different techniques, different models, and different resolutions will be beneficial for the diverse needs of CLIVAR. In addition to historical climate analyses for research, ocean assimilation for analysis and prediction at seasonal-to-interannual time scales will be undertaken as part of GODAE.

US CLIVAR recognizes that NOPP and GODAE have put together a powerful program that is addressing CLIVAR goals. The CLIVAR strategy will be to support the NOPP and GODAE efforts; stay informed of their progress; and, for the time being, attempt to influence these efforts through scientific dialogue. The primary concerns are building the computational machinery for assimilation these efforts should be the primary responsibility of the NOPP/GODAE teams. Evaluation and improvement of the assimilation product and of the underlying dynamical model will begin soon. This effort should involve CLIVAR.

In the longer term, CLIVAR objectives will require us to design and use assimilation products to test climate hypotheses and design observing systems. This objective will require additional studies, such as determination of data-error and model-error statistics; preparation and quality-control of observations; pre-processing data to reduce data volume and make assimilation more efficient; comparisons of model output with data and with simple models to detect model deficiencies; validation and use of assimilation products in ACVE, PBECS, and process studies; and utilization of assimilation tools for observing system design. US CLIVAR, GODAE, and the NOPP must develop appropriate mechanisms for supporting and shaping such high-priority studies. Because GODAE and the current NOPP consortia terminate before CLIVAR, the CLIVAR effort will have to follow on with its own data assimilation as a fundamental component of its strategic plan.

Coupled Assimilation and Reanalyses

The ultimate goal of US CLIVAR is to obtain a dynamically and energetically consistent depiction of the global climate system ocean, atmosphere, land surface, and cryosphere by assimilating climate data into coupled land-ocean-atmosphere models and subsequently deploying those models to reanalyze past climate data. We are unlikely to meet this technically audacious goal in the next 5 years; over the program s 15-year lifetime, however, CLIVAR research will address major obstacles to coupled assimilation. The development of a successful ocean assimilation system, as described here, and continued refinements in atmospheric assimilation systems are necessary first steps. Model representations of boundary fluxes will be advanced by a concerted effort at model development that makes use of the increased density and accuracy of flux observations. Similar observation-driven improvements will occur in models of the separate components of the climate system, especially the ocean. Encouragingly, coupled climate models already produce stable and realistic simulations of the coupled climate without resorting to flux corrections. Finally, on the extended time scale of this effort, technological advances are expected to remove computational barriers to coupled assimilation.

Major Issues of Data Assimilation

Although the ultimate goal of ocean data assimilation is clear, many practical issues must be overcome before the effort can be successful.

Determining* a priori *data and model errors. Because data assimilation is based on fitting data and models to within specified errors, the most critical aspect is determining and understanding the error covariances of the data and the model. Errors in a model solution come from many sources. Some are associated with external factors (initial state, surface fluxes); others are internal (poor parameterizations, inadequate model resolution, or missing physics). To some extent, assimilation can correct errors from external factors by treating them as control variables. Internal model errors must be corrected by forward-model improvement. Errors from processes that are not represented by the model and thus are not correctable by data assimilation must be included in the data-error covariance or the model-error covariance to avoid forcing the model to fit data it cannot represent. Model errors are most difficult to characterize. Their identification depends critically on having sufficient data to evaluate model performance. For this reason, the increase in observational density and in ocean processes observed by CLIVAR will improve assimilation products not only by increasing the data constraints but also through better assessment of model errors. Significant work is needed on the methodology of characterizing model errors as well as determining them for specific models.

Determining data uncertainties also is difficult. For example, the uncertainties of altimetric sea-level data depend on errors associated with satellite orbit, tides, atmospheric corrections, and the inverted barometer effect. For *in situ* data such as hydrography, the point-wise measurement error usually is small and the major error is in how well *in situ* samples can constrain the large-scale, low-frequency state of interest. In this context, transient signals such as eddies captured by the hydrographic casts are noise, and a covariance of eddy structure is needed to develop the data-error covariance.

Validation. Complete evaluation of the quality of assimilation products is critical to identify inappropriate *a priori* error characterizations or model weaknesses and improve them. As with elementary linear regression, there are two conventional approaches to evaluating goodness of fit: systematic examination of residual model-data misfit for nonrandom patterns and cross-validation using independent data (e.g., withholding data for later comparison with the assimilation product). Improvement of data-assimilation techniques and products depends on significant efforts in evaluating the products.

Computational resources. Limited computational resources compute cycles and memory are hindering progress in applying data assimilation to basin-scale ocean problems. This limitation applies particularly to complex models and advanced assimilation schemes. Most supercomputing centers fail to meet assimilation requirements because of competition with other users, insufficient memory availability, and incompatible queuing schedules. CLIVAR and GODAE must secure the computational resources needed for modern model-assimilation studies. A one-degree state estimate with state-of-the art assimilation methods and models requires a sustained 20 Gflop/s throughput. Whereas GODAE can deliver routine near—real-time products through its data and product servers, CLIVAR will have different distribution requirements that must be addressed.

2.1.3 Climate Observation and Product Centers

Observations, analyses, data assimilation products, and climate model output are all needed to achieve CLIVAR objectives. To take full advantage of these data, several challenges must be met, especially in light of the significant expenses required to produce and provide them. In particular, there must be

- focused effort to ensure observations of suitable quality for climate monitoring, modeling, and analysis;
- exploitation of new information technologies to insure seamless, timely, and accurate dissemination of data and products, including ease of access; and

- minimization of institutional and programmatic barriers to accessing data and products.

The magnitude of these challenges and the relatively large scope of CLIVAR suggest a distributed set of activities. Cooperation and interaction with ongoing institutional activities, as well as complimentary US and international efforts in other research programs, also will be critical.

Implementation Elements

CLIVAR scientists will need access to multidisciplinary streams of observations and products to develop, interpret, and evaluate scientific hypotheses. Investigators often are unaware of existing data sets or are handicapped by data that are difficult to access. New, updated, or improved versions of data also are difficult to sort out (and associated documentation often is not widely available), so determining which data set provides the best or at least the latest estimate of a particular climate variable often is difficult.

Although CLIVAR will contribute new efforts toward improving the instrumental record and observing system, particularly for the ocean, numerous observing systems already in place are in need of attention and support to maximize their usefulness for climate studies. Known deficiencies, even in the most mature components of the climate observing system, must be addressed, and observing systems must be monitored to ensure that correctable deficiencies do not jeopardize future measurements. Observations and meta-data must be assembled, documented, and subjected to high levels of quality control. Access to these and other archived data from the observing system and important process experiments is critical. Suitable archive strategies must be developed. A dedicated, not transitory, effort is required.

Working with international partners, CLIVAR will identify or establish a distributed network of climate *observation* providers to provide the critical infrastructure needed to ensure the availability of high-quality observations, especially from immature observing efforts and critical process studies undertaken as part of CLIVAR. Such providers would assemble, process, integrate, and ultimately distribute observational data and meta-data to the research community. Ideally, they would be intimately familiar with the observation system as well as with research applications. They also would allow for and utilize feedback from the user community to improve data quality and perhaps the observational system itself. Similarly, designated climate *product* providers will be identified or developed to facilitate distribution of a variety of assimilated and model data sets to the CLIVAR community.

Implementation Strategy

To develop strategies to address the challenges of providing data, experts in information exchange and dissemination technology will need to work with the observation and product providers. Scientists who are interested in synthesizing relevant climate information should guide their efforts. The goal will be to develop virtual data center functionality through the use of Web-based data catalogues. The primary purpose of the data catalogues will be to provide easy access to atmospheric, oceanic, land, and cryospheric variables and associated meta-data, as well as proxy records. Initially, a set of interconnected Web pages pointing toward existing, publicly available data might suffice. Anticipated growth in the number, size, and variety of the data sets, however, requires more than an ad hoc effort.

There are three critical steps in implementation:

1. Close collaboration with ongoing complementary US efforts (e.g., GODAE, ARGO, the World Ocean Circulation Experiment [WOCE] ocean Data Assembly Centers, the US Virtual Ocean Data Hub, National Oceanographic Data Center (NODC), and National Climatic Data Center (NCDC) will lead to a resource-efficient system that addresses broad climate needs.
2. Coordination of efforts with other research programs and international CLIVAR partners will take advantage of global expertise and resources.
3. Recognition of data and product management activities will be a high priority in US planning and budget development.

Early efforts to develop thoughtful plans and actions will ensure maximum benefit from the significant investment in US CLIVAR observations and avoid more-expensive alternatives resulting from delayed planning and implementation.

2.1.4 Surface Fluxes

The ocean is driven by the air-sea fluxes of momentum, heat, and freshwater; the fluxes of heat and latent heat (freshwater) are how the ocean imposes long-timescale variability on the otherwise rapidly evolving atmosphere. Because the time scales of oceanic and atmospheric processes are so different, air-sea fluxes have particular acuity in diagnosing processes involved in the coupled phenomena of climate. Despite this importance, available flux estimates for the ocean basins, in many places are in error by much more than is required to generate significant climate anomalies. Uncertainties severely curtail our ability to study ocean model response to atmospheric variability, verify air-sea fluxes produced by coupled climate models, or empirically diagnose the lead-lag relationships between oceanic and atmospheric variability on different time scales.

CLIVAR requires a combination of a few high-quality surface observations, many routine surface observations, satellite observations that provide global coverage, constraints developed from ocean-data assimilation efforts, and surface fields from operational weather prediction centers to produce flux fields. Eventual partnerships with the operational centers are needed to benefit from their methods for combining all available information. Realistic uncertainty targets for monthly averages are 10 W/m^2 for net heat flux and 10 percent in wind stress. A 10 W/m^2 flux would warm the ocean s upper 500 m by 0.15ºC in one year comparable to observed decadal changes. To achieve this target, each component of the net heat flux must be accurate to a few watts per square meter. Such accuracies are achievable at a point in several week-long mean values from research-quality surface buoy and ship deployments. However, the errors in routine air-sea heat fluxes and wind stress from observations and models are much larger; production of basin-scale fields during CLIVAR will require improving the observational basis and methods for flux analyses.

Surface data now come mainly from *in situ* measurements on ships and buoys, remote sensing from satellites, and output from numerical weather prediction (NWP) models such as those from NCEP and ECMWF. Moderate-quality *in situ* observations of some surface variables are routinely available on ship routes from Volunteer Observing Ships (VOS). Complete high-quality surface meteorology and fluxes can be obtained from moored buoys and specially instrumented ships whose numbers are limited by cost. Moored TAO, Pilot Research Moored Array in the Tropical Atlantic (PIRATA), coastal National Data Buoy Center (NDBC) buoys and surface drifters provide surface observations. Satellites provide global measurements of sea surface temperature (SST), surface radiation, and vector wind; the extent to which sensible and latent heat fluxes can be derived from remotely sensed data is under study. In contrast to *in situ* observations and satellites, NWP models provide global surface meteorological and flux fields at time intervals that resolve diurnal and synoptic weather variability. Unfortunately, these fields now contain large uncertainties as a result of model deficiencies. Furthermore, they do not routinely assimilate all available satellite and *in situ* surface meteorological data missing, at times, the chance to use accurate data to better constrain the fields they produce. The CLIVAR strategy is to improve the flux fields, based directly on *in situ* and remote observations, while addressing ways to use NWP models to eventually blend all data into global flux fields.

At OceanObs99, strategies for obtaining surface fluxes globally were examined. CLIVAR s goals can be achieved at fixed points; buoys can accurately and continuously measure incoming shortwave and longwave radiation, barometric pressure, relative humidity, air and sea temperature, rainfall, and vector winds, allowing determination of freshwater, heat, and momentum fluxes. Comparisons of well-instrumented buoys with ship measurements of surface fluxes (including direct eddy-covariance measurements) have shown that monthly-mean heat fluxes from buoys are accurate to 10 W/m^2. On a limited basis, buoys also can measure turbulent fluxes directly, providing accurate mean surface observations and defining transfer coefficients for bulk formulae. Thus, surface buoys provide accurate reference sites that will provide the basis for correcting other fields of surface meteorology and air-sea fluxes. Cost, however, limits buoy deployments to select locations.

We recommend that the United States provide eight surface flux reference site moorings four in the Atlantic and four in the Pacific at sites chosen to maximize their impact on NWP analyses and provide flux time series in climatically important regions. (High-priority sites are shown in Figure 2.3 of Section 2.2.4.) With international partners contributing as well, this effort should lead to a global array of 15 to 25 surface flux reference sites.

The longest records of air-sea fluxes are based on surface meteorology from VOS, using empirical formulas. Most VOS instrumentation is limited; it includes barometers, anemometers, engine-injection temperature sensors, and wet- and dry-bulb thermometers. Shortwave and longwave radiation are inferred from cloud observations. Approximately 7,000 ships regularly report surface meteorological observations, and these data remain a valuable resource. Early VOS data had quality problems because of methods for obtaining SST, disturbance of airflow by the ship, and errors in calculating the absolute wind velocity. The Southampton Oceanography Centre (SOC) has developed VOS-based net heat fluxes by using corrections that significantly improve accuracy. Limited comparisons indicate that surface observations from research-quality buoys and SOC VOS are much more consistent with each other than with NCEP or ECMWF analyses that frequently differ from the observations by as much as 50 W/m^2. VOS data with corrections like those applied by SOC will be used in CLIVAR flux analyses.

Accurate surface observations also can be made on VOS by using research instrumentation, including wind velocity, air and sea temperature, relative humidity, barometric pressure, incoming shortwave and longwave radiation, and precipitation. Upgraded VOS can complement moored reference sites by sampling in space as well as time. They can span basins, sampling a wide range of meteorological regimes to develop corrections for NWP model and satellite fields, to develop empirical formulas for analysis of regular VOS data (e.g., inference of radiation), and to characterize scales.

We recommend instrumenting 5 to 10 VOS lines in the Atlantic and Pacific with US research-quality observations to augment reference moorings.

In situ data alone cannot provide the spatial and temporal resolution or the consistent basin-scale coverage needed for CLIVAR. The coverage limitations of flux fields derived from *in situ* data alone are evident when they are compared with those from NWP reanalyses. OceanObs99 noted that the correlation between the fields decreases away from heavily traveled ship routes. The time resolution and global coverage required depend on combining *in situ* data with global satellite observations inside the dynamic framework for data assimilation provided by the NWP models.

Development of NWP models is driven by weather forecasting, without much attention to the quality of surface fluxes. As a result, accurate *in situ* surface data may differ significantly from model surface fields. Work is needed on the models before they can beneficially assimilate surface meteorological and flux data. In fact, the quality of NWP flux estimates may degrade when forecast skill is improved and assimilation of accurate surface meteorological data can result in degradation of forecast skill. To prevent this degradation, NCEP assigns large uncertainties to *in situ* data (e.g. 2.2—2.5 m/s for surface winds, 1.6 mb for sea-level pressure, 2.5°C for air temperature, and 20 percent for humidity), and many observations are not assimilated. NWP models do not simulate clouds or radiative fluxes well, and their boundary layer structure may not be well resolved. Flux parameterizations in the models may introduce error, and in many locations the model mean surface conditions are much more accurate than are model fluxes.

Satellite data are global and particularly valuable for fields that are not well defined by NWP models (e.g., precipitation and radiation). In addition, satellites provide SST, wind, and potentially the turbulent heat fluxes (see OceanObs99). The remote sensing emphasis for CLIVAR is on scatterometry for winds, getting timely analyses of precipitation and radiation fields, and maintaining adequate *in situ* observations for calibration and verification of all needed remote sensing measurements including SST.

We recommend efforts to ensure timely availability of satellite fields of SST, surface wind stress vector, radiation, and precipitation fields for CLIVAR flux analyses.

CLIVAR s short-term goal for flux analysis will be to produce accurate gridded flux fields, using buoy and upgraded VOS data to identify biases in NWP fields and correct them. This procedure assumes that errors in NWP fields have large space and time scales (which should be verified). Although these analyses produce only an empirical regional patch for model deficiencies, they will be valuable for empirical and model studies. The WCRP Working Group on Numerical Experimentation has agreed to work on comparison of model fluxes with quality surface observations in parallel with their ongoing Atmospheric Model Intercomparison Project (AMIP). This effort should lead to improvement of the model flux parameterizations. Although recent process studies such as TOGA COARE have improved the bulk formulas for point observations, adaptations may be necessary for the formulas to work well at model grid points.

We recommend efforts to develop empirical corrections for NWP flux fields as soon as adequate in situ and remote-sensing data are available to develop corrections.

This effort will require a partnership with efforts to provide remotely sensed data particularly precipitation and radiation to produce calibrated fields in a timely fashion. The MCSST data set prepared by optimal interpolation of satellite-based Advanced Very High Resolution Radiometers (AVHRRs), moored buoys, drifting buoys, and VOS SSTs provides a model of how to proceed. A workshop on determining turbulent fluxes via remote sensing in July 1999 brought together the *in situ*, remote sensing, and NWP communities to lay the groundwork for an intercomparison project. CLIVAR will contribute data from its surface reference sites to this comparison and work toward improving combined remotely sensed and *in situ* data sets.

In parallel but with a longer view and in partnership with NCEP, ECMWF, and other modeling groups efforts should be made to improve surface fields and fluxes in NWP models and find ways to better assimilate *in situ* surface data and satellite radiation data. This work may require improved model treatments of the planetary boundary layer. These efforts will require computer resources beyond those used in running the operational models and should be undertaken by teams with expertise with *in situ* hardware and data, model codes for assimilation, and model representation of atmospheric processes. This work could be accomplished, for example, in partnership with modelers at NCAR and GFDL who are working on the next-generation model for NCEP. The model s abilities to assimilate surface data and produce flux fields would be improved before it becomes operational, and the model's performance would be studied once it became operational.

Joint studies by CLIVAR researchers and those developing and testing NWP models examine the sources of error in model flux fields, improve flux parameterizations, and improve the assimilation of surface data with the aim of improving NWP surface fluxes.

Data from select surface flux reference sites should be withheld from routine assimilation during the AMIP to test the flux fields from NWP models. Research-quality surface data from VOS lines also should be used to study issues associated with assimilating surface data and the time/space characteristics of model and observed surface fields.

NWP models assimilate remotely sensed atmospheric profile and surface data; efforts should be made to improve this assimilation and the impact of data on them. One approach uses NWP fields, satellite data, and *in situ* data as input to an assimilation process that accounts for the error characteristics of the model and data. Variational objective analyses of this type have been applied in several wind analyses, based on scatterometer, SSM/I, or VOS data. This kind of analysis would make use of cross-validations with high-quality flux observations from surface-flux reference sites and improved VOS. As CLIVAR progresses, more ocean data will be available and pilot ocean data assimilation will begin, possibly allowing ocean heat and water budgets to be added as constraints in producing flux fields.

2.2 Improve Data Record Through Observations

2.2.1 Weather Observations for Climate

The *in situ* observations of the World Weather Watch (WWW) on which we base much of our understanding of climate variability are in general decline and are undergoing changes that are altering the climate record in ways that are poorly understood. Much of the WWW decline has been driven by funding limitations, but it also is partly related to the advancing technology and methods of the weather research and prediction community. Every climate research program has lamented the decline of the WWW over the past 15 years, but the decline has continued. To make progress, US CLIVAR must take a new approach or fail as those before have.

Because of its weather focus, the WWW was not designed to provide long and stable climate records. Even a major new infusion of funds for weather observations might be used not to improve the network of surface and upper-air *in situ* observations but to build a system in which modern atmospheric data analysis techniques would be used to combine remotely sensed data from surface and satellite sensors with adaptive *in situ* observations (i.e., observations that are taken where they have the greatest impact on the forecast; see Daebberdt and Schlatter 1996). Therefore, US CLIVAR cannot expect the weather analysis and prediction community to provide strong support for improving the climate observing capabilities of the conventional *in situ* weather observing network; even the WWW has never achieved full implementation.

US CLIVAR therefore must take the lead in seeking to improve the surface and upper-air observation system for the study of seasonal to decadal climate variability. CLIVAR will contribute to the design and development of augmentations to the *in situ* atmospheric climate observing system to monitor climate variability in the Pacific, Atlantic, and Pan American regions. (Details of these efforts appear in the Pan American, Pacific and Atlantic plans.) Over heavily populated areas of North and South America, the US CLIVAR observing system is an overlay on the WWW, with enhancements in temporal sampling and sensors. CLIVAR process studies will contribute to the improvement of existing GCOS stations and deploy new surface and upper air stations in data sparse areas of North and South America in collaboration with CLIVAR VAMOS (ie international project to study the variability and predictability of the American monsoon system). Over the oceans, CLIVAR will encourage reestablishment or improvement of key island stations, deployment of additional moored air-sea interaction buoys, greater use of VOS lines as platforms for high-quality climate observations, and testing of new observational technologies. Development of regional climate observing systems will contribute directly to the implementation of GCOS.

To achieve a better understanding of climate variations on time scales of a decade or longer, we must be wise in how we implement *in situ* observing systems (NRC 1998). The need to create a long-term observational record suggests the following steps for improving the *in situ* atmospheric observing system for US CLIVAR research:

- Focus on implementing GCOS *in situ* atmospheric observations for the Atlantic, Pacific, and Pan American regions. Select high-priority stations and seek funding to maintain them. High priority should be placed on maintaining existing surface and upper-air stations and observation systems with long, uninterrupted records. In developing new observations, place highest priority on data-sparse regions, key climatic regimes, and providing adequate temporal resolution.
- Improve the past climatic record. Continue data prospecting to identify and digitize good-quality *in situ* observations that are not currently available. Continue efforts to document and assess the impact of past changes in the *in situ* observing system on the climate record, including changes in upper-air sensors and practices such as the recent introduction of automated surface weather stations.
- Explore the use of new cost-effective technologies for *in situ* monitoring of atmospheric structure in data sparse areas (e.g., soundings from VOS, super-pressure balloons, profiling balloons, rocket or remotely piloted aircraft platforms).
- Ensure open, low-cost, and easy access to *in situ* atmospheric observations that are essential for the success of the program. Every effort should be made to ensure that quality-controlled surface and upper-air data are readily available to researchers. All data should be archived in a timely manner to assure their assimilation into the climate analyses.

Pan American Climate Observations

US CLIVAR will promote establishment of an integrated network of ocean, atmosphere, and land climate observations in the Pan American region. The network will be built on existing operational networks and the legacy of the TOGA program in the Pacific. Major US CLIVAR enhancements of the global ocean observing system are discussed in Sections 2.2.3 and 2.2.4. These enhancements will provide observations of oceanic and surface conditions over the ocean, although vast areas of the tropical and southern Pacific and Atlantic Oceans are virtually without routine upper air soundings (see Figure 2.1). Upper-air observations are less dense over Latin America than over the United States, and large areas of South American are without operational upper-air soundings.

The US CLIVAR strategy for improving upper-air observations in the Pan American region is to implement all of the GCOS priority atmospheric upper-air stations and then add high-quality stations in key climatic regimes that are inadequately sampled in time and space.

Highest priority will be to maintain existing surface and upper-air stations and observation systems with long, uninterrupted records. CLIVAR process studies may contribute to the improvement of existing GCOS stations and deploy new surface and upper-air stations in data sparse areas of North and South America in collaboration with CLIVAR VAMOS. An example of US CLIVAR activities that may enhance the upper-air observations system is the NOAA Pan American Climate Studies Sounding Network (PACS SONET) (see Figure 2.1) project, which provides seed money for upper-air sounding equipment and training in Latin America and is involved in enhanced monitoring for the Monsoon experiment in South America (MESA) and North American Monsoon Experiment (NAME) field studies. Every effort will be made to upgrade or add stations through the WWW, but failing this, alternative funding will be sought within and outside of CLIVAR.

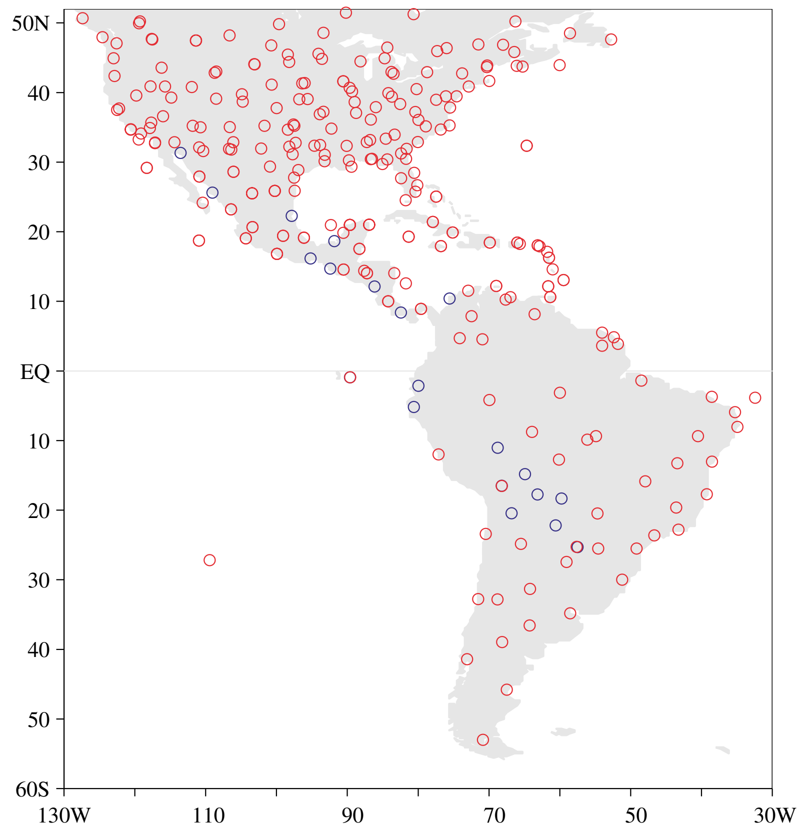

Figure 2.1 Existing upper-air sounding stations in the Pan American region. Stations providing operational data for weather analysis and prediction are indicated by red circles. Supplementary pilot balloon stations (SONET) indicated by blue circles are an element of the PACS program.

2.2.2 Satellite Observations of the Atmosphere and Land

Current products for atmospheric climate analyses are heavily dependent on satellite data. The weather analyses and reanalyses (see Section 2.1.1) whose time series provide climate data are produced by statistically optimum merging of model, satellite sounding, and *in situ* data. Satellite soundings of temperature and humidity are essentially the only atmospheric observations over the ocean. Satellite instruments measure thermal and microwave emissions that originate from different atmospheric layers and depend on the layer temperatures and humidity. Current practice is to use the radiances directly to correct model temperatures rather than first inverting the data to an observed temperature. Inversion for surface winds and humidity remains problematic and requires independent observations for validation.

In addition to these weather products, several other types of satellite data sets have been key ingredients for observational study of climate variability. In particular, data sets based on visible and thermal (outgoing longwave radiation or OLR) imagery are used extensively to characterize the dynamics of atmospheric clouds and convection. OLR, as a monthly index, largely indicates the height and extent of tropical clouds, and hence the intensity of convective storms. Other algorithms with the same measurements provide an estimate of precipitation intensities. Many such multiyear data sets have been standardized and made available as part of the WCRP, including precipitation data from the International Precipitation Climatology Project (IPCP) which combines land rain gauge information with satellite microwave and thermal sensing and the International Satellite Cloud Climatology Project (ISCCP), which generates uniform data sets for cloud properties from thermal and visible imagery. Because clouds are the primary factor controlling solar radiation incident at the surface, surface radiation budget (SRB) data sets also are derived from the same observations. Because humidity derived from standard analyses has been unreliable in the upper troposphere, special climate data sets have been derived for upper troposphere humidity (UTH). Aerosol thickness also is estimated from satellite data most readily over the oceans from visible imagery because of the low albedo of the underlying ocean.

Satellite imagery also is the primary means of measuring the climate variability of the land surface. In principle, direct estimates of soil moisture are possible from microwave emission, but adequate instrumentation has not yet been developed and obscuration by vegetation is difficult to correct. The most useful measure of climate variability over land has been the Normalized Difference Vegetation Index, which uses the difference between Channel 2 and Channel 1 of the AVHRR imaging instrument on NOAA weather satellites to look at greenness of land vegetation. These data not only clearly show annual cycles of global land greenness but also interannual climate variability for example, from ENSO. Although such data are now available for up to two decades, longer-time scale natural variability may be confused with the effects of vegetation changes from land use modification such as deforestation. A more physically based derived parameter is the fraction of photosynthetically active radiation (fPAR) that is absorbed by the land surface. More detailed representation separates the data into effects of plant type, leaf area index (LAI), and fraction of land that is vegetated. Land surface temperatures obtained from infrared and microwave emission are potentially as valuable as SSTs but have had limited use because of difficulties in correcting for emissivities and diurnal variation. They are more closely tied to surface fluxes and other land purposes, however, than are screen-level air temperatures.

Much improved land data is being developed through the NASA EOS program. Some initial data already are in hand from the Terra morning satellite, and the Aqua afternoon satellite is scheduled for launch in the latter half of 2001. The MODIS instrument on both satellites has a large number of spectral channels to provide information on land. Additional capabilities are provided by the MISR, with its simultaneous use of nine view angles. Important forthcoming products include seasonally varying land albedos, a variety of vegetation classifications, and several measures of LAI. Data from both satellites should be available for a period of at least several years. NASA s small GRACE satellite mission will measure the earth s gravity to an accuracy sufficient to monitor seasonal and interannual variations of soil and groundwater. The vegetation canopy lidar (VCL) will provide global data on the height of vegetation an important component of surface flux determination.

Operational satellite measurements will evolve over this decade into the National Polar-orbiting Operational Environmental Satellite System (NPOESS) system, which should provide continuity with current AVHRR land measurements and with more spectral channels in the VIIRS replacement of AVHRRs improved information on vegetation. New microwave instruments also may provide useful measurements of soil moisture.

2.2.3 Satellite Observations of the Ocean

The ocean figures prominently in the dynamics and thermodynamics of ENSO and probably of lower-frequency fluctuations of the climate system because of the ocean s ability to store and transport large quantities of heat. Historically, most *in situ* sampling of the ocean has relied on ship-based observations; as a result, vast reaches of the ocean are poorly sampled. Consequently, space-based observations of the ocean will play an important role in US CLIVAR by providing high spatial resolution, broad spatial coverage, and frequent sampling to complement and tie together sparse *in situ* observations. Satellite-based measurements of the surface wind stress vector (an indicator of atmospheric climate and forcing of the ocean), sea-surface height (SSH, which describes oceanic heat storage and near-surface transport), and SST (a direct indicator of the ocean s influence on the atmosphere) are most useful for ocean climate purposes. The interannual and longer time scales of variability that are the focus of CLIVAR require continuous, uninterrupted observations of these variables over at least the next 15 years. Long, continuous, and consistent time series exceeding the typical 3- to 5-year lifetimes of individual satellite missions or instruments are extremely difficult to acquire outside operational programs and present a serious challenge to CLIVAR. Ocean satellite capabilities expected during CLIVAR are reviewed below.

Sea-Surface Height

Altimetric measurements of SSH provide unparalleled space-time coverage of important climate signals such as heating of the ocean and large-scale, low-frequency variability of upper-ocean geostrophic currents. Consequently, coupling the profiles of density, temperature, and velocity measured by ARGO and VOS with satellite sea-level variations will impose strong constraints on data assimilation models to be used for ocean analyses.

From the TOPEX/POSEIDON altimeter there is now a continuous 8-year record of SSH variability beginning in October 1992. This data record will be continued with the launch of the joint US/French (i.e. NASA/CNES) Jason-1 altimeter in early 2001. Planning is underway for a follow-up NASA/CNES Jason-2 mission with an expected launch in 2005. Thereafter, NASA plans to transition altimetry to the US NPOESS operational satellite program before 2010. NPOESS has recently adopted a formal requirement for a high-precision altimeter in the orbit established by TOPEX/POSEIDON and the Jason-1 and Jason-2 follow-on missions. Such a mission has not yet been approved for the NPOESS program, but the prospects look very hopeful.

Thus, CLIVAR requirements are likely to be met through 2010. CLIVAR depends on continuation of highly accurate altimetry beyond 2010 and therefore requests that the NPOESS planning process approve the launch of a Jason-2 follow-on altimeter early enough to avoid a data gap in the SSH time series established by TOPEX/POSEIDON, Jason-1, and Jason-2.

Surface Wind Stress

Surface wind analyses from NCEP and ECMWF operational weather forecast models are the main sources of surface wind forcing for ocean modeling. The modeling implications of the limited spatial resolution of these surface wind analyses have not yet been fully explored. For example, although ECMWF grid spacing is 1°, its analyses appear to underestimate the intensities of structures with scales shorter than 500 km. This problem is especially acute in the tropics, where air-sea coupling is central to climate variability, and near eastern boundaries. In these regions, winds vary over scales that are much shorter than 500 km, generating narrow bands of strong wind-stress curl that should significantly affect SST through oceanic upwelling and the generation of Rossby waves that perturb the SST field at distant locations.

Present satellite measurements of surface wind stress are from microwave radar scatterometers. With the development of realistic boundary-layer parameterizations in numerical atmospheric GCMs, assimilation of scatterometer measurements can improve operational weather forecasts. Implementing these improvements in operational assimilation schemes should improve not only weather forecast skills but also the accuracy of analyzed surface stress and surface heat flux fields derived from operational weather forecast models.

A nine-year record of surface winds is available from European ERS scatterometers. These data are of somewhat limited utility because of the narrow 500-km swath width of the ERS scatterometers. A one-year record of high-quality and dense coverage of surface winds has now been established by the SeaWinds scatterometer on the QuikSCAT satellite launched in 1999. SeaWinds has swath width of 1600 km. The QuikSCAT record is expected to continue for at least three more years, and a SeaWinds scatterometer has been approved for the Japanese NASDA ADEOS-II mission to be launched in late 2001. ADEOS-II will extend the QuikSCAT data record to at least 2006; moreover, simultaneous operation of the QuikSCAT and ADEOS-II scatterometers will provide unprecedented space-time sampling of the global surface wind field. A follow-on SeaWinds scatterometer is planned for the proposed NASDA GCOM-B1 satellite with expected launch in 2006. Wind observations from the broad-swath SeaWinds scatterometers on QuikSCAT, ADEOS-II, and GCOM-B1 will be augmented by the ASCAT scatterometers onboard a sequence of three European Space Agency (ESA) METOP missions approved for 2003—2017. ASCAT accuracy should be similar to that of SeaWinds, but the spatial coverage will be less by half, limiting its utility.

The United States plans to transition satellite measurements of surface vector winds to NPOESS operational satellites after 2010. NPOESS has recently adopted a formal requirement for vector winds, but the planned NPOESS configuration does not include radar scatterometry. As a substitute, NPOESS is pursuing a low-power passive polarimetric microwave radiometer technique for estimating vector winds. Although this techniques is promising, it is unproven and will not be tested from space before the launch of the US Navy's WindSat/Coriolis satellite in 2002. CLIVAR depends on continuation of accurate surface vector wind measurements beyond 2010.

Sea-Surface Temperature

SST is a key variable that describes the ocean s influence on atmospheric climate. SST is the surface boundary condition for the overlying atmosphere and the basis for indices of climatic variability. Satellite SST observations provide more complete space-time coverage than ships and buoys, but absolute calibration of satellite SST retrievals is a concern.

AVHRRs provide high-quality SST estimates from the two NOAA Polar Orbiters that usually are in service. There also are infrared radiometers on the GOES satellites and on several European and Japanese satellites. MODIS, which is on the EOS Terra mission and the upcoming EOS Aqua mission, includes an improved infrared radiometer, and infrared radiometers for SST will be incorporated into the NPOESS satellite to be launched in 2009. Infrared radiometers measure SST only in cloud-free conditions, however. The sea surface is obscured by clouds about 60 percent of the time in the tropics and more than 75 percent of the time at middle and higher latitudes. Undetected clouds are a major source of error in infrared estimates of SST, as are stratospheric aerosols from major volcanic events. To achieve an accuracy of better than 0.5^{O}C, it has been necessary to blend satellite infrared data with *in situ* measurements to address calibration problems resulting from environmental factors.

The environmental factors that inherently limit the accuracy of infrared measurements of SST can be overcome with passive microwave sensing at lower frequencies where, in rain-free conditions, the atmosphere is nearly transparent even in overcast cloudy conditions. The Tropical Rainfall Measuring Mission (TRMM) has been measuring SST since December 1997 over the latitude range 38^{O}N to 38^{O}S with 46 km resolution and an accuracy of 0.5^{O}C. Planned satellites promise improved microwave SST measurements with the Advanced Microwave Scanning Radiometer (AMSR). AMSR is included on the EOS Aqua mission to be launched in early 2001 and the ADEOS-II satellite to be launched in late 2001. Microwave measurements of SST will be made by the Conical Microwave Imaging Sensor (CMIS) on the NPOESS satellite to be launched in 2009.

Thus, there appears to bean international commitment to ensuring that infrared and microwave measurements of SST will be available operationally throughout the 15 years of CLIVAR. Development of an improved operational product blending of infrared, microwave, and *in situ* measurements of SST should be an area of high-priority research for CLIVAR.

Summary

The ocean-sensing satellites needed for CLIVAR should be available through 2006, and the prospects for satellite observations through 2010 look promising. CLIVAR is hopeful that the post-2010 requirements for satellite observations of the ocean will be met by approved and proposed missions through the transition to NPOESS. Infrared and microwave SST measurements seem assured for the 15 years of CLIVAR. SSH and vector surface winds are critical to CLIVAR science.

The success of US CLIVAR requires that the NPOESS planning team make every effort to include highly accurate SSH and vector surface wind measurements on NPOESS at an early enough date to avoid gaps in the climate data records.

2.2.4 Sustained *In Situ* Observations of the Ocean

Many of the climate variability phenomena that are of interest to CLIVAR involve coupling between the ocean and atmosphere. ENSO is coupled because equatorial SST is sensitive to thermocline depth, which is driven by winds that themselves respond to SST. Some theories for decadal modulation of ENSO involve oceanic connections between the subtropics and tropics. Some models simulate decadal modulation of patterns such as the PDO and NAO by using ocean-atmosphere interaction, and ocean variability connected with these patterns is prominent in observed time series. The ocean is an important factor in climate variability primarily because of its ability to store and transport heat. For this reason, the main ocean properties of interest to CLIVAR are temperature and velocity. Because of the geostrophic relation, which generally holds below the surface layer, indirect measures of velocity are provided by temperature, salinity (through its effect on density), and SSH. At the surface, improved winds and sampling of mixed layer structure will allow the wind-driven, or Ekman, transport to be estimated, although CLIVAR process studies are needed to further refine our understanding of the depth penetration of the ageostrophic flow.

In the 1980s and 1990s the WOCE and TOGA research programs investigated, respectively, the basin-scale circulation of the global oceans and the role of the tropical ocean in atmospheric variability in and outside the tropics. These programs were international and did much to foster the international collaborations required for large-scale sampling. They also determined the accuracies and, to first order, the resolution needed for observing climatically significant variability in the ocean, sea-surface fields, and atmosphere. CLIVAR builds on the significant foundation laid by these programs.

Fortunately, some of the large-scale *in situ* sampling elements from WOCE and TOGA have continued and now provide regular observations of the ocean: VOS surface meteorological reports, sea level stations, the Expendable Bathythermograph (XBT) network, the Surface Velocity Program, and the equatorial TAO and PIRATA moorings. Many research measurements ceased, however, and the continuous temporal coverage and homogeneous data quality needed to study climate variability are unavailable. Satellite observations provide continuous and reasonably homogeneous observations of SST and SSH but only indirectly describe the heat transport that occurs below the surface layer.

US CLIVAR has developed a pragmatic strategy for implementing an ocean observing system for climate that utilizes the legacies of WOCE and TOGA. The strategy is based on three perceptions:

- A rudimentary ocean observing system for climate now exists
- For the foreseeable future, satellite observations of SST, SSH, and surface winds should be available (see Section 2.2.3)
- Ocean data assimilation (see Section 2.1.2) is developing rapidly and holds great promise for integrating observations of different variables taken with different instruments.

The strategy entails relying on existing satellite and *in situ* observations and the ability of data assimilation to integrate diverse observations. US CLIVAR will then augment available *in situ* observations where additional coverage is needed for climate studies. This augmentation will entail adding observations that can be feasibly maintained for the decadal time scales of the phenomena of interest. It also will mean focusing on observations that extend the basic satellite coverage either downward or to variables not sensed to provide a full three-dimensional set of observations of all essential variables for ocean data analyses on climate scales.

OceanObs99 together with a series of associated workshops achieved a consensus on the next steps in implementing a sustained global ocean observing system for climate research and forecasting. All elements of the observing system were discussed, and participants were asked to present plans that were not only effective but also practical and efficient. The conclusions of that conference are fully consistent and integrated with US CLIVAR planning. The United States is expected to provide a substantial fraction of the global system, but it cannot do so alone; it must rely on compatible efforts by partner countries to leverage its contribution.

Many of the required sustained ocean observations are fundamentally regional for example, measurements of deep convection where it occurs, tracking transports of specific currents, special equatorial observations. In addition to the surface flux program described in Section 2.1.4, however, several sustained ocean observations that are central to CLIVAR are best regarded in a global context.

ARGO

The ARGO profiling float array will be the central element of the *in situ* ocean observations of temperature and salinity profiles that are crucial to the success of CLIVAR. ARGO is designed to provide a global array of temperature, salinity, and velocity measurements spanning the interior of the world s ice-free ocean. Aspects of the ocean s role in climate that will come directly from ARGO sampling include pathways, circulation, and transport, as well as heat and freshwater storage. The goal is for 3,000 floats with approximately 3-degree spacing, each lasting about 5 years, to report profiles of temperature and salinity every 10 days from about 1500 m to the sea surface. Float motion between profiles will measure absolute subsurface currents with which to reference the geostrophic shear inferred from the profile data. The array will provide information in near-real time for data analysis, model initialization, and assimilation; it also will tie together more regional elements of the ocean climate observing system (see Section 3). ARGO is an international collaboration in which several other countries have agreed to match the US contribution.

A key aspect of the ocean climate observing system is how ARGO and satellite altimetry work together to provide a dynamically complete description of the oceanic pressure field and the associated geostrophic velocity field. Satellite altimetry provides a relatively high-density (in time and space) picture of a combination of integrated buoyancy storage and variability in the surface geostrophic flow. ARGO will provide a lower-density picture of how the buoyancy storage is distributed in depth, as well as the apportionment between heat and freshwater storage. ARGO also provides a description of geostrophic flow, including the mean. Without ARGO, inferring mean velocity, separating barotropic flow perturbations from buoyancy-storage variability, separating the effects of freshwater from heat storage, or inferring the climatological mean portion of ocean transport is difficult. With ARGO, all of these data will be known.

Studies show high coherence between altimetric data and dynamic height in the tropics, indicating the dominance of baroclinic variability at low latitudes. This high coherence can be exploited to estimate subsurface density structure from altimetric height. Thus, the high along-track spatial resolution of the altimeter can be used to interpolate between more widely spaced subsurface density profiles. Even in the tropics, however, there are significant residuals in SSH because of barotropic variability. These residuals increase with latitude; the barotropic pressure contributions are large at high latitudes. The need to measure SSH and interior distributions is strongly emphasized in an ocean-scale observing system. Moreover, temperature alone is not sufficient to adequately estimate dynamic height because salinity variability is a significant contributor to SSH in some regions.

The design of the ARGO sampling array involves balancing scientific requirements against the practical limitations of technology and resources. A complicating factor is that the statistics required for accurate array design are poorly known in many regions. Therefore, the design of the ARGO array is based on the following factors:

- *Previous float studies.* Results from the WOCE arrays in the tropical and South Pacific Ocean and in the Atlantic s subpolar gyre indicate that ARGO sampling will be able to resolve climate variability on time scales of years but not months.
- *The existing upper-ocean thermal network.* Statistical descriptions that are based on XBT data indicate that the ARGO array will determine heat storage in the surface layer with an accuracy of 10 W/m^2 on seasonal and 1000-km scales. The precision improves to about 3 W/m^2 for interannual fluctuations; it improves further by combining profile and altimetric data.
- *Altimeter data.* Spectral analysis of altimetric data shows that the instantaneous signal-to-noise ratio for climate signals with scales longer than 1000 km will be 2:1.

All ARGO data will be publicly available on an hours-late basis via the global telecommunications system (GTS). A data set with scientific quality control including expert examination of individual profiles and sequences, comparison to ancillary data sets and climatologies, and best recalibration of salinity data will be available 3 months after data collection.

US CLIVAR supports the ARGO goal of global sampling and recognizes ARGO as essential to its strategy in the Atlantic and Pacific sectors. Global sampling is important, and ARGO forms the foundation of US CLIVAR s approach to studying climate variability in the ocean outside its areas of focus. At the same time, US CLIVAR is investing in basin-scale studies of the Pacific and Atlantic. ACVE and PBECS, which are planned for these regions (see Sections 3), depend on obtaining a high enough sampling density to well constrain ocean analyses. Therefore,

The success of US CLIVAR requires that ARGO place high priority on achieving the planned arrays of ,1200 floats in the Pacific north of 40^{O}S and 550 floats in the Atlantic north of 30^{O}S as quickly as possible.

High Resolution Temperature-Salinity Transects

The ARGO array is designed for broad-scale sampling to measure heat and freshwater storage over large ocean areas, as well as volume and heat transport by large-scale components of the circulation. However, accurate determination of the oceanic transport of heat, freshwater, and thermocline water masses involved in climatically important processes such as advected temperature anomalies or subduction requires observation of boundary current transport and interior eddy transport as well. Placing observers on VOS and using expendable probes measuring temperature (XBTs) and salinity (XCTDs) make obtaining upper-ocean hydrographic sections with high enough spatial resolution to measure the volume and heat transport by concentrated boundary currents and mesoscale eddies feasible and affordable.

The High-Resolution XBT (HRX) program provides boundary-to-boundary profiling along selected lines; closely spaced XBTs are used to resolve the spatial structure of mesoscale eddies, fronts, and boundary currents. Probe spacing typically is 10 km in boundary regions and 50 km in the ocean interior. Most profiles go to 800 m, and XCTDs measure salinity on a subset of stations. The longest time series of HRX sections is 13 years (between Auckland and Suva in the South Pacific). Most of the present HRX lines, shown in Figure 2.2, span the TOPEX era with a repetition frequency of about four times per year. The HRX transects provide required eddy-resolving measurements along a few transoceanic lines, providing transport variability on seasonal and longer time scales. In conjunction with altimetry, HRX lines can reveal the subsurface structure of mesoscale and boundary-scale variability features that are not resolved by the float array.

These same VOS sections would support deployment of ARGO floats, improved sustained surface observations as a basis for enhanced air-sea flux analyses (see Section 2.1.4), and possibly upper-air soundings. With a technician or scientist onboard, HRX transects provide a platform for testing new expendable and recoverable instrumentation and installation of fixed equipment (thermosalinographs are one example).

Although the need for measurements of the volume and heat transport of concentrated currents is self-evident, the importance of oceanic eddy fluxes to climate variability is not. In averages over several hundred eddies on the Taiwan-to-San Francisco line between 1992 and 1998, Roemmich and Gilson (2000) found that the net effect of eddies is to significantly enhance the shallow meridional overturning cell. The eddies transport surface water northward and thermocline water southward as a result of a systematic eddy tilt toward the west with decreasing depth. Eddy heat transport averages 0.1 pW, which is small compared with the total transport of 0.76 pW but is the most significant component in the interannual variability of temperature transport below the Ekman layer and may be a significant cause of temperature change on decadal time scales. Basin-wide effects of eddy-scale phenomena must be taken into account in CLIVAR; these effects are not addressed by other elements of the observing system.

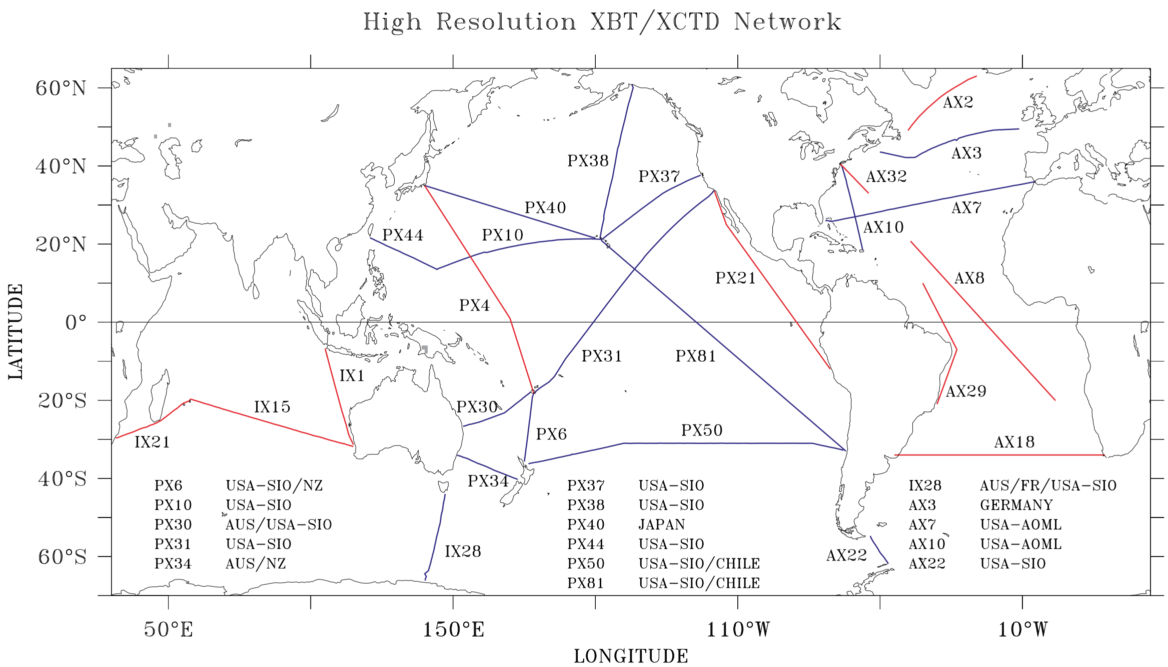

Figure 2.2. High-resolution XBT/XCTD (HRX) sections are occupied several times per year. Blue lines represent HRX sections recommended for continuation; red lines are proposed new HRX sections. The HRX array is maintained by an international consortium, and US participation would be needed on all proposed lines.

A review of existing XBT networks for use in climate research was carried out as a prelude to the OceanObs99 conference. US CLIVAR has examined its needs for a global array to measure fluctuating volume and heat transports; generally accepting OceanObs99 recommendations, US CLIVAR makes the following proposal:

All existing HRX lines (shown in blue in Figure 2.2) should be retained, and proposed lines (shown in red) should be brought up to full HRX standards.

Reasons for maintaining and adding specific lines to augment the HRX network on a regional basis are given in Section 3. As ARGO is deployed, XBTs should transition from the present broad-scale sampling to more selective line-based, high-resolution and frequently repeating modes. This transition should align the network with CLIVAR objectives by providing required eddy- and boundary-scale information.

Surface Drifters

On decadal time scales and longer, advection is significant in the upper ocean heat and freshwater budgets of the ocean that is, the advective flux may exceed the storage term in temperature and salt evolution equations. The advection process is complex and three-dimensional, and variability of advective effects arises from variations in temperature and freshwater coupled with mean currents, variations in currents with mean property gradients, and the interaction of variable current and property fields. In contrast to seasonal-to-interannual phenomena in which the storage rate of heat is key in decadal processes, knowledge of the velocity field is paramount.

For assimilation analyses to be useful in describing decadal-scale changes, the analyzed upper-ocean circulation must be constrained by, and tested with, direct velocity observations. For example, in the shallow limb of the subtropical overturning cell, the Ekman component depends on the distribution of small-scale mixing processes, which are highly parameterized in models. To adequately test models, researchers must directly observe this circulation component.

The Surface Velocity Program (SVP) is an international effort to obtain long-term global observations of near-surface currents, using current-following, satellite-tracked buoys (drifters) with subsurface drogues that are designed to make the drifter accurately follow the horizontal water motion. Since 1988, drifter observations made with drogues at 15 m have provided continuous sampling of the tropical Pacific's near-surface velocity and SST. In 1999, for example, the drifter array within 20 degrees of the equator provided more than 32,000 daily-average velocity and SST observations. These tropical observations will be continued as part of the ENSO observing system and enhanced by the Consortium on the Ocean s Role in Climate.

Between 1992 and 1997, the SVP sampled the surface circulation of the global ocean as part of WOCE, with the objective of charting the mean circulation as well as the statistics of its variability. Sampling in the North Pacific and North Atlantic generally was more complete than in other regions. In the subpolar North Atlantic, observations reveal strong topographic constraints on surface current systems indicating a significant barotropic component of the circulation that can confuse attempts to infer buoyancy storage from altimetry. Drifters have proven to be good platforms for economical monitoring of SST with which to detect and remove satellite biases introduced by clouds and aerosols.

Near-surface velocity and SST measurements from drifters will be made in the tropical region for the next 3 years. Observations in the subtropics and subpolar oceans will no longer be available unless CLIVAR mounts them. Without such measurements, SST coverage will degrade, and direct measures of circulation will be virtually absent over much of the globe.

US CLIVAR recommends that an array of surface drifters be maintained globally to meet the needs of accurate SST mapping; a subset should be used to augment surface observations of sea-level pressure and wind.

Repeated Hydrography

The distribution of properties in the ocean is known to be changing, presumably in response to changes in the earth climate system. Observed changes of water mass properties and volumes on decadal time scales already have led to speculation about climatic changes in water-mass formation processes, the meridional overturning circulation, and global climate. The distributions of oceanic CO_2, nutrients, and oxygen are indicative of the carbon cycle and the fact that the ocean is a major sink for atmospheric carbon dioxide. These properties particularly time-tagged tracers such as chlorofluorocarbons (CFCs) and tritium/helium provide important descriptions of subduction, mixing, and advection processes that cannot be obtained from temperature and salinity alone.

Hydrography remains the only feasible way accurately to measure full-depth, vertically resolved, basin-scale distributions of the full multivariate suite of ocean properties. Hydrography is the most practical way to obtain accurate measurements of any properties in the deeper half of the ocean. Accurate shipboard hydrographic measurements are needed to ensure the accuracy of ARGO salinity measurements, which are based on sensors that operate without calibration for several years. Similarly, ARGO measurements will be limited to the upper 1500—2000 m of the ocean, and full-column hydrographic measurements will be needed so that changes in the deep ocean can be observed. Although the density field that ARGO floats will track well can change rapidly, water property distributions on density surfaces evolve slowly and vary over large scales. Thus, sampling can be infrequent along a relatively limited number of repeat hydrographic lines.

In addition to documenting water mass variability, these data will constrain models now under development that will assimilate observations from other observing systems. Volumetric and property changes by density class that reflect the time-integrated effects of air-sea exchange and ocean circulation will be particularly useful in constraining models that simulate water mass renewal from air-sea interaction.

Repeated hydrography is needed to build on the century-long record that is available now and the substantial global survey completed by WOCE between 1990 and 1998. The density of lines and the frequency at which each should be reoccupied depends on processes renewing the water in a region, as well as their time scales. (These factors are discussed in Section 3.) International planning for CLIVAR points to globally repeated surveys of approximately 15 lines on repeat cycles between 6 and 10 years. Many nations are expected to share in this project; the United States would occupy some lines in the Atlantic and Pacific (Figure 2.3 shows tentative lines). Planning for studies of the global carbon cycle also has identified repeat lines as a high priority, and collaboration with the US Carbon Program to occupy a core set of US repeat lines is anticipated.

US CLIVAR recommends collaboration with the US Carbon Program and international partners to occupy two zonal and two meridional lines in the Atlantic and in the Pacific.

CLIVAR and the US Carbon Program may seek more frequent lines in specific areas. The core set of eight lines in each basin would be occupied every 6 to 10 years, however.

Ocean Time-Series Sites

Time series stations at select sites are a key element of *in situ* observations for CLIVAR; they provide continuous data at select sites that complement drifting, VOS, and other observations. Time series stations can provide high vertical and temporal resolution from the atmospheric boundary layer down through the ocean mixed layer and into the deep ocean. Many different observations can be made through the water column—including biological, chemical, and optical properties, as well as physical variables. Maintained at fixed sites, time series stations provide continuity of measurement and serve as reference points for other observations. They can be visited by ships making observations to provide accuracy that is unattainable with unattended measurements (e.g., reference salinities for ARGO floats) or to add to the diversity of the time series.

Historically, time series sites such as the Ocean Weather Stations have provided data used to develop much of our understanding of the ocean. For example, simultaneous observation of surface forcing and temporal evolution of the vertical structure of the upper ocean at Ocean Station P in the northeast Pacific provided the basis for early efforts to develop ocean mixed-layer models. Occupying such sites with staffed vessels is costly, but modern mooring technology makes establishment of several such sites feasible. The OceanObs99 report spells out CLIVAR's objectives for these observations: investigating and observing water mass formation and transformation; providing air-sea flux reference sites; investigating ocean variability, including the deep ocean; and multidisciplinary observations. Air-sea flux reference sites are discussed in Section 2.1.4; we discuss time series observations of the ocean interior here.

Interior ocean observations are made at a very few repeated hydrographic stations that provide time series of multiple water properties and, in some cases (when co-located with moorings), velocity. Maintaining a small number of such sites around the world's oceans is considered an important contribution to CLIVAR. Existing time series have been invaluable in investigating oceanic climate variability, such as the strong manifestation of the PDO in the California Current, fluctuations in water properties of the subtropical North Atlantic tentatively associated with variations of convection in the subpolar gyre, and fluctuations of salinity on fixed density surfaces at Hawaii that have been connected to changes in the freshwater cycle of the subtropical North Pacific. The multivariate nature of these series also supports studies of the relation of climate variability to ocean biology and biogeochemical cycles, including the biological carbon pump. All of these observed variations help to define the statistics of ocean climate and errors in climate model hindcasts—in addition to the purely exploratory goal of defining new modes of climate variability that are masked in less well sampled data sets by stronger, shorter-term fluctuations.

US CLIVAR recommends continuation of Bermuda, HOT (Hawaii), at least some CalCOFI (California Current) water property sampling, and continued US support of moored measurements at Station B (Labrador Sea).

The location of these time-series stations is shown in Figure 2.3. These stations should be maintained in partnerships with efforts in biology and geochemistry, but their importance as touchstones for the changing ocean climate more than justifies inclusion in CLIVAR. Observations at Bermuda have been made for many years at Station S; more recently, a multidisciplinary time series was started at the Bermuda Area Time Series (BATS) site. We recommend maintenance of a unified Bermuda site and preservation of the historical link via a multi-year overlap with all present observations.

As discussed in Section 2.1.4, surface flux reference moorings are a central part of the CLIVAR effort to improve our knowledge of air-sea fluxes. These and other sites could be occupied to monitor water mass formation and transformation. These sites should provide the high vertical and temporal resolution needed to study local dynamics, storage, and variability, as well as comparisons with ocean models. Discussions between the Ocean Observations Panel for Climate (OOPC) and the CLIVAR Ocean Observations Panel (COOP) are underway to identify locations for these sites and develop international commitments that would support their occupation.

We recommend a multi-disciplinary, international approach to locating, equipping, and maintaining a small number of new sites in key locations.

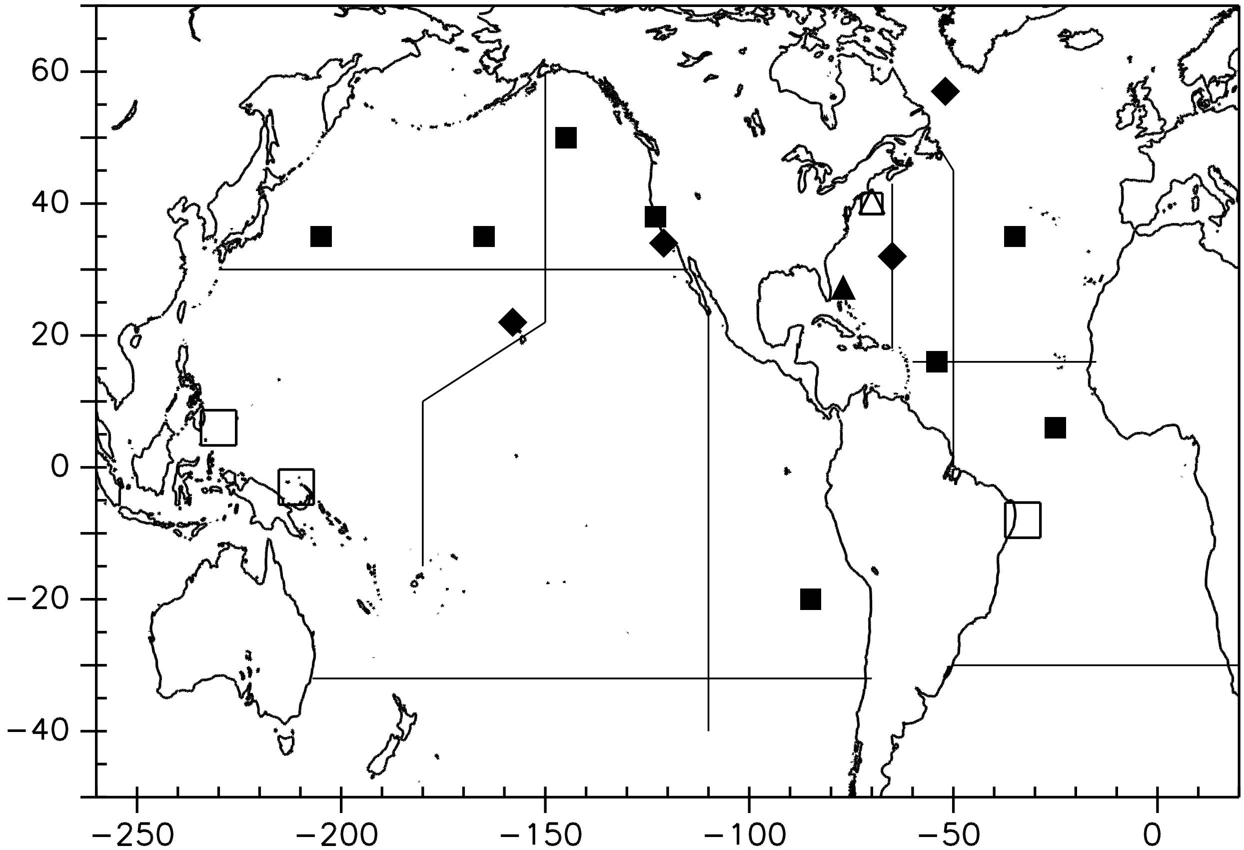

Figure 2.3. Proposed moored surface-flux reference sites (filled square), time series stations (filled diamond), moored hydrographic stations (triangle), and western boundary current arrays (open square) and hydrographic sections to be repeated every 6—10 years (solid line). The station south of Cape Cod combines a time series and reference flux mooring. The three flux reference sites now occupied should be continued. All time series stations are operational and should be continued. Moored hydrographic stations and western boundary current are new.

Observing Concentrated Currents

Because of the need for high temporal and meridional resolution required to measure currents and temperature variability, moorings have been particularly valuable in observing changes in the equatorial zone. Equatorial moored arrays (TAO, PIRATA) are in place in the Pacific and the Atlantic. Initially, they were instrumented to observe surface meteorology and upper-ocean temperature structure; only a few observed currents. Although velocity measurements are not yet used to initialize climate forecast models, they are vital to diagnosing equatorial ocean dynamics. We recommend additional current measurements from PIRATA (see Section 3.1) and TAO (see Section 3.2) to measure zonal transports. We also recommend inquiries into how to monitor three-dimensional circulation at the equator cost-effectively.

Most of the foregoing ocean observations are most appropriate for the broad scales of the ocean interior. The most concentrated oceanic transports of mass and heat occur in boundary currents, particularly those along the ocean's western boundary. These currents will not be well measured by ARGO, and altimeters have difficulty monitoring the associated surface flow. High-resolution XBT/XCTD sections cross important boundary currents in a few places, but their frequency is less than required and some key locations are not crossed by VOS lines. CLIVAR will be unable to diagnose key climate processes without measures of volume and heat transports of the most important currents as they vary with the climate. The highest-priority boundary currents identified by US CLIVAR's regional panels are shown in Figure 2.3.

Historically, western boundary current transports have been measured by using large arrays of current meter moorings. Because of the high cost of moored arrays, however, few long-term boundary current measurements have been made. To maintain the long-term observations needed for CLIVAR cost-effectively, another technology will be needed. Two new technologies may provide methods of obtaining the required measurements. A single moored profiler or an autonomous underwater glider (virtual mooring) can cost-effectively report time series of temperature, salinity, and velocity profiles with sampling intervals on the order of one day. With temperature and salinity profiles only, a pair of such autonomous stations can provide an integrated measure of the geostrophic transport between them. Alternatively, a single autonomous underwater glider fitted with a Conductivity, Temperature, and Depth (CTD) and acoustic doppler current profilers (ADCP) could repetitively cross the current to gather sections of salinity, temperature, and velocity; this direct approach may be particularly attractive at low latitudes, where geostrophy may be unreliable.

Although the new technologies have not yet demonstrated their utility in boundary currents, they are critical to CLIVAR observations of boundary currents (see Sections 3.2 and 3.2); thus, they should be tested soon. We also encourage other technologies. Moreover, some currents—such as the Mindanao Current near the bifurcation of the Pacific's North Equatorial Current (see the PBECS Plan)—are so complex that, even with appropriate technology, we would not know how to monitor them cost-effectively. Effective transport monitoring may require pilot studies to determine feasibility and the most effective methods.

US CLIVAR recommends support for testing of new technologies and carrying out pilot studies needed to develop cost-effective ways to monitor western boundary currents.

2.2.5 Paleo Observations

A subset of paleoclimate issues is relevant to the CLIVAR science objectives and dictates a unified CLIVAR-PAGES approach. Compared to instrumental data, paleoproxies provide far longer records over a much more varied and extreme set of climate conditions. Proxies present difficult problems of interpretation, precision (when interpreted as climate variables), and uncertainties in dating, however. Their most likely contributions to CLIVAR will consist in extending the record of climate variability and large, widespread, abrupt changes. By lengthening the record of natural variability, paleoproxies improve the baseline for detecting and understanding anthropogenic changes and allow model testing under conditions beyond the small range documented instrumentally.

ENSO through the Holocene. Knowledge of the evolution of ENSO and possibly related monsoon changes will enhance our understanding of recent anomalous behavior and contribute to prediction. Focus on the Holocene will be especially valuable for several reasons:

- There is a rich Holocene set of proxies for mean climate/seasonal cycle/monsoon (lake strata, pollen, etc.) and for interannual variability (lake deposits, corals, etc.).
- Perturbation forcing during the Holocene is predominantly seasonal, which is ideal for studying the interaction of the seasonal cycle/monsoon and ENSO.

- Study of the best observed climate signal in the Holocene the enhancement of the northern hemisphere monsoon should help us to understand the present monsoon and its interaction with ENSO, as well as to evaluate climate model responses including land-ocean-atmosphere feedbacks.
- In addition to the Pacific, the study of Holocene climate variability could be extended into the tropical Atlantic and Indian Ocean, which connect to the North Africa monsoon and South Asia monsoon variability.

Changes in teleconnection patterns. Modern observations show that much important climate variability is expressed through a few large-scale patterns (e.g., PNA, NAO). Using high-time-resolution records of several proxies (i.e. corals, ice cores, tree rings), progress is being made to understand what part of PNA variability is associated with ENSO. Because other processes also contribute to the PNA, improved PNA proxies would be useful as would assessment of the relative importance of various processes (tropical forcing, intrinsic mid-latitude atmospheric dynamics, and atmosphere-ocean coupling in the mid-latitudes) to variability in the PNA. An analogous activity should be focused on the AO/NAO, with particular emphasis on the relation between the AO/NAO and the tropics, especially TAV.

Abrupt change. The paleoclimate record shows that large, rapid, widespread changes have occurred repeatedly within decades or less. There is no accepted explanation for any of these abrupt changes, including those linked to the ~1500-yr Dansgaard-Oeschger cycles and the ~6000-yr-spacing Heinrich events. Mounting evidence shows that the 1500-year cycles continue into the Holocene; the Little Ice Age that is so well documented in Europe may be the last extreme phase. Global reconstructions are lacking, but regional changes were appreciable fractions of glacial-interglacial changes. No strong external forcing is known. If abrupt changes were forced, the climate system must include an amplifier. If they were unforced, the climate system must admit large-amplitude internal instabilities. Climate models do not produce such changes suggesting that the models are less volatile than the real climate system, with obvious consequences for their predictions of future climate change. The period during the most recent deglaciation from the Bolling transition through the Younger Dryas and into the Holocene offers the best possibility of well-dated, highly resolved, globally distributed records of abrupt changes.

North American hydrologic variability. Policy issues of water allocation, flood, and drought hinge on the probabilities of hydrologic events with planning horizons extending 30 or 100 years. The limitations of historical records for policy analyses of extreme floods are illustrated by the scientific and political debates about the adequacy of methods for assessing the likelihood of events such as the 1927 and 1993 Mississippi River floods, the 1986 and 1997 American River floods, and the 1982—87 Great Salt Lake flood that were dramatic in the regional historic context. Drought characterization across North America is similarly limited by data. Examples include the 1930s and 1950s multiyear droughts that devastated the northern and southern Great Plains, respectively.

Hurricane/typhoon variability. There is great debate regarding the variability of hurricane strength and frequency, particularly in the face of possible global warming. Paleoclimatic investigations may reveal whether the number of "hits" by large hurricanes and typhoons has varied significantly in time.

The collection and compilation of calibrated, high-resolution paleoclimate records from various proxies is essential to improving our understanding of global and regional climate variability and climate change during the past 500 to 2,000 years. Paleo records will have a significant impact on the models, analyses, and predictability studies that CLIVAR hopes to produce. In addition, hypotheses and understanding gained in CLIVAR can assist in analyses of paleoclimatic observations made within the PAGES program. For this reason, a joint US CLIVAR and PAGES working group has been established to facilitate communication between the two communities and to serve as a focal point for research that involves both.

We recommend support for a joint PAGES and CLIVAR working group to facilitate communication between the two programs.

2. 3 Global Modeling

2.3.1 Seasonal-to-Interannual Modeling and Prediction

CLIVAR will use models as integrators of knowledge and as tools for improving understanding, estimating predictability, making predictions, and conducting observing system simulation studies. Prediction may be the best test of our ability to model the climate system, and it is the means by which CLIVAR research efforts can directly benefit society. Accordingly, seasonal-to-interannual modeling and prediction efforts will facilitate the development of models that can predict seasonal-to-interannual (S-I) variations of the coupled ocean-atmosphere-land system. This effort on S-I time scales will be just the first step in expanding the scope of predictive prediction systems to cover a wider spectrum of time scales and regions.

Past efforts to exploit the predictability of S-I variations have focused mainly on predicting interannual variations in the tropical Pacific Ocean specifically, certain aspects of ENSO. Future efforts will expand to include the predictability of global S-I variations, including the possible effects of the tropical Atlantic Ocean, the tropical Indian Ocean, and global land surface conditions.

Improving S-I modeling requires coordinated efforts that focus on quantifying model deficiencies (establishing metrics, sharpening uncertainty estimates of predictions, and rigorous assessment of relative strengths/weaknesses) and establishing a more methodical approach to model development. Improving S-I prediction requires coordinated efforts that focus on understanding what controls/limits the predictability of ENSO and its global teleconnections, understanding sources of predictability beyond ENSO, and developing improved probabilistic forecasts that incorporate the spectrum of uncertainties (model and other). US CLIVAR s approach includes model development in the context of coordinated modeling experiments among modeling groups and rigorous model evaluation.

Strategy

Fundamental improvements in atmospheric and oceanic GCMs, land surface process models, and coupled atmosphere-ocean-land models will be addressed through continued basic research that focuses on key questions (e.g., the role of model resolution) and deficiencies (e.g., critical physical parameterizations) and through the use of coordinated model experiments. These experiments can be conveniently organized into five areas, each corresponding to a key approach or critical issue: dynamic seasonal prediction, using atmosphere-land models; coupled dynamic seasonal prediction, using ocean-atmosphere-land models; the role of land-surface processes in S-I predictability and prediction; S-I data assimilation; and regional modeling. Ocean data assimilation in support of S-I prediction will be advanced through cooperation with GODAE. Specifically, we anticipate that some groups participating in GODAE will undertake invaluable assessments of the impact of data on the initializing ocean fields used for prediction with coupled GCMs. GODAE also will pay attention to extratropical ocean initialization and the assimilation of new data types and sources, such as ARGO.

The Seasonal-to-Interannual Modeling and Prediction (SIMAP) Panel will coordinate comparative and cooperative studies in this area. The panel s approach is outlined in the SIMAP Plan.

2.3.2 Testing Climate Models Using Natural Variability

Although the ability of models to reproduce interannual and perhaps even decadal variability can be determined through comparison with observations, such comparison is not possible for models of slower climate change or the impact of anthropogenic forcing on climate. A broader range of physics may be involved in climate change than in seasonal to interannual variability, but observed modes of climate variability can be viewed as natural modes of the climate system that are likely to participate in all aspects of climate change. Thus, they must be adequately simulated by models that are used to study predictability of variability and by models that provide the scientific basis for projections of climate change. Because the amplitudes, spatial distributions, and time scales of climate responses to anthropogenic influences (such as greenhouse gas concentration, aerosol loading, and land-use change) involve the same internal model processes as natural variability, testing climate models by their ability to reproduce modes of variability may be the most convincing means of assessing the ability of models to predict all kinds of future change.

The atmospheric and land components of climate variability can be reproduced to some extent with prescribed interannually varying SSTs. Several standard SST data sets are commonly used to run such tests. Especially useful has been the Atmospheric Model Intercomparison Project (AMIP) and AMIP-II data sets developed by Department of Energy/Lawrence Livermore National Laboratory (DOE/LLNL) scientists in support of the Working Group on Numerical Experimentation (WGNE). These projects have been used to establish the capability of GCMs to reproduce the atmospheric and, to a lesser extent, land components of ENSO occurring over the past two decades, given the SSTs.

Finding meaningful observational tests of coupled models is more challenging. International CLIVAR, through its Numerical Experimentation Group-2 (NEG-2), coordinates the Coupled Model Intercomparison Project (CMIP) to compare coupled global models against observations. This project is described at CMIP s Web site (<www.pcmdi.llnl.gov/covey/cmip/cmip.html>):

> The purpose of CMIP is to examine climate variability and predictability as simulated by models and to compare the model output with observations where available. So far CMIP is examining a relatively small subset of model output. This subset includes spatial and temporal averages of 20 meteorological and oceanographic variables, together with three-dimensional fields of just a few variables such as surface air temperature.

CMIP has received output from 18 different coupled CGM control runs, including three very long (1,000-year) simulations. Early models generally have been deficient in their ability to reproduce many regional aspects of natural climate variability; data to allow such analyses also have been inadequate. US CLIVAR will provide the data sets on climate variability required for meaningful testing of regional climate variability in GCMs participating in future versions of CMIP.

By providing required observation, US CLIVAR will facilitate and, where needed, organize future model intercomparison activities of the WCRP that test the capabilities of global models to simulate natural variability on seasonal and longer time scales.

2.3.3 Process and Modeling Teams

US CLIVAR planners have been drawn to two structural aspects of the field that slow progress in climate research. Both problems arise at the interface between specialties one between experimentalists studying individual processes and model developers who must incorporate understanding of these processes into climate models, the other between researchers who maintain comprehensive climate models and scientists who are developing theories and process models of specific phenomena that should be better represented in climate models. We propose cross-specialty teams to bridge these structural gaps.

Certain subgrid-scale processes must be included accurately in models to make more realistic climate predictions possible. Nevertheless, the selection and design of climate-related process studies and the ways that existing knowledge is incorporated into models are haphazard. Modelers need greater understanding of the literature and the state of the art of small-scale processes; experimentalists need to better understand how their results are being used and what process studies would be most helpful.

We recommend a focused effort by process teams to understand and parameterize the important processes that are not properly included in climate models.

The objectives of these process teams will be to improve climate models and better focus studies of subgrid-scale process studies by

- examining models to improve their use of existing knowledge about subgrid-scale processes,
- identifying new information about subgrid-scale processes that is essential for realistic climate predictions,
- estimating which parts of that new information can be incorporated into models within 10—15 years and suggesting how models should evolve to use subgrid-scale information that is likely to be available after 15 years, and
- suggesting how instrumentation and field work can be designed to produce results useful to climate predictions.

The US CLIVAR approach will be to establish a few small working groups of modelers and experimentalists focusing on specific problems (e.g., boundary-layer clouds, small-scale ocean transport processes) to summarize existing observational evidence, the state of model parameterizations, suggestions for improved approaches to modeling, and recommendations for further process observations. These groups should report on approximately annual intervals through rapid publication journals. Working groups might involve additional specialists for specific one-year topics or call workshops, but the group itself should have enough continuity to undertake long-range studies of broad areas as long as their work is productive.

In the same way, US CLIVAR will establish teams to facilitate transferring the understanding gained in theory and process models into the code of comprehensive climate models. This knowledge transfer will be difficult because experiments with comprehensive models must be carried out in parallel with the model s main uses, and the scientists maintaining these models who have the expertise to understand their requirements, efficiencies, and peculiarities have little time to test new experimental schemes. Success in transferring knowledge from process models to comprehensive climate models, where it will be of operational and research benefit, will require teams to fully understand the details of specific climate models, develop ways to represent the behavior of process models within the efficiency and resolution constraints of comprehensive models, and utilize computer resources to allow extensive testing of the modified comprehensive model in parallel with the model s main use (e.g., operational forecasting, IPCC runs).

We recommend development of teams to transfer theoretical and process-model understanding into improved treatment of processes inside comprehensive climate models.

2.4 Empirical Studies

US CLIVAR will include efforts to mine the observational record and results from comprehensive model runs for strong relationships between predictable large-scale, low-frequency patterns of climate variability over the ocean, atmosphere, and land, including the relationship between these patterns and the probability of extreme weather events. Observational studies of interactions between the tropical ocean and the global atmosphere conducted during the late 1960s and 1970s laid the groundwork for advances in numerical prediction of ENSO and its impacts on global climate that took place during TOGA. They demonstrated the linkage between tropical sea-surface temperature and circulation anomalies and the extratropics, and they revealed and illuminated the essential ocean-atmosphere feedback mechanisms that give rise to the ENSO cycle. The knowledge gained from these investigations shaped atmospheric and oceanic GCM experiments during TOGA and stimulated the development of a new generation of coupled models that were capable of simulating what scientists believe to be the essential aspects of the ENSO cycle.

Improved data sets and analyses of the ocean, atmosphere, and land system during the CLIVAR period will provide a wealth of new empirical information. Operational tropical ocean-atmosphere data assimilation began at NCEP more than a decade ago, taking advantage of the observing system developed during the TOGA program. In CLIVAR, we envision a global ocean observing system with a concurrent expansion of data assimilation activities. The situation for climate researchers who are interested in coupled ocean-atmosphere phenomena is expected to be similar to that experienced by meteorologists in the 1970s, when decade-long weather analyses first became available. Major advances in understanding basic features of the atmospheric general circulation occurred during that period. The nature of variability of atmospheric circulations from weather systems to intraseasonal oscillations was clarified. These empirical results stimulated theoretical and modeling studies of large-scale atmospheric disturbances and their interaction with the background climatic state. We can expect similar advances in understanding of ocean circulation as a result of empirical studies of new ocean data sets that will stimulate and guide theoretical and modeling studies of oceanic variability on time scales from seasons to decades. In addition, the analysis of the CLIVAR data set in combination with new GEWEX land-surface observations will provide the first mutually consistent analysis of climate variability in the ocean-atmosphere-land system.

Analysis of the historical record also may provide valuable information on feedbacks among ocean, atmosphere, and land. At best, the period of new CLIVAR observations will be only 15 years long. Improved proxy data sets and historical data sets over the period of the instrumental record are expected to become available during the CLIVAR period, however. Empirical studies of the proxy and historical records will be especially valuable in the development of testable hypotheses for modeling of decadal-to-centennial variability and climate change.

3. REGIONAL FOCI

Although the phenomena of concern to US CLIVAR affect large areas, they are also geographically specific. Many of the studies described above are global in nature; they designed to deal with all forms of climate variability. In addition to these efforts, US CLIVAR includes studies that are designed to look particularly at regional phenomena (e.g., TAV, ENSO) and the behavior of climate phenomena in specific regions (e.g., equatorial upwelling).Section 2 summarizes some of these regional activities to be repeated in several locations around the globe (time series sites, flux reference sites). These and other regional studies were developed by the US CLIVAR Sector Implementation Panels. This section describes the regional studies and the scientific basis for them.

US CLIVAR includes complex regional studies of key large-scale processes that are important to climate variability. These studies such as the Atlantic Climate Variability Experiment (ACVE) and Pacific Basin Extended Climate Study (PBECS) and the Pan American Climate Studies program (PACS) have the objective of developing a full picture of large-scale variability in a key region over many years. These experiments were nationally planned in the sense that suggestions developed from community-wide meetings were used by CLIVAR committees to establish the elements of the experiments before these elements were associated with specific investigators. Other CLIVAR studies may require national planning if the effort needs to be sustained beyond the period of individual grants and /or if the required resources are large. When national planning is required, those plans will be developed by a standing or newly formed US CLIVAR committee.

US CLIVAR will support selected short-duration regional and process experiments to examine specific dynamic questions that must be answered to improve climate models. Experiments of this sort often are best planned by the investigators who want to carry them out. Such "investigator planned" studies should be brought for review to an appropriate US CLIVAR committee, which will advise the funding agency(s) regarding the proposed study’s potential to address major deficiencies in climate prediction models, to extend intensive observations collected over time periods of months to climate time scales, and to provide scientific guidance for planning future observing systems.

3.1 ATLANTIC SECTOR

The climate of the Atlantic sector and surrounding continents exhibits substantial variability on a wide range of time scales. This variability manifests as coherent fluctuations in ocean and land temperature, rainfall, and surface pressure with a myriad of impacts on society and the environment. Of central importance are three interrelated phenomena: TAV, the NAO, and the Atlantic Meridional Overturning Circulation (MOC) (see Figure 3.1). The TAV refers to substantial variations on interannual and interdecadal time scales in tropical Atlantic SST with direct impacts on the climates of Africa and the Americas, among other (at this point, more tentative) links. The NAO dictates much of the climate variability from the eastern seaboard of the United States to Siberia and from the Arctic to the subtropical Atlantic; its intensification in recent decades has contributed significantly to observed global warming. Fluctuations of the NAO and TAV alter the wind stress on the ocean, as well as air-sea heat and freshwater fluxes. These fluxes, in turn, induce substantial changes in wind- and buoyancy-driven ocean circulation, as well as in the sites and intensity of water-mass transformation, which influence the strength and character of the Atlantic MOC. Indeed, the atmosphere drives much of the observed ocean variability over the Atlantic; the response of the atmosphere to changes in tropical and extratropical SST distributions and the role of land processes and sea ice in producing atmospheric variability are central problems for US CLIVAR.

The aforementioned climate phenomena extend over the entire Atlantic basin, including the Arctic, from the deep ocean to the stratosphere. Moreover, remote forcing from the extratropics and ENSO affects TAV; the NAO may be viewed alternatively as a hemispheric-scale oscillation (the Arctic Oscillation [AO] or the northern annular mode), and the Atlantic MOC is part of the global thermohaline circulation. Therefore, successful implementation must include the entire Atlantic sector, rather than just part of it, and it must account for influences on and by the global circulation.

3.1.1 Goals and Strategy of Atlantic CLIVAR

The long-term goals of Atlantic CLIVAR are as follows:

- Describe and model coupled atmosphere-ocean-land interactions in the Atlantic sector, quantify their influences on and interactions with the regional and global climate system, and determine their predictability.
- Assemble quantitative historical, proxy, and real-time data sets that may be used to test, improve, and initialize models of coupled Atlantic climate variability.
- Investigate the sensitivity of the MOC to changes in surface forcing.
- Assess the likelihood of abrupt climate change.

Atlantic CLIVAR will adopt a balanced, integrative approach between existing and new observations, modeling, and theory, as well as diagnostic studies, to better understand the primary climate phenomena, their interactions, and the potential for predictability. A network of sustained, basin-wide observations will be augmented through regional and process studies that are required to improve our understanding of particular regions and key processes. Comprehensive, three-dimensional observations of the entire Atlantic Ocean including its shallow and deep boundary currents, air-sea fluxes, and the overlying atmosphere will be collected over a period of 15 years.

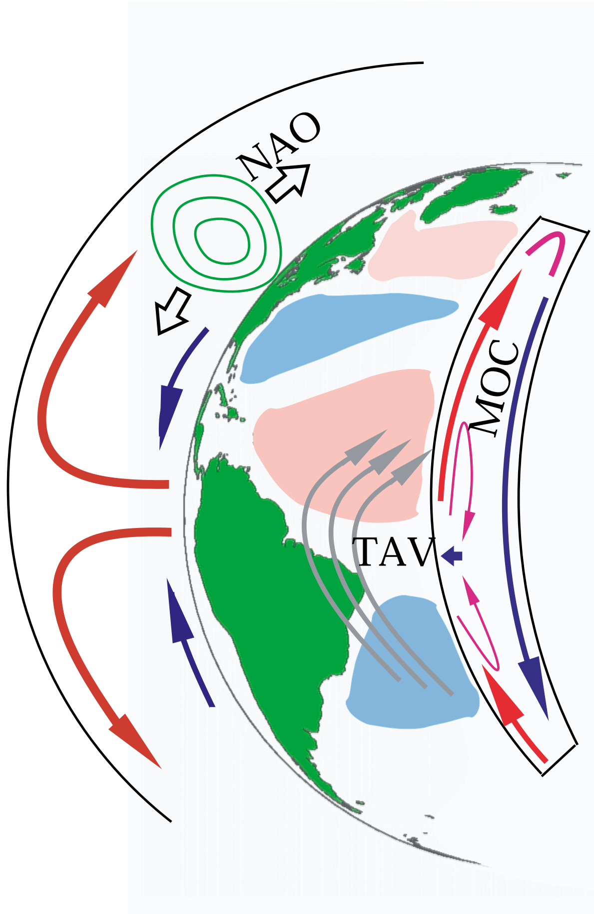

Figure 3.1 Three major climate phenomena in the Atlantic Sector. The North Atlantic Oscillation is associated with a meridional displacement of middle-latitude westerly winds (green contours of zonal wind velocity centered at 40…N). The Northern Hemisphere tropical lobe of the SST anomaly tripole (the sign of which is associated with the negative phase of the NAO) also is related to the second climate phenomenon, in which changes in the cross-equatorial SST gradient interact with the overlying atmosphere to produce changes in ITCZ rainfall. A warm anomaly north of the equator (which also can be induced during a warm ENSO phase) results in anomalous cross-equatorial winds (denoted by three light grey arrows). During this phase, the ITCZ is displaced northward, producing dry conditions over the Nordeste. Changes in the strength and position of tropical convection also may affect the position and strength of the mid-latitude storm track (blue arrows) and thus the phase of the NAO. The schematic representation of the North Atlantic meridional overturning circulation depicts the northward transport of warm water and southward transport of newly ventilated cold water. Changes in the surface density within the subpolar gyre and subarctic basins can influence the strength of the overturning and heat transport. The high-latitude density can change as a result of anomalous advection of Arctic freshwater or changes in air-sea heat fluxes. The NAO systematically influences the strength of the Atlantic Ocean overturning resulting from both effects. The tropical ocean has two additional shallow overturning cells (thin arrows) driven by Ekman transports in the trade winds zone. They can communicate surface temperature anomalies from subtropical regions to tropical upwelling zones and thus cause a delayed feedback on tropical surface temperatures. The three major climate phenomena in the Atlantic sector clearly interact, which motivates a comprehensive investigation of Atlantic climate variability.

Data-assimilating atmospheric and ocean models will bring the different elements together, facilitating quantitative diagnoses of the mechanisms involved in Atlantic climate variability.

The US strategy has been developed largely through a series of open community meetings that are summarized in the ACVE prospectus and implementation plan. It also has been developed with the emerging plans and priorities of other programs and nations in mind. For instance, close collaboration with the Arctic Climate Systems Study (ACSYS) and the Study of Environmental Arctic Change (SEARCH) initiatives are needed to ensure that freshwater export from the Arctic to the North Atlantic is adequately monitored and key processes are understood. Similarly, coordination with SPARC is required to achieve a better understanding of the dynamics of the NAO, and coordination with PAGES is needed to ensure the extension of important instrumental records throughout the Atlantic basin. Monitoring of the southern ocean (south of 30°S) is not directly addressed in the current US implementation strategy. Therefore, effective communication with international partners and US interest groups is necessary to ensure better understanding of inter-ocean exchanges and their importance for the climate of the Atlantic sector. Because about 60 percent of the global oceanic CO_2 uptake takes place in the Atlantic sector as a consequence of its intense MOC, coordination with the emerging US carbon cycle initiative also is required.

3.1.2 Sustained Observations

The broad, basin-scale sampling of the atmosphere and ocean outlined in Section 2 is central to the success of Atlantic CLIVAR. Further recommendations for Atlantic-specific aspects of a sustained observing system are predicated on the preservation of critical elements of the existing observing system. More detailed discussions are provided in the ACVE prospectus and plan, as well as the Atlantic plan.

In addition to the elements outlined in Section 2, US CLIVAR recommends the following:

- A US contribution of approximately 280 floats to the larger international temperature- and salinity-profiling ARGO array. This contribution, which is essential to the Atlantic strategy, is required to provide the desired 3° spatial coverage in the Atlantic Ocean north of 30°S (see Section 2.2.4). A 3° array translates to only about 5 floats in the Labrador Sea; therefore, an augmentation of 30–40 floats is recommended in this key region.
- A basin-wide 5° surface drifter array is required in the Atlantic sector for adequate monitoring of near-surface currents and accurate SST mapping (see Section 2.2.4). In addition, a subset should be used to augment surface observations of sea-level pressure and wind. An array of drifters is ensured for the tropical Atlantic (20ºS to 30ºN) over the next 3 years, so an extension poleward has high priority.
- Continuation of existing Atlantic VOS-based high-resolution XBT sections (see Figure 2.2 and Section 2.2.4) and implementation of high-resolution sampling on five lines (AX2, AX8, AX18, AX29 and AX32). Some of these lines also should support upgraded meteorology and surface flux observations.
- Continuation of the existing network of telephone cable-based transport measurements in the Florida Straits. In addition, newly instrumented lines between the Caribbean Islands and South America should be evaluated and, if successful, maintained.
- Continuation of the present PIRATA surface mooring array, which is of central importance to studies of TAV. The array, and possible additions to it, are discussed below.

Atlantic CLIVAR will depend on a dedicated ocean data assimilation effort, with an emphasis on providing initial conditions for Atlantic climate predictions.

3.1.3 Unique Atlantic CLIVAR requirements

The NAO and the Role of the Stratosphere

Atmospheric GCMs (AGCMs) provide strong evidence that the basic structure of the NAO results from the internal, nonlinear dynamics of the atmosphere. The observed spatial pattern and amplitude of the NAO are well simulated in AGCMs that are forced with fixed climatological annual cycles of solar insolation and SST, as well as fixed atmospheric trace gas composition. Such intrinsic atmospheric variability exhibits little temporal coherence; indeed, the time scales of observed NAO variability do not differ significantly from this reference.

A possible exception is the observed interdecadal NAO variability, especially the strong trend toward the positive index polarity of the oscillation over the past 30 years. Multi-century AGCM experiments like those described above do not reproduce interdecadal changes in the NAO that are of comparable magnitude to the recent trend. At present there is no consensus on the process or processes that most influence the NAO on interdecadal time scales. The NAO may be modulated by changes in tropical and/or extratropical SST distributions, although most evidence suggests that the latter effect is quite small compared to internal atmospheric variability. The equivalent barotropic structure of the NAO that reaches into the stratosphere, coupled with a considerable body of evidence, supports the notion that tropospheric variability can drive variability in the stratosphere. The opposite view less commonly held but with some observational and modeling evidence suggests that the upward trend in the NAO over recent decades is associated with a stronger stratospheric polar vortex, perhaps as a result of reductions in stratospheric ozone and increases in greenhouse gases.

Dynamic coupling of climate variability between the troposphere and stratosphere is mediated primarily by quasi-stationary planetary-scale Rossby waves. Diagnosing such coupled variability requires reliable observations of these waves and their influence on the mean flow. There are significant uncertainties in our knowledge of planetary wave driving from existing atmospheric analyses and reanalyses; stationary wave heat fluxes in the lower stratosphere, calculated from different products, differ by as much as 20 percent. These differences may stem from problems with the data and with the assimilation models. Potential problems with the models include the effects of the model lid, uncertainties in the treatment of gravity wave drag, and errors in the treatment of solar thermal tides. Problems with data aside from scarcity can include biases resulting from the use of different types of radiosondes and aliasing of tidal signals in data from sun-synchronous satellites or once- or twice-daily radiosondes.

Research into climate variability involving the stratosphere requires reliable analyses of stratospheric fields, beginning with the satellite era in the late 1970s, continually updated with current data. Reports that the new US radiosondes have improved penetration of and reliability in the stratosphere up to 10—15 hPa are encouraging.

In addition to a better understanding of the response of the extratropical North Atlantic to changes in tropical and extratropical SST distributions and the role of land processes and sea ice in producing atmospheric variability, US CLIVAR recommends work toward improved analyses of the stratosphere through the following steps:

- Extension of assimilation model domains into the mesosphere, which is required for an accurate depiction of planetary waves throughout the stratosphere.
- Research into the treatment of gravity waves in assimilation models. The deleterious effects of known errors in gravity-wave parameterization schemes are most severe in the stratosphere, where gravity waves are responsible for a significant portion of momentum transport.
- Determination and correction in reanalyses of radiosonde biases.
- Archiving of future data with sufficient temporal resolution to avoid aliasing of the semidiurnal tide. Tides in assimilation models should be validated with high-temporal-resolution data and tidal models.

Tropical Atlantic Variability

Dynamic processes that affect TAV are complex and depend on location and season. Among these processes are remote influences from ENSO and the NAO and land-atmosphere-ocean interactions that are local to the tropical Atlantic. Approximately 25 percent of the total SST variance in the Caribbean region can be explained by Pacific ENSO-related fluctuations. The tropospheric bridge for this remote forcing occurs primarily over the western tropical North Atlantic, through the effects of altered northeasterly trades on evaporative and sensible heat fluxes. On the other hand, SST anomalies in the warm ocean affect atmospheric convection, providing a potential for local air-sea feedback and a source of remote influence to climate variability over the North Atlantic and other regions.

Within the deep tropics there is some evidence that the ocean and atmosphere are coupled via thermodynamic and dynamic feedbacks. The thermodynamic feedback involves wind-induced latent heat fluxes interacting with cross-equatorial SST gradients, whereas the dynamic feedback takes place between trade wind changes and SST anomalies along the equator (akin to ENSO in the Pacific). The former feedback seems to have its strongest manifestation during boreal winter and spring, when positive (negative) tropical North Atlantic SST anomalies often are observed to be associated with northward (southward) anomalies in the cross-equatorial wind field, a northward (southward) displacement of the ITCZ, and a weakening (strengthening) of the northeasterly trade winds. The dynamic feedback occurs mainly during boreal summer and fall, when warm (cold) SST anomalies occur along the equator in association with relaxed (enhanced) trade winds. These anomalies usually are unrelated to conditions in the tropical Pacific.

A comprehensive observing system in the tropical Atlantic is crucial to advance our understanding of the underlying physics of TAV. PIRATA provides a backbone observing system that can be regarded as an Atlantic extension of the Pacific TAO array. Its configuration consists of 12 ATLAS moorings extending along the equator and two meridional lines along 38°W in the tropical North Atlantic and 10°W in the Tropical South Atlantic. This design provides basic equatorial coverage of wind forcing in the western basin and seasonal-to-interannual SST variability in the central and eastern basin, as well as off-equatorial regions of high SST variability in the tropical North and South Atlantic. The variables measured are surface winds, SST, sea surface salinity, air temperature, relative humidity, incoming shortwave radiation, rainfall, subsurface temperature, and salinity. An acoustic Doppler current profiler mooring at 20°W on the equator and two high-resolution XBT lines (AX8 and AX27) will allow for monitoring of current variations in the tropical Atlantic. This observing array should provide basic, direct observations that are required to test the hypotheses for TAV. Thus, US CLIVAR recommends full support for this effort.

There also is a need for enhancements to the observing array in the tropical Atlantic. In particular, there is a pressing need to improve the accuracy of surface flux measurements in critical regions where coupling between the ocean and atmosphere is believed to be strong. A combination of high-quality surface flux measurments from VOS lines (AX8) with a small number of surface flux buoys, which can be successively deployed at optimal sites, is needed.

We recommend establishment of 4 surface flux reference sites in the Atlantic (Figure 2.3). The highest priority for initial deployment is in the tropical Atlantic warm pool (16°N, 54°W and 6°N, 25°W), where a thermodynamic feedback is likely operating; near the Azores (35°N, 35°W); and in the high flux regime inshore of the Gulf Stream (40°N, 70°W).

Tropical western boundary currents are the main pathways for oceanic communication between different latitudes, including cross-equatorial transport. As in the Pacific, the highest priority is to observe the transport of western boundary currents in both hemispheres at relatively low latitudes. As discussed in Section 2.2.4, however, the proven technologies available for this are too expensive for long-term deployment of arrays sufficient to accurately measure these transports. While new technologies are being tested, a feasible approach is proposed.

The 38°W PIRATA should be extended to the South American coast to provide an index of cross-equatorial flow along the western boundar,y and US scientists should contribute to the German mooring array in the North Brazil Current near 8°S to ensure its sufficiency.

Simultaneous information on the western boundary current near the equator, the interior zonal flows along 38°W, and upstream in North Brazil Current near 8°S would help to provide an improved understanding of the role of ocean dynamics in the coupled system.

The Atlantic MOC

The Atlantic portion of the global MOC is distinct from that of the other basins, which leads to some special aspects of required climate research in this sector. Cold water from high northern latitudes in the Arctic and Nordic Seas and from the Labrador Sea is transported southward beneath the mid-latitude and tropical thermoclines to the Southern Ocean. This cold flow is compensated by a northward flow of warm water through the Atlantic. The South Atlantic is unique in that it transports heat equatorward rather than poleward; this transport is greatly enhanced by the surface heat exchange in the tropical Atlantic. The result is a North Atlantic meridional heat transport that is as large as that of the North Pacific in spite of the narrower width of the basin. This heat transport results from a combination of the Atlantic MOC flow intensity, the large temperature difference of the Atlantic MOC warm and cold limbs, and the full water column structure of the Atlantic MOC. The Atlantic MOC delivers a substantial fraction of its heat transport past 50°N another contrast with the North Pacific. The ultimate delivery of that heat to the subpolar and polar atmosphere represents the unique role of the Atlantic MOC in higher latitude climate and is the forcing for the transformation of warm water to cold.

Changes in the MOC have been associated with and may be critical to long-lived climate shifts of the past. These shifts sometimes have been rapid, occurring in decades but leaving altered climatic states that persist for millennia. The sensitivity of the Arctic, Nordic, and Labrador Seas cold-water formation sites to surface flux fluctuations is thought to underlie abrupt change in MOC and, potentially, the overlying atmospheric state (e.g., the shutdown of the MOC by freshwater anomalies suppressing convection or a change of wind or buoyancy forcing limiting the intergyre flow of warm water).

The warm limb of the Atlantic MOC involves upper-ocean gyres and intergyre exchanges; thus, it shares many observing system design and dynamics issues with the rest of the global ocean including a network of high-resolution XBT lines (see Figure 2.2). Because of the sensitivity of the global MOC to North Atlantic warm-to-cold water transformation and the involvement of cold limb flow by a system of Deep Western Boundary Currents (DWBC), however, some unique systems and studies are required in the Atlantic. In particular, two aspects of the MOC are important for Atlantic CLIVAR: The first is the relationship between the MOC and the NAO, and the second is the ability to assess rapid shifts in the MOC that might presage longer-term climate variability.

As outlined in Section 2.2.4, the strategy is to supplement distributed measurement systems with an internationally funded array of fixed-point time series hydrographic stations at critical locations and a set of repeat-sampled hydrographic sections across key circulation elements.
As part of the international effort on carbon sequestration in the ocean, a tentative array of hydrographic sections to be reoccupied on 5- to 10-year intervals is being planned.

In collaboration with this carbon effort, US CLIVAR recommends that the United States should maintain two repeated zonal trans-ocean hydrographic lines near 16°N and 30°S and two meridional hydrographic lines along 65°W and 50°W (see Figure 2.3).

Although the integrated zonal sections provide a picture of the vertical structure of the MOC, this structure masks the fact that most of the cold-water return is concentrated in the western Atlantic. For this reason, we propose the two meridional lines.

To observe changes in the MOC, monitoring of changing hydrographic properties in the main water-mass transformation sites of the subpolar North Atlantic and in the western subtropical gyre is desirable as a US contribution to the international array of time-series hydrographic stations.

We recommend continued US support for the international effort at station Bravo in the central Labrador Sea and continuation and modernization of the station at Bermuda.

Moored hydrographic time series stations also provide a limited measure of circulation because pairs of stations yield net baroclinic transport between them. Although these time series data are not as complete or accurate as repeated hydrographic stations, they also track changing water properties. On the basis of transport pathways and key sites for water mass properties, two sites have the highest priority for this type of measurement.

We recommend installation of two moored hydrographic stations: one inshore of the Gulf Stream near 40°N, 70°W and one near Abacco (27°N, 77°W) (see Figure 2.3).

None of the foregoing observations can track climate variability of western boundary currents. The mass and heat transports of these currents play a critical role in the MOC, so our inability to affordably monitor them is a limitation to our understanding. Progress in understanding the role of western boundary currents in MOC variability depends on the development of new, cost-effective technologies and methodologies (see Section 2.2.4).

Freshwater and Heat Exchange with the Arctic

A key requirement of Atlantic CLIVAR is monitoring of the freshwater and heat exchange with the Arctic Ocean. Principal freshwater sources for the Arctic are river discharge and the import of low-salinity water through the Bering Strait. Major freshwater outflows are through the Fram Strait, largely in the form of sea ice, and the Canadian Arctic Archipelago (CAA). Warm, salty Atlantic water enters the Arctic Ocean through the Fram Strait and across the Barents Sea shelf.

Within ice-covered sectors of the Fram Strait and Davis Strait, for instance, moored arrays with upward-looking sonar are needed to measure ice drift and monitor temperature, salinity, and water velocity. Point data from such arrays will be complemented with estimates of ice velocity and mass flux from remote sensing.

Two technical problems are common to measurements of fluxes in the far North Atlantic. One is measurement of ocean properties in the surface waters of an ice-covered area. Much of the lateral freshwater flux occurs there, but instruments that are fixed at shallow depth are destroyed by thick ice. Anticipated solutions are profiling instruments or specially reinforced sensors. The other challenge is to obtain repeated hydrographic sections at adequate resolutions. We hope that new, automated profiling floats and gliders will be able to make such sections repeatedly over long periods of time, at least in the only partially ice covered regions.

US CLIVAR recommends close coordination with emerging international plans such as the Arctic-subarctic ocean flux array (ASOF) program presently funded though individual grants, predominantly in Europe.

3.1.4 Regional and Process Studies

Several process experiments and regional studies probably will be needed to fully understand Atlantic climate variability. There are special regions where ocean-atmosphere-land coupling seems to be high, where interactions between ocean basins are not well quantified, and where key mixing processes are not well understood. Basin-wide observations will not be adequate to address these uncertainties.

In the ACVE Prospectus and Plan, the community has initially expressed interest in three regions: air-sea interactions along the North Atlantic Storm Track; atmosphere, ocean, and land interactions between the tropical North Atlantic and the Amazon; and freshwater fluxes between the North Atlantic and Arctic Oceans. These studies, which do not exclude other possible studies, are expected to be investigator planned, as outlined at the beginning of Section 3. They will be reviewed by the Atlantic Sector Implementation Panel and the US CLIVAR SSC for their potential to improve overall understanding, parameterization, and treatment of key processes in predictive climate models. Special attention will be paid to readiness to accomplish the goals, as well as to cost-effectiveness.

3.2 Pacific Sector

Coupled atmosphere/ocean processes across the Pacific Ocean region exhibit perhaps the most pronounced interannual-to-decadal variability anywhere on earth, and their influences on climate encompass much of the globe and affect much of its human population. A basic understanding of ENSO has been developed, which has led to routine ENSO forecasts with useful skill at ranges approaching one year. Many aspects of ENSO still are not well understood, however, including its decadal modulation. Our understanding of coupled decadal variability in the Pacific sector and its predictability is rudimentary. Several plausible theories invoke very different atmospheric, oceanic, and coupled mechanisms. However, we lack long and comprehensive data records, particularly from the ocean, to test these theories or quantify many of the pathways and processes that regulate transport and exchanges of heat and freshwater in the coupled system. For example, our understanding of atmospheric processes such as deep convection and ocean processes such as diapycnal mixing must improve if we are to rely on the predictions of coupled models. More complete discussions of the hypotheses and dynamic issues with climate variability in the Pacific sector appear in the PBECS Prospectus and Plan; we only summarize those discussions here.

Accurate predictions of the effects of the 1997—98 El Niño demonstrated that we have achieved significant skill in forecasting the evolution of the tropical Pacific and its extratropical teleconnections at least six months ahead, especially once a warm event has begun. By the first months of 1997 (when strong westerly winds were first observed in the western equatorial Pacific), several models were suggesting that a moderate or larger El Niño was developing and would grow through the rest of the year. By mid-1997, models were forecasting the evolution over the next six months quite realistically. This ability is a clear application of the successes made possible by a concentrated effort that combines long-term observations, modeling, and assimilation techniques. At the same time, much before the initiating winds, even the best models had only a slight ability to forecast the onset of the 1997 event, and none predicted the extremely large amplitude it would reach. For situations less dramatic than the growth stage of a major El Niño, our skill at predicting the smaller variations of tropical Pacific SST remains relatively weak. Although many models simulate the growth, propagation, and maintenance of El Niños, the dynamic and thermodynamic balances among upwelling, zonal advection, meridional advection, diapycnal mixing, and air-sea heat fluxes that these models display are different. Even the role of the equatorial waves so prominently observed in sea level and thermocline depth is uncertain. We do not have a clear understanding or description of what an El Niño precursor state looks like. Therefore, the fact that models failed to predict the extreme amplitude reached by the 1997—98 event is not surprising. Similarly, although some El Niños have quickly reversed into a strong La Niña state (e.g., 1986—87 evolving into the 1988 La Niña), others have not (e.g., 1991—92) and we do not understand the conditions that govern these changes.

Although scientists have known for 30 years that the ENSO cycle is a coupled phenomenon, the details of the coupling mechanisms are poorly observed. Equatorial surface zonal winds are very sensitive to the zonal SST gradient, and these winds in turn modulate the thermocline depth, which is a major influence on SST through upwelling that brings thermocline water in contact with the surface layer. SST cooling through upwelling is determined by vertical mixing in a region of strong shears and property gradients, however, so the efficiency of upwelling-induced cooling is an extremely complex interaction of many processes that are difficult to observe or diagnose. Further complicating the observational picture is the existence of large-amplitude variability on short time scales, such as ubiquitous tropical instability waves. Modeling these processes also has been challenging because the above-thermocline layer can be quite thin relative to the vertical resolution of most basin-scale models, so vertical exchanges often are parameterized rather crudely. The CLIVAR strategy for resolving these issues is a program of continued model experimentation and improvement (see Section 2.3.1) coupled with a significantly improved observing system including short-term, intensive observational studies to examine the processes that bring thermocline-level water to the surface. The aim is a data assimilation synthesis that would accurately represent the effects of the complex mix of processes that change equatorial SST and thereby foster ocean-atmosphere coupling.

Just as predicting individual El Niño events is important, the envelope of ENSO activity has societal impacts. ENSO has varied greatly on decadal time scales. Many hypotheses have been proposed to explain this variability, including the effects of (ocean-reddened) atmospheric noise or nonlinearity in ENSO itself (for example, how oceanic modifications by one El Niño affect the next event). Many models suggest that the background state of the equatorial thermocline is a key factor in determining the nature of an El Niño event because it is such a strong influence on the efficiency of upwelling to cool SST. Observations show that the slope of the equatorial thermocline is linearly related to the equatorial zonal wind on time scales of a few months, although its zonal mean depth is not clearly connected to equatorial wind forcing. Instead, changes of mean thermocline depth may be caused by winds on larger meridional scales (the entire tropics) that change the net Ekman divergence from the tropics and thereby produce a general shoaling or deepening in the upwelling region on slower time scales. This process is one possible mechanism by which events outside the tropics can have an effect on the decadal envelope of the ENSO cycle.

Other theories backed by some suggestive observations and model runs argue that the characteristics of the water in the equatorial thermocline are determined by air-sea interaction in the southeast and northeast subtropics, where the water is subducted into the thermocline. These properties are carried by the geostrophic circulation, usually via low-latitude western boundary currents, to the equator, where they are upwelled. If there is substantial variability influencing the characteristics of the subducted water, and if these characteristics survive the 10-year or so advective pathway, they may modulate the properties of the upwelled water and affect the slow evolution of the ENSO cycle. Finally, weak signatures of mid-latitude decadal wind anomalies reaching down into the tropics may have their tropical effects magnified by the sensitivity of equatorial SST gradient-zonal wind feedbacks. The CLIVAR strategy for understanding decadal modulation of ENSO and its potential predictability involves improving analyses of basin-scale fields so that the slow evolution (including property advection) can be viewed as a whole. This goal will be achieved through major enhancements to the observational database that is available to be assimilated into models (especially ARGO profiles; see Section 2.2.4), specific enhancements such as monitoring of western boundary currents and equatorial Ekman divergence (see Section 3.2.4), and improvements to the wind forcing of the assimilating models as scatterometer records lengthen.

The Pacific sector also experiences significant decadal variability in mid-latitudes, the persistence of which contributes to the skill of operational climate predictions for North America. The PDO is a complex of phenomena, including very broadscale wind and SST anomalies, that comprises the most energetic low-frequency mode seen in the few long oceanic time series around the basin and has important effects on salmon fisheries and decadal variations of snowpack in the Pacific Northwest. The spatial patterns of the PDO resemble those of ENSO (see Figure 3.2). One interpretation is that the PDO is simply the low-frequency modulation of the ENSO cycle, which is spatially broadened because lower frequency Rossby waves have wider meridional scales.

Some coupled GCMs develop a fully coupled mid-latitude basin mode, however, in which the key process is variation of heat transport by the Kuroshio that feed back to modify the wind-stress curl that produces the subtropical gyre. In these experiments, the time scale of the oscillation is set by the transit time of Rossby waves (driven by the wind-stress curl) that set up the Kuroshio (about 20 years). A difficulty with this hypothesis is that many AGCMs suggest that the mid-latitude atmosphere is not sensitive to mid-latitude SST, which implies that the key feedback would not occur. Resolving this issue is a subject of current research; some observations appear to show that the sensitivity resides in the response at synoptic time and space scales in the Pacific storm track, which at present are not well resolved.

Other hypotheses for decadal variability in the North Pacific point to strong air-sea heat exchange in the Kuroshio Extension region, where cold dry continental air flows out over the relatively warm water of the Kuroshio. If the oceanic heat transport or the patterns of winter outflow vary, the change in heat flux could be substantial. Finally, some studies support the point of view that the PDO cannot be statistically distinguished from simple oceanic reddening of atmospheric noise; as in other regions, the shortness of the instrumental record relative to the decadal periods of interest makes statistical confidence difficult to obtain. Because the 15 years of CLIVAR will not lengthen the observed record sufficiently to produce unambiguous statistical confidence, the strategy instead is to gather observations and to test and improve the models to be able to evaluate physical hypotheses.

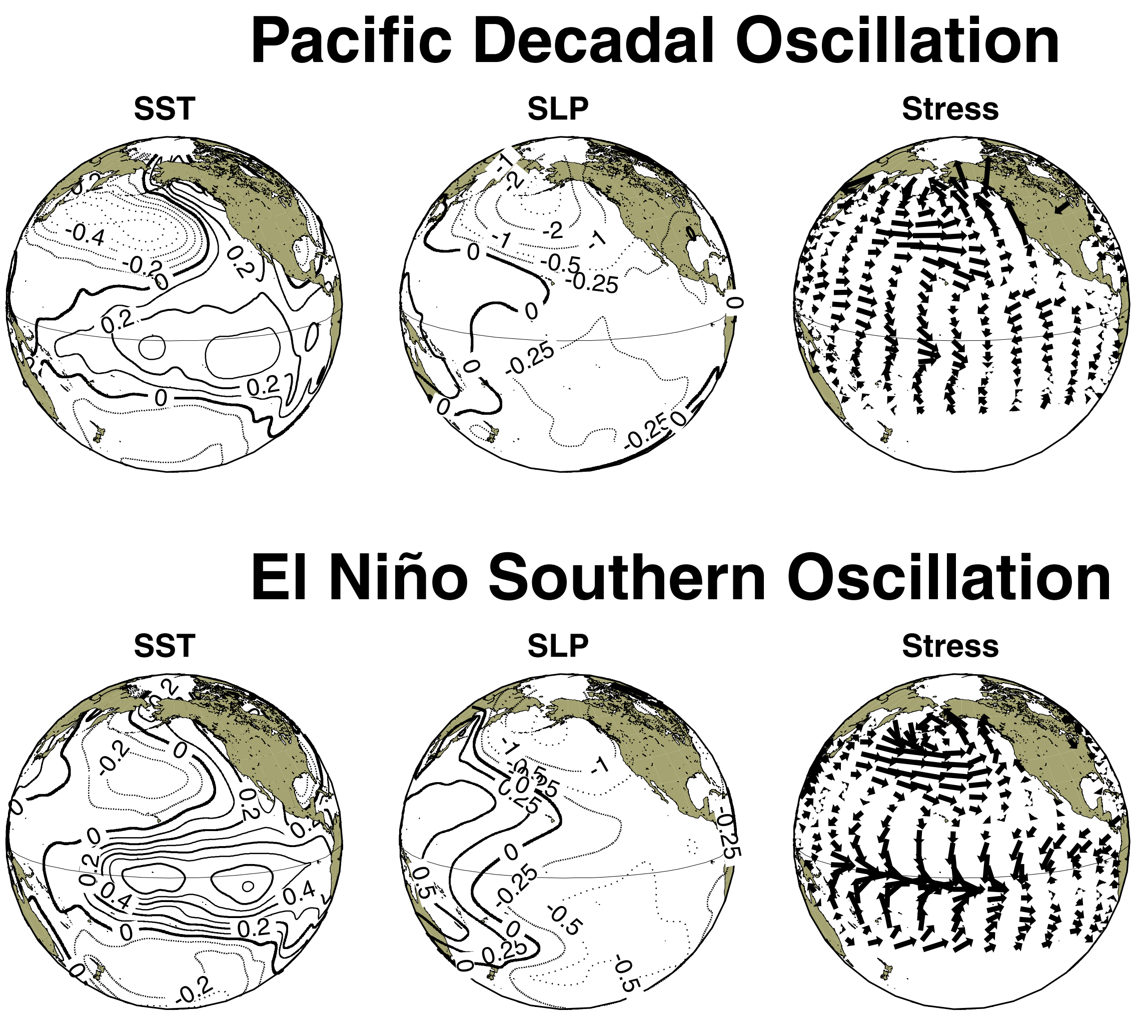

Figure 3.2. Patterns of sea-surface temperature (SST), sea-level pressure (SLP), and wind stress associated with the PDO (upper) and with ENSO (lower), from Mantua et al. (1997).

Central to the implementation of Pacific CLIVAR is collection of a comprehensive three-dimensional set of observations of the entire upper Pacific Ocean including its boundary currents and air-sea fluxes as well as the overlying atmosphere, over a period of 15 years. Also central to implementation is the use of data-assimilation modeling to quantitatively diagnose the mechanisms involved in climate variability. To date, the decadal modulation of ENSO, the dynamics of ENSO, and decadal variability in the Pacific Basin have been identified as Pacific climate phenomena of immediate interest; implementation plans have been driven largely by the desire to better understand these phenomena. In considering these phenomena, Pacific CLIVAR must be able to observe the variability of the upper 1500—2000 m of the ocean and overlying atmosphere, resolve transport pathways, and clarify the causal relationships associated with the observed variability.

Much of the sampling required will be provided by broad, basin-scale sampling. Within the Pacific basin, there will be some unique elements of the observing system; in addition, specific regions that are important to climate variability must be addressed with more complete observations than those of the global program. Finally, process studies of shorter duration are anticipated that will strengthen our understanding of important physical processes such as upwelling, mixing, cloud feedbacks, and deep convection.

3.2.1 Goals of Pacific CLIVAR

The long-term goals of Pacific CLIVAR are as follows:

- Better understand Pacific basin-scale atmosphere-ocean variability, its predictability on seasonal and longer time scales, and anthropogenic impacts, with particular attention to ENSO and its decadal variability and to the PDO.
  - Document time-varying temperature, salinity, and currents in the upper ocean at 300 km, 10-day resolution over the entire Pacific basin north of 40ºS for a 15-year period, with higher resolution in boundary currents and near the equator. Use an ocean data assimilation model to provide a three-dimensional, time-dependent gridded analysis of this data.
  - Document time-varying vertical and lateral fluxes and air-sea exchanges of heat, freshwater, and momentum over 15 years, not only on the basin scale but also with good spatial resolution in the boundary and equatorial regions of the Pacific basin.
  - Document the variability of the atmosphere over the Pacific over 15 years, with resolution of synoptic weather events and the vertical structure of the lower atmosphere, to improve the accuracy of the specification and our understanding of air-sea coupling and to examine the role of episodic forcing events.
- Improve physical parameterizations in OGCMs, AGCMs, and NWP models used to simulate the Pacific through the use of process studies and by using ocean data assimilation to identify apparent systematic errors in the atmospheric forcing of the ocean or the assimilating ocean model.

Existing and new CLIVAR-supported global observations, as well as empirical and modeling studies, provide the context for Pacific CLIVAR and are key to implementing it. In addition, the scientific and coupled modeling issues that are at the heart of Pacific CLIVAR are being studied. The strategy will be to integrate these efforts and add supplemental observations and studies to understand climate variability in the Pacific sector. These supplemental efforts will include broad-scale sampling, fielding of regionally focused programs that are unique to the Pacific, and conducting process studies to address shortcomings in understanding and parameterization. All elements will be brought together in the framework of assimilative modeling. Comprehensive analysis, testing, and improvement of coupled models are anticipated.

This effort will require modelers, analysts, and data gatherers to work together. An annual meeting will be held to build the desired interactions. This meeting will have the goals of attracting and fostering interaction with the broad community of scientists working on Pacific climate variability and showcasing Pacific CLIVAR data sets. In conjunction with these meetings, Pacific CLIVAR will develop a modeling interface aimed at promoting analysis of decadal variability in coupled models and improving physical parameterizations in AGCMs and OGCMs.

3.2.2 Sustained Observations—Pacific Basin Extended Climate Study

PBECS which is described at length in the PBECS Plan is a long-term (2001—2015) study of the main climate phenomena of the entire Pacific basin, including ENSO, ENSO s decadal modulation, and the PDO. Its foundation is a collection of basin-wide observing components, selected time series and regional arrays to define critical climate elements, and a program of data assimilation intended to synthesize these observations and provide a framework for testing models and hypotheses about climate dynamics. The main components of PBECS are as follows:

- *ARGO.* An array of temperature and salinity profiling floats on a 3° grid extending from the Aleutian Islands to 40°S is central to PBECS goals.
- *High-resolution XBT.* PBECS depends on continuation of the existing Pacific VOS-based high-resolution XBT/XCTD shown in Figure 2.2 and implementation of the two new north-south lines (PX4 and PX21). A significant fraction of these lines also should support upgraded surface meteorology and flux observations.
- *Assimilation.* An ocean data assimilation effort with adequate computing and staffing resources is important to syntheses of all PBECS data and to test dynamic hypotheses.
- *TAO/TRITON.* The present TAO/TRITON array of wind and subsurface temperature measurements should be maintained to the high temporal resolution needed in the equatorial region. Moorings with current observations along two meridional TAO lines should be added to describe the Ekman limb of the shallow overturning circulation. The possibility of adding near-surface salinity observations to TAO is under study.
- *ENSO Observing System.* Drifter observations of surface circulation and SST, tide gauges, and (until ARGO is at full strength) broad-scale VOS XBT sampling should be continued.
- *Flux reference moorings.* Two to four moored surface buoys providing time series of surface fluxes and meteorology as well as subsurface temperature, salinity, and horizontal velocity are needed in regions of special interest, including the Kuroshio Extension, Ocean Station P (50ºN, 145ºW), the central North Pacific (a PMEL mooring is at 35ºN, 165ºW), off the west coast of North America (perhaps in coordination with other coastal weather or marine ecology studies), and the stratus region off the west coast of South America (a NOAA-funded buoy is at 20ºS, 85ºW). These moorings will contribute to the international network of surface-flux reference sites and ocean time-series stations.
- *Ocean time series.* At select locations, the United States should maintain long time series of oceanic variability over the water column. The Hawaii Ocean Time series (HOT) is a unique, multidisciplinary time series station off Hawaii that is gathering ocean thermodynamic profiles and a variety of biological and chemical measurements. It is an important element in the Pacific of the growing intersection of interest between CLIVAR and the national ocean carbon program. At other locations, moorings, autonomous vehicles, or frequent occupation by a ship may be used to observe the temporal variability and vertical structure of temperature and salinity variability, currents and transports, and biological and chemical quantities. Siting of these time-series stations is under discussion with international partners.
- *Enhanced atmospheric monitoring.* Many radiosonde and profiler sites around the Pacific basin that nominally take soundings at least daily apparently are not getting soundings into the operational data stream on a regular basis. Pacific CLIVAR priorities will be to facilitate timely communication of all available upper-air data; to reinstate radiosonde launches at Galapagos, Midway, Wake Islands, and at least one radiosonde site in the Line Islands (2—6°N, 157—162°W), which provide a unique natural cross-section across the central Pacific ITCZ; and to implement regular GPS-sonde sampling from the TAO deployment cruises and investigate the feasibility of deploying radiosondes from high-resolution VOS lines.
- *Repeated hydrography.* Two zonal and two meridional hydrographic lines should be occupied every 6—10 years. Present planning with the international carbon program is for lines along 30ºN, 32ºS, 110ºW in the South Pacific, and 150ºW in the North Pacific.
- *Western boundary currents.* Time series of heat and mass transport are needed in key western boundary currents implicated in decadal variability, especially the PDO, and decadal modulation of ENSO. Beginning regular measurement of the Mindanao Current and New Guinea Coastal Undercurrent both of which are sources of water that form the equatorial

thermocline and are potentially important to decadal modulation of ENSO is critical. Effective technologies and methods for this measurement have not been identified; work to develop these methods is needed. The boundary currents off Japan, Taiwan, and eastern Australia are monitored by high-resolution VOS/XBT sections, but the frequency of sampling should be increased.

The duration and comprehensive nature of PBECS which includes atmospheric, oceanic, and coupled studies that use modeling, empirical, and observational approaches dictates continuing oversight, evaluation, and guidance of the program. Thus, PBECS will be planned nationally by the Pacific Sector Implementation Panel, which also will participate in international CLIVAR Pacific implementation meetings to review and coordinate activities within PBECS.

3.2.3 Other Regional and Process Studies

We envision several process experiments and regional studies that will be required to meet the program s goals. Regional studies are appropriate in places where a combination of processes is of particular climate interest and the foregoing basin-wide observations may not be adequate to define the phenomena. The cold tongue ITCZ and stratocumulus cloud deck regions of the eastern Pacific, the bifurcation of the North Equatorial Current at the western boundary, and the Kuroshio Extension are special regions that may warrant regional studies. Process studies focus on a specific phenomenon that is important in more than one region. The dynamics of stratus clouds and convection, oceanic mixing, low-level jets, and equatorial upwelling are potential subjects of process experiments.

Examples of regions and processes that are candidates for special studies are discussed below. In some cases, CLIVAR may augment or approve studies that already are planned. In others, a general need for further study has been identified, but no plans have been developed.

The Eastern Pacific

Coupled model studies show the sensitivity of the coupled climate system to stratus clouds in the eastern Pacific. The strong meridional SST gradients between the eastern Pacific cold tongue and the warm pool to its north, and the intertropical convergence zone in the atmosphere above, in part reflect strong local coupling. There is evidence of organization of SST anomalies on a space scale that is comparable to the width of the basin and on time scales that are longer than the characteristic thermal damping time of the mixed layer. Coupled model simulations of SST in the western hemisphere warm pool, which extends from the eastern Pacific waters off Central America to the Gulf of Mexico, do not have the desired quantitative accuracy.

Smaller-scale regional variability escapes the resolution of basin-scale OGCMs but may be significant in the upper ocean heat, mass, and momentum budgets. For example, over the eastern Pacific, the region up to a few hundred kilometers off Central America generally is very warm but can cool rapidly in response to winter northerlies blowing through gaps in the American cordillera. South of the equator, the annual coastal upwelling signal has been cited as important for the development of much larger-scale phenomena, but the processes by which the narrow coastal features might influence the larger scale have not yet been clearly elucidated. Present basin-scale OGCMs handle these near-coastal signals poorly. The question of closure of the equatorial and tropical current systems in the east Pacific particularly the fate of water flowing eastward in the

North Equatorial Countercurrent and Equatorial Undercurrent is obscure. To date, these currents have been understood only as features of the broad central Pacific, far from boundaries. Similarly, the source of water upwelled in the equatorial cold tongue, the depth from which it originates, and the meridional extent of the upwelling cell have not yet been established, nor has the upwelling water been traced back to the surface in extratropical regions, as theory has suggested. Questions about the closure of current systems in the east Pacific speak to the most fundamental aspects of the ocean circulation; they will become tractable as the community develops confidence in the performance of OGCMs in the tropical eastern Pacific.

The Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC) is a process study to improve the description and understanding of processes that are responsible for the structure and variability of the extensive boundary-layer cloud decks in the southeastern Pacific. The results of EPIC are expected to improve the performance of coupled ocean-atmosphere models over the eastern Pacific and result in improved short-term climate analysis and prediction system for the Pan American region. The scientific objectives of EPIC are as follows:

- To observe and understand the ocean-atmosphere processes that are responsible for the structure and evolution of large-scale heating gradients in the equatorial and northeastern Pacific portions of the cold-tongue/ITCZ complex (CTIC)
- To observe and understand the dynamic, radiative, and microphysical properties of the extensive boundary-layer cloud decks in the southeasterly tradewind and cross-equatorial flow regime; their interactions with the ocean below; and the evolution of the upper ocean under the stratus decks.

Descriptive and diagnostic studies of the oceanic and atmospheric boundary-layer structure and interfacial fluxes in the CTIC provide a large-scale context for process-oriented field studies in EPIC. CTIC studies were conducted in the equatorial Pacific at 125ºW during 1997. Enhanced monitoring of the CTIC in the monsoon regime further to the east continues some elements from the pilot studies, initiates new elements, and provides spatial and temporal context for future EPIC activities.

While US CLIVAR was being organized, a group of investigators set out a plan for EPIC (see EPIC Scientific Steering Committee 1999) and its first field phase. EPIC 2001 is a one-month intensive observational examination of the CTIC, with an exploratory stratus deck component (see Raymond et al. 1999). US CLIVAR seeks to accelerate progress in improving simulations of the CTIC and the stratocumulus regime through informal groups of EPIC observers and modelers who will synthesize results from EPIC enhanced monitoring and intensive observations.

A second phase of EPIC is being planned as a process experiment to concentrate on interactions between the marine boundary layer and South America on a variety of time scales. EPIC Phase II (2003—2005) will be a larger international study and an element of VAMOS within international CLIVAR. Because of its international nature and potential scope, the Pacific and Pan American panels will nationally plan this second phase of EPIC. The scientific goal is to look at possible covariations and feedbacks involving stratus clouds and boundary layer properties with deep convection over the South American continent. Deep convection over South America might affect the stratus by modulating compensating subsidence and/or free-tropospheric humidity and temperature. If this process affects radiative cooling within the PBL, it also would affect the strength of the subtropical high, near-coastal winds and coastal upwelling, which on longer time scales might feed back on the convection. Diurnal through synoptic time scales of variability could be addressed in such an experiment. South American countries may provide considerable support, with San Felix Island off Chile and ships measuring horizontal divergence and cloud/boundary layer structure. Coastal and mountain stations could help quantify the role of orography and the links between land and ocean. More preliminary study is needed to identify whether the stratus-convection link is clear enough to be of major climate importance.

Western Boundary Currents

Western boundary currents have been identified as of high interest within the Pacific sector. Transport variations in the East Australia and Kuroshio Currents play critical roles in some theories of decadal variability by modulating heat transport to mid-latitude storm-track regions. Present high-resolution XBT sections traverse each of these currents at two latitudes, but the low frequency, limited depth, and lack of direct velocity of observations limit their use for climate purposes. We hope that scientists from Japan, Taiwan, and China will continue to measure the Kuroshio at low latitudes.

The Indonesian Throughflow is the main conduit between the tropical Pacific and Indian Oceans. The climate requirements for monitoring it can be met with the US-Australian high-resolution XBT section; we recommend continuing support for this effort.

Tropical western boundary currents in the Pacific are poorly known, but limited evidence suggests that they fluctuate significantly on short time scales and are important conduits between the equator where ocean-atmosphere coupling is direct and subtropical regions, where water properties are determined by air-sea interaction. Thus, these boundary currents are key in the study of decadal modulation of ENSO and decadal variability. Time series of mass, heat, and (ideally) salinity transport in the Mindanao Current and the New Guinea Coastal Undercurrent are needed to examine the importance of their variability to equatorial air-sea interaction. New technology and methodology, and perhaps a regional or process study, will be needed to develop cost-effective ways to monitor these currents.

Planning for sampling of the mid-latitude Kuroshio is further along because of pioneering work by Japanese oceanographers and the Kuroshio Extension System Study (KESS), a joint project of the United States and Japan. The design of KESS (summarized in the PBECS Plan) predates US CLIVAR planning, but its goal of clarifying how SST anomalies in the Kuroshio-Oyashio outflow region are created makes it an important contribution to CLIVAR. KESS is a five-year project that includes high-resolution subsurface velocity, temperature, and salinity measurements, as well as remote sensing and perhaps a Japanese TRITON buoy now being tested in the region. The focus is on variability of the western boundary current inflow, eddy-mean interaction, recirculation dynamics, and cross-frontal exchange. KESS will examine the upper-ocean heat budget by assimilating *in situ* and satellite observations into an ocean circulation model. Accurate regional forcing estimates are needed, and the addition of *in situ* meteorological buoys to serve as references for NCEP or other surface fields would greatly improve our ability to describe the upper-layer heat budget. Because KESS aims to elucidate important climate processes in the complex Kuroshio Extension region and because it is providing the information needed to design an affordable monitoring system, US CLIVAR should consider, in cooperation with Japanese scientists, augmentations to KESS that would significantly increase its utility for climate studies.

Because of the potential importance of the western boundary currents to coupled ocean-atmosphere interaction and tropical-extratropical pathways, interest in the Kuroshio extension region is likely to continue beyond KESS. A CLIVAR regional climate study in this area may be in order.

Equatorial Upwelling

Equatorial upwelling is a central process in determining the SST variability in ENSO and perhaps decadal variability. Despite its importance, we have no direct measurements that allow us to know the mass and heat transports associated with equatorial upwelling, nor has there been a process experiment focused on upwelling dynamics. Sustained observations of the volume and temperature/salinity variability of water upwelled at the equator are needed to enable us to understand the relative roles of local winds and remotely driven changes in thermocline structure in determining equatorial SST variability. We do not know how to carry out this monitoring over the 15 years of CLIVAR. A process experiment focusing on equatorial upwelling would allow examination of parameterizations and model performance for processes associated with upwelling; it also could provide information with which to design a sustained observing system for equatorial upwelling. Pacific CLIVAR will encourage process studies that do this.

We recommend a pilot study focusing on quantifying equatorial upwelling and developing the means to monitor it.

Process Studies

We anticipate that during CLIVAR, investigators or groups of investigators will organize field and modeling studies aimed at better understanding the physics of the ocean and atmosphere and improving physical parameterizations of processes in OGCMs, AGCMs, and NWP models used to simulate the Pacific.

3.2.5 Supporting Studies

The Pacific CLIVAR research program also will be helped by insights and data derived from many other upcoming programs. A few salient examples:

- *The Consortium for Ocean Research and Climate (CORC).* CORC is a long-term ocean-observation program in the central and eastern tropical Pacific. CORC focuses on the cold tongue, upwelling, and other branches of the shallow overturning circulation that are implicated by some theories in modulating the evolution of ENSO. Data assimilation modeling will be used to synthesize and maximize the value of the observations. Surface drifters focus on surface currents and heat advection with additional surface meteorology measurements. The VOS program includes basin-wide high-resolution XBT/XCTD sections (lines PX50 and PX51 in Figure 2.2 are now maintained, and PX5 will be added in 2001) and upgraded meteorology (IMET) packages to provide high-quality surface meteorological observations as reference for routine observations and analyzed flux fields. Until ARGO is online, an array of approximately 30 profiling floats is being maintained to supplement and extend TAO observations east of the dateline and to support EPIC. New technologies (an underway CTD and underwater gliders) are being explored for routine use. CORC predates US CLIVAR planning, but the commonality of their objectives and techniques suggests that closer coordination is desirable.
- *TRMM and future NASA projects.* The TRMM satellite should provide high-resolution swath observations of rainfall over the tropics and subtropics through at least 2003, improving our

understanding of tropical convection and precipitation distribution. Further space-based precipitation radars (and the CLOUDSAT/PICASSO-CENA mm-wave radar and lidar combination for active cloud remote sensing) are being planned.

- *The Hemispheric Observing System Research and Prediction Experiment (THORPEX).* Pacific CLIVAR also may benefit from observations and observing system simulations from THORPEX, which is coordinated by USWRP. THORPEX will start in 2001, with a major field phase in 2003—2005; it will include a variety of supplemental surface and upper-air observations over the North Pacific Ocean. Depending on results from THORPEX, some of this operational enhancement of the atmospheric observational network over the North Pacific may become permanent.
- *The Global Air-Ocean* In Situ *System (GAINS).* GAINS is being proposed to WMO and national funding agencies as a 50-year international program utilizing balloons drifting in the stratosphere as platforms for deploying dropsondes over remote oceanic locations. A pilot study is proposed for 2003.

3.2.6 Coordination

Pacific CLIVAR depends on a blend of sustained observations synthesized within simple and complex models; a range of process and regional field studies; empirical analyses; and studies that use a spectrum of models, from simple to complex. There also are many non-CLIVAR programs contributing to and benefiting from US CLIVAR activities in the Pacific.

To ensure coordination of CLIVAR Pacific and facilitate rapid dissemination of research results, we recommend an annual meeting focusing on climate-related topics in the Pacific.

3.3 PAN AMERICAN SECTOR

The season-to-season memory of the coupled ocean-atmosphere-land system resides in the processes that determine the slowly evolving and potentially predictable changes at the earth s surface: SST fields, soil moisture, snow cover, and vegetation. SST in the Atlantic and Pacific Oceans is known to determine a great deal of climate variability over the tropical Americas, and it affects the wintertime climate at middle and high latitudes. Predictability of seasonal rainfall has been demonstrated, and seasonal predictions with modest skill up to a year in advance are issued routinely by the US National Centers for Environmental Prediction and other organizations. Warm-season precipitation is not yet predictable, however. In particular, the relative contributions of SST and land surface processes in shaping the annual march of the Pan American monsoons and the evolution of warm-season rainfall anomalies are not well understood.

US CLIVAR Pan American research will focus on the phenomena that are crucial for organizing seasonal rainfall patterns: monsoons, the oceanic ITCZs, and the tropical and extratropical storm track. It will emphasize the contribution of land surface processes to warm-season climate variability.

Regional rainfall anomalies over the Americas involve intensification, weakening, or subtle displacements in the positions of these seasonally varying, climatological-mean features. The climate processes addressed by the research have significant economic benefits and are the same as those involved in assessing the effects of anthropogenic climate change.

3.3.1 Goals of Pan American Research

US CLIVAR Pan American research has three specific objectives:

- Promote better understanding of and more realistic simulation of coupled ocean-atmosphere-land processes, with emphasis on
    - the response of planetary-scale atmospheric circulation and precipitation patterns to potentially predictable surface boundary conditions such as SST, soil moisture, and vegetation;
    - mechanisms that couple climate variability over ocean and land;
    - the seasonally varying climatological mean state of the ocean, atmosphere, and land surface; and
    - the effects of land surface processes and orography on the variability of seasonal rainfall patterns.
- Determine the predictability of warm-season precipitation anomalies over the Americas on seasonal and longer time scales.
- Advance the development of the climate observing and prediction system for seasonal and longer time scales.

3.3.2 Strategy

US CLIVAR Pan American research necessarily encompasses a broad range of activities. Empirical and modeling studies, as well as the development and analysis of historical data sets, will contribute to better understanding and simulation of the phenomena that control the annual march of seasonal rainfall patterns and their variability on seasonal-to-decadal time scales. US CLIVAR will make a major contribution to improving the climate observing system in the oceans and seas adjacent to the Americas; it will collaborate with CLIVAR VAMOS and with national and international agencies and organizations to improve the quality and coverage of atmospheric climate observations. Three field programs the North American Monsoon Experiment (NAME), the Monsoon Experiment South America (MESA), and EPIC (see Section 3.2.4) will improve our understanding of key climate processes that are hindering advances in climate simulation and prediction over the Americas.

Informal groups of observers and theoreticians will work together to understand and simulate key phenomena and processes and hence to accelerate progress.

US CLIVAR and GEWEX are complementary programs in the Pan American region. US CLIVAR emphasizes the planetary-scale context and variability of the weather systems that produce rain on seasonal and longer time scales; GEWEX emphasizes land-atmosphere interaction on intraseasonal-to-interannual time scales. Mesoscale modeling of continental and oceanic precipitation in a climate context is a common element of both programs. US GEWEX projects focus on North American rainfall, and the Brazil/NASA-led Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA) hydrometeorology program focuses on rainfall in the Amazon basin. A NOAA PACS/GCIP research initiative focuses on the seasonal-to-interannual variability of warm-season rainfall, surface air temperature, and the hydrologic cycle over North America.

NAME and MESA will be developed jointly with GEWEX and will collaborate with CLIVAR-SIMAP, GEWEX-GLASS, and International Satellite Land Surface Climatology Project (ISLSC- GSWP).

Understanding and Simulating Pan American Climate Variability

Empirical and modeling studies of coupled climate processes are central to US CLIVAR s implementation strategy for the Pan American region. Improved historical data sets and climate reanalyses will be used to understand the complex mechanisms that govern Pan American climate variability and to formulate hypotheses to be tested with the use of climate models. Fully coupled ocean-atmosphere-land models will be used to study the role of land surface processes in climate variability. A limited amount of high-resolution modeling will be required to understand and synthesize observations from EPIC, NAME, and MESA. The regional distribution of precipitation over the Americas depends on small-scale phenomena such as the low-level jets over the continents, the mesoscale convective systems that form the highly persistent ITCZ, the equatorial cold tongues with their shallow oceanic mixed layers, and the marine boundary layer cloud decks in the eastern Pacific. Simulating such processes provides a major stimulus for the development of high-resolution global climate models that exploit increasingly powerful supercomputers.

Understanding Pan American phenomena requires major advances in our understanding of large-scale ocean-atmosphere-land interactions and state-of-the-art climate modeling.

Atmospheric Response to Boundary Conditions

The ENSO cycle modulates rainfall over much of the United States, especially for the cold season and southern states. The strength and dependability of possible warm-season linkages is not yet well known. Hence, US CLIVAR will conduct statistical studies that document relationships between anomalous boundary forcing and climate anomalies over the Americas and diagnostic studies that elucidate the physical and dynamic mechanisms through which these linkages occur. Anomalous boundary forcing includes SST and land surface processes; climate anomalies refer not only to mean temperature and rainfall but also to the frequency of droughts, floods, and severe thunderstorm outbreaks, as well as tropical and extra-tropical storm tracks.

Empirical studies, complemented with numerical experimentation, will examine the complex interactions between SSTs, land processes, their effects on rainfall anomalies, and resulting surface wind systems.

AGCMs can explore the relative contributions of oceanic and land processes to the determination of the seasonal cycle of precipitation. For example, modifications of the prescribed seasonality of SSTs, the seasonal cycle of solar heating, or other model parameters can be used. Initial studies suggest that precipitation in the eastern Amazon is controlled by oceanic conditions, whereas the western Amazon is influenced more by the seasonality of land solar heating. AGCM experiments, together with detailed observations of regional weather phenomena, show how the slowly evolving planetary-scale atmospheric response to boundary forcing modulates the more intermittent, higher-frequency synoptic and subsynoptic phenomena that are responsible for the individual episodes of heavy rainfall and significant weather (e.g., flare-ups in the ITCZ and the SACZ, migrating frontal systems, and higher-latitude blocking events associated with wintertime cold air outbreaks). Although deterministic prediction of phenomena such as these is not feasible on seasonal and longer time scales, realistic models may provide more accurate and detailed information concerning their frequency or likelihood of occurrence than empirical evidence alone.

Current AGCM simulations forced with climatological-mean boundary conditions exhibit systematic biases in regions of interest to US CLIVAR (e.g., underestimation of wind stress in the equatorial belt). Increasing the horizontal resolution may alleviate this problem by increasing the poleward eddy momentum flux. It also may provide a better representation of topographic effects on the low-level flow. The Andes, for example, may help determine the prevailing alongshore surface winds off Peru and the associated oceanic upwelling in that region. Models also underestimate the coverage of oceanic stratus clouds, hence their reflection of solar energy and the consequences for the atmospheric planetary boundary layer (PBL) and the ocean mixed layer that is believed to be responsible for much of the equatorial asymmetry of SST in the tropical Atlantic and eastern Pacific. These well-defined biases within the Pan American region highlight basic deficiencies in atmospheric models that need to be corrected to pave the way for the development of realistic coupled models.

Coupling Between Land and Ocean

Empirical and modeling studies are needed to explore the mechanisms that link oceanic climate variability to that over land in the Pan American region. Do land surface processes simply respond to signals that are largely determined externally by coupled ocean-atmosphere interaction, or do they actively determine climatic features such as seasonal precipitation patterns over land? With prescribed atmospheric forcing, land may respond in a deterministic fashion. Feedbacks that involve the ocean and atmosphere may introduce stochastic or chaotic behavior into the climate system over land system, however.

The representation of land surface processes influences the subtle mechanisms that couple climate variability over the ocean and land during the warm season.

Physical parameters that are determined by land surface schemes are net radiation absorbed by the surface, how that energy is partitioned between latent and sensible heat, conductive heat storage, and the radiative temperatures of the land surface and boundary layer air that are required for energy balance. Vegetation is a major factor in the surface energy and water balance. The vertical movement of water and heat within the soil column also is significant. In the present generation of land surface schemes, observational data on the horizontal distribution of vegetation types, properties, and soil characteristics are used as model parameters. Vegetation characteristics affect basic properties such as albedo and roughness length. Soil properties affect the partitioning of rainfall between runoff and infiltration, as well as the radiative, thermal, and water holding capacities of the land.

Analogous to initial efforts to represent the effects of clouds in climate models, parameterizations of the energy and water conservation requirements of the land surface were introduced with very simple schemes. More complex schemes are now included in most operational forecast and data assimilation systems. An explicit representation of vegetation and its role in the hydrological cycle has been introduced, along with more detailed treatments of soil moisture, snow, runoff, and river routing.

Seasonally Varying Mean Climate

The synoptic climatology of rainfall and significant weather events over the Americas is in need of further elaboration, particularly for the warm season. Topography over the Americas gives rise to several distinctive local features in the synoptic climatology, such as low-level jets with moist, poleward flow to the east of the Rockies and Andes; disruption of the northeast trade winds by Mexico and Central American mountain ranges; and strong diurnal variations in rainfall patterns. Informal groups of US CLIVAR investigators will focus on improving understanding and simulation of these important contributors to precipitation patterns over the Pan American region. Empirical studies that define and elucidate the fundamental characteristics of these features will be complemented by efforts to simulate observed features with high-resolution regional climate models.

Mesoscale processes affect the distribution of continental-scale precipitation and its variability on seasonal and longer time scales. Along the coasts and over the mountainous terrain of the Americas, simulated rainfall in the AGCMs and coupled GCMs cannot be compared directly with station data because the weather systems and the topographic features that are responsible for observed rainfall patterns have length scales that are almost an order of magnitude smaller than those resolved by GCM grids currently in use. AGCM and coupled GCM simulations are particularly poor in summer, when mesoscale convective systems organize the precipitation over the Americas and in the ITCZs over the eastern Pacific and western Atlantic oceans. Consequently, seasonal precipitation fields produced by assimilation of climatological data into state-of-the-art climate models do not agree well with independent precipitation data, especially over the data sparse regions of Mexico, Central America, and South America.

Improvement of simulations of seasonally varying mean features and their variability depend both on empirical and modeling studies and on the development of improved data sets and climate analysis methods.

Many aspects of the detailed distribution of rainfall over the Americas and in the oceanic ITCZs can be understood without resolving mesoscale processes over the entire globe. High-resolution regional models have demonstrated a useful capability to downscale coarse-resolution information from global climate models to provide more accurate and detailed descriptions of regional precipitation. Appropriate numerical methods and strategies for these variable resolution models need to be addressed. Advances in supercomputing technology may make resolving mesoscale processes within a global climate model feasible by the end of the CLIVAR period.

Evolution of Tropical Sea Surface Temperature Anomalies

Prediction of seasonal rainfall anomalies requires accurate prediction of SST anomalies. With interests in the Pacific, Pan-American, and Atlantic sectors, US CLIVAR will provide unprecedented observations of upper-ocean structure from the eastern tropical Pacific through the Caribbean Sea and Gulf of Mexico into the tropical Atlantic Ocean. These oceans are subject to the ENSO phenomenon, as well as modulation by ENSO and variability on decadal-to-centennial time scales. Of high interest to the Pan American program is whether these long-term changes should be regarded as deterministic fluctuations in the coupled climate system or merely a reflection of sampling variability associated with the ENSO cycle. In addition to the EPIC program, empirical studies also will provide guidance for the design of the NAME and MESA field studies focusing on the mechanisms of large-scale atmosphere-ocean-land coupling that will be proposed for the CLIVAR period.

3.3.3 Field Studies in the Pan American Region

US CLIVAR will carry out field programs to observe and understand key climate processes that are hindering advances in climate simulation and prediction over the Americas. The framework for Pan American CLIVAR field studies is built on three major initiatives: NAME, MESA, and EPIC. NAME and MESA are joint initiatives of CLIVAR and GEWEX and major components of the international CLIVAR VAMOS program, which is being developed by VAMOS scientists and agencies in North and South America. The success of EPIC, NAME, and MESA depends on US CLIVAR s unprecedented observations of upper-ocean structure and variability over the Atlantic and eastern Pacific Oceans, including the western hemisphere warm pool region from the eastern tropical Pacific through the Caribbean Sea and Gulf of Mexico into the tropical Atlantic Ocean.

NAME and MESA plans, and their links to EPIC, are described in this section. Section 3.2 includes details on EPIC implementation plans being developed in collaboration with the Pacific panel . US CLIVAR ocean observation plans in the Pan American sector are described in Sections 3.1 and 3.2.

North American Monsoon Experiment (NAME)

NAME focuses on determining the sources and limits of predictability of warm-season precipitation over North America, with emphasis on seasonal-to-interannual time scales. NAME is a major nationally planned process study of US CLIVAR.

NAME s principal objectives are as follows:

- Better understanding of key components of the North American monsoon system and its variability
- Better understanding of this system s role in the global water cycle

- Improved observational data sets
- Improved simulation and monthly-to-seasonal prediction of the monsoon and regional water resources.

Achieving these objectives will require empirical and modeling studies of the monsoon system and its variability, enhanced monitoring of key seasonally varying features of the North American monsoon, and intensive field studies over portions of the core monsoon region. Results should include better understanding and simulations of ocean-atmosphere-land interactions during the warm season, especially clarification of the role of the diurnal cycle and other transients that shape the regional precipitation fields of the North American monsoon. Other anticipated benefits of NAME include joint international experience in the exploitation of *in situ* data and new satellite sensors measuring atmospheric, surface, and hydrological parameters over the Americas; joint international experience in assessing the capabilities and limitations of assimilated data products for capturing these parameters; advancements in coupled model development over land and ocean areas; advancements in the development of the climate observing system; and production of consistent data sets over North America that can act as testbeds for the validation of numerical models.

NAME links CLIVAR programs with an emphasis on ocean-atmosphere interactions and GEWEX programs, which have an emphasis on land-atmosphere interactions and ground hydrology. It implements the North American monsoon objective of GEWEX/GAPP (GAPP is the GEWEX Americas Prediction Project) and expands efforts begun under the NOAA PACS/GCIP research initiative on the seasonal-to-interannual variability of warm-season precipitation. In addition, NAME is a major component of CLIVAR/VAMOS.

NAME objectives will be achieved through a mix of diagnostic, modeling, and prediction studies that are based on existing data sets and new field observations. This research necessarily will be diverse because it seeks to answer scientific questions relating to several different coupled processes and phenomena. We propose a multi-scale (tiered) approach to the analytic, diagnostic, and model development activities of NAME. The initial field campaign will include intensive field observations in the core monsoon region and enhanced climate observations on regional and continental scales. We refer to the levels in this hierarchy of scales as Tier 1, Tier 2, and Tier 3, respectively (see Figure 3.3). Each tier has a specific research focus that aims at improving warm-season precipitation prediction; activities related to each tier are designed to proceed concurrently.

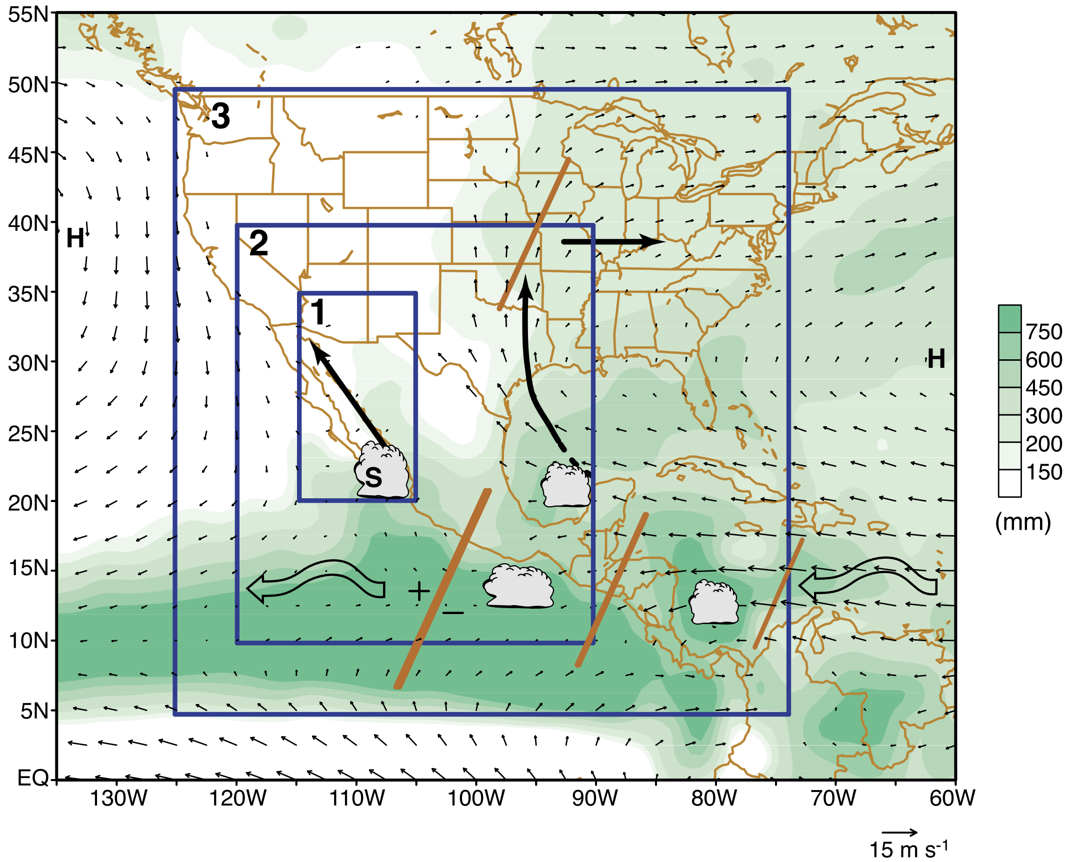

Figure 3.3. Schematic illustration of multi-tiered approach of the North American Monsoon Experiment (NAME). Also shown is the climatological mean (July—September 1979—1995) 925 hPa vector wind and precipitation (shading), in millimeters. Circulation data are taken from the NCEP/NCAR Reanalysis archive.

Tier 1 studies the core region of the North American monsoon over data-sparse areas of northern Mexico, the southwestern United States, and the waters of the eastern Pacific and the Gulf of California. These studies focus on low-level circulation and precipitation patterns in the core monsoon region and improved monitoring and modeling of the coupling between the sea breeze/land breeze and mountain/valley circulations.

Coupling in the core monsoon region is intimately related to the diurnal cycle of moisture and convection in the region, so a better understanding of this cycle is fundamental to improved warm-season precipitation prediction. Some principal scientific questions are the following: How is the coupling between the sea breeze/land breeze and mountain/valley circulations along the Gulf of California related to the diurnal cycle of moisture and convection? What role does the Gulf of California low-level jet play in the summer precipitation and hydrology of southwestern North America? What are the dominant sources of precipitable moisture for monsoon precipitation over southwestern North America? What are the relative roles of local variations in SST and land-surface parameters (topography, soil moisture, and vegetation cover) in modulating warm-season precipitation in this region? What are the effects of aerosol loading from dust, smoke, and anthropogenic emissions on precipitation in the core monsoon region?

Tier 2 focuses on regional-scale features over southwestern North America and the warm pool region to the southwest of Mexico. These studies are intended to provide an improved description and understanding of intraseasonal aspects of the monsoon. Key questions are as follows: How important are interactions between Tropical Easterly Waves (TEWs) and Gulf of California moisture surges in the prediction of monsoon precipitation? What is the nature of the relationship between the Madden-Julian Oscillation (MJO), tropical cyclone activity, and monsoon precipitation? What portion of the skill of summer precipitation forecasts, in addition to that from ENSO, will arise from an ability to forecast MJO activity over a season? What is the physical setting for the bimodal distribution (i.e., wet-dry-wet) in warm-season precipitation over Mexico and Central America, and what factors influence its interannual variability?

US CLIVAR ocean observations and EPIC enhanced monitoring and field studies in the northeastern tropical Pacific will provide a useful context for Tier 2 field activities.

Tier 3 focuses on aspects of the continental-scale monsoon circulation to improve description and understanding of spatial/temporal linkages between warm season precipitation, circulation parameters and the dominant boundary forcing parameters and asks: How is the evolution of the warm season precipitation regime over North America related to the seasonal evolution of the boundary conditions? What are the interrelationships between year-to-year variations in the boundary conditions, the atmospheric circulation, and the continental hydrologic regime? What are the links, if any, between the strength of the summer monsoon in southwestern North America and summertime precipitation over the central United States? What are the relationships between the statistical frequency and magnitude of extreme events (e.g., floods, droughts, hurricanes) and climate variability on intraseasonal-to-interannual time scales?

Elements of the field study would include special soundings (rawinsondes, pilot balloons), improvements to the rain gauge network (simple and digital recording rain gauges), transects from the Gulf of California to the Sierra Madre Occidental (wind, surface temperature, sea-level pressure from automated weather stations), research aircraft flights, and other ground-based elements (e.g., 915 MHz wind profilers, radars). The overall philosophy for observing-system enhancements will be to augment existing routine observing systems over the region of interest with special observations that will adequately describe the features of interest. Regional mesoscale models and regional data assimilation systems will be used to guide enhanced monitoring activities. These studies will be carried out in tandem with land surface model experiments and land data assimilation experiments and will benefit from multi-year regional reanalyses and retrospective soil moisture analyses.

NAME is a multiyear process study that would extend through most of the CLIVAR period. Enhanced monitoring for the first NAME field campaign is scheduled for the first half of the CLIVAR period (2002—2004). Enhanced monitoring activities in the core region of the monsoon would require observations during at least four summer months (June—September), to coincide with the peak monsoon season. During this period, there would be several intensive observing periods (IOPs), each lasting 2—5 days, to describe aspects of the regional low-level circulation in greater detail than can be provided by twice-daily soundings. A second NAME observational campaign that is being planned for the latter part of the CLIVAR period would focus on the role of the western hemisphere warm pool in the North American monsoon.

US participation in NAME will be planned by the Pan American panel, perhaps through a special working group.

Monsoon Experiment South America (MESA)

MESA is an internationally coordinated process study to improve prediction of the monsoon and its variability over South America, with emphasis on warm-season precipitation. MESA is a joint project of CLIVAR VAMOS and GEWEX. Several key components of the South American monsoon system have yet to be adequately described and understood. MESA investigators will conduct enhanced monitoring and intensive observations of the low-level jet on the eastern slopes of the Andes and its role in determining the seasonal rainfall patterns over the La Plata River basin. Plans also are being developed in collaboration with EPIC investigators to study the mechanisms that link the seasonal varying structure of the ocean and atmosphere over the southeastern Pacific to the South American monsoon. In addition, CLIVAR and GEWEX LBA investigators will collaborate to better understand ocean-atmosphere-land interactions between the Amazon basin and the tropical Atlantic regions. MESA benefits from recent field experiments (such as LBA and campaigns over the Altiplano) that have begun to shed light on land-atmosphere interactions in South America.

The principal objectives of MESA are as follows:

- Better understanding of key components of the American monsoon systems and their variability
- Better understanding of these systems role in the global water cycle
- Improved observational data sets
- Improved simulation and monthly-to-seasonal prediction of the monsoon and regional water resources.

MESA is designed to use a two-stage approach; each stage has its own scientific objectives, and the first stage is preparatory for the next. MESA s Stage 1 comprises the component of the American Low-Level Jets (ALLS) program that focuses on the moisture corridor between the Andes and the Brazilian Altiplano. The main objective of this component is to better understand the role of moisture transports, their variability, and links to remote and local climate anomalies of the South American low-level jet (SALLJ). Scientists from Argentina, Brazil, Chile, and the United States have developed a field program on SALLJ under the auspices of VAMOS. Scientists from Bolivia and Paraguay are expected to participate in the campaign, which is planned for 2002—2005. Stage 1 includes a VAMOS EPIC (VEPIC) component focusing on ocean-atmosphere-land processes centered on the coast of Chile and Peru. VEPIC will implement the international collaboration for EPIC Phase II, tentatively scheduled for 2003—2005 (see Section 3.2). Stage 2 will be a study of the hydroclimatology of the La Plata River Basin (PLATIN). Here the goal is improved description and understanding of spatial/temporal linkages between precipitation and streamflow. Scientists from Argentina, Brazil, Uruguay, and the United States have prepared a document in preparation for a field campaign. The tentative dates for PLATIN are 2005—2010.

US participation in MESA will be planned by individual investigators and reviewed by the Pan American panel. Proposed US commitments to international efforts will be prepared by the panel for approval by the SSC.

3.4 OTHER REGIONS

3.4.1 Arctic

The Arctic is a significant component of the global climate system for several reasons:

- Arctic Ocean stratification and ice cover provide a control on the surface heat budgets of the northern polar region and thereby on the global heat sink. A changed distribution of arctic sea ice would alter surface fluxes and affect regional and global climates.
- Export of low-salinity water and sea ice can influence the ocean s overturning cell by controlling convection in the subpolar gyres. North Atlantic and Eurasian decadal climate variability may be predictable from the variability of upstream forcing in the Greenland Sea.
- Arctic marine life is conditioned by sea ice, nutrient availability, and water density. Changes in these factors may affect critical marine ecosystems and biogeochemical cycling. Changes in the terrestrial hydrologic cycle may alter soil moisture, affecting plant communities and their grazers.
- Arctic soils are significant sources and sinks of global carbon dioxide and methane and appear to respond sensitively to altered soil moisture and temperature.
- A dominant change in the atmospheric circulation of the Northern Hemisphere in recent decades involves substantially lower sea-level pressure throughout the Arctic. This signal, in part, reflects the trend in the AO/NAO (Section 3.1), which several recent modeling studies suggest is symptomatic of anthropogenic climate change.
- Modeling studies indicate that the Arctic is a sensitive indicator of global change; under global warming scenarios, temperature increases will be amplified in the Arctic, and upper Arctic Ocean salinity will decrease as a result of enhanced precipitation at high latitudes.

Variability and Long-Term Trends

There has been short-term variability, as well as multi-decadal and longer trends, in several key Arctic variables. Northern Eurasian and North American land areas have warmed significantly since the 1970s, in broad agreement with anthropogenic change experiments. Reconstructions based on proxy sources indicate that late-20th century Arctic temperatures are the highest in 400 years, and statistical analysis of this time series and records of known forcing mechanisms suggests that the recent warming has an anthropogenic component. Long-term and recently augmented reductions in sea ice cover have been observed.

Arctic soils have been a significant overall sink of carbon over historic and recent geologic time scales, resulting in large stores of soil carbon. Recent data suggest that past carbon accumulation has changed to a pattern of net loss, with growing-season release of up to 150 g $m^{-2}yr^{-1}$. Present conditions appear to represent significant deviations from historic and Holocene carbon fluxes, and the potential exists for a positive feedback on global change through losses of CO_2 to the atmosphere of as much as 0.7 Gt C y^{-1} (about 12 percent of total emissions from fossil fuel use).

Alarmingly rapid changes have occurred during the past decade in the ocean, as the influence of Atlantic water is becoming more widespread and intense. Several cruises in 1993—1995 indicate that the boundary between the eastern and western halocline types has advanced from over the

Lomonosov Ridge to roughly parallel to the Alpha and Mendeleyev ridges; thus, the area occupied by the eastern water types is nearly 20 percent greater than previously observed. Results from these cruises suggest warming of Atlantic water cores over the major ridge systems that apparently began in the late 1980s.

The shift in oceanic frontal positions is associated with a change in ice drift and atmospheric pressure patterns. The ice drift and pressure fields for the 1990s are shifted counterclockwise 40º to 60º from the 1979—1992 pattern, just as the upper-ocean circulation pattern derived from the hydrographic data is shifted relative to climatology. This change is consistent with the observed decrease of annual mean sea-level pressure that is part of the recent large change in atmospheric circulation of the Northern Hemisphere characterized as the Arctic Oscillation.

Terrestrial variables have changed as well. Changes in air temperature have been attended by reductions in spring snow cover since the mid-1980s. Arctic glaciers have exhibited negative mass balances, paralleling a global tendency. Other studies point to increased plant growth, northward advances of the tree line, increased fire frequency, and thawing and warming of permafrost.

SEARCH and CLIVAR

In response to results from the observations and modeling studies described above, the Arctic community is planning a new initiative to describe, understand, and possibly predict the future evolution of observed changes in the Arctic the Study of Environmental Arctic Change (SEARCH). A science plan has been developed (<http://psc.apl.washington.edu/search/>) encompassing physical as well as biological and social elements of the Arctic system. The plan describes the major scientific questions addressed, as well as implementation strategies. A full implementation plan is being developed. SEARCH is guided by a steering group that oversees the integration of these components in a systems approach.

A connection between CLIVAR and SEARCH is vital for proper connection of low and high latitudes. Achieving CLIVAR s goals, especially those of the Atlantic program element, requires a solid understanding of high-latitude processes that significantly affect lower-latitude climate (e.g., freshwater export from the Arctic; the nature of the AO/NAO). At the same time, the Arctic system can be fully understood only if the effects of lower-latitude coupling to the Arctic are known (e.g., heat transport into the Arctic). To facilitate the connection between CLIVAR and SEARCH, a joint working group has been formed and endorsed by US CLIVAR and SEARCH. This working group will consist of members from the Arctic and lower-latitude climate communities; it will focus on the physical aspects of the coupled climate system.

3.4.2 Austral-Asian Monsoon Region

The Austral-Asian monsoon, which is driven by land-sea differences in heating, is one of the strongest seasonal phenomena in the global climate. This monsoon undergoes interannual variability with substantial and direct impacts on food production, safety, health, and the commercial well-being of more than half of the world s population. One cause of this variability is ENSO either directly through atmospheric connections or indirectly through SST, which apparently responds mainly to ENSO-induced changes in radiative heating. The magnitude, structure, and predictability of ENSO s impact on the Austral-Asian monsoon and the possibility that non-ENSO variability in the Indian Ocean may affect the monsoon and its predictability, or that snow cover and soil moisture may modulate the monsoon in a potentially predictable way, give the study of variability of the Austral-Asian monsoon scientific and practical importance.

US CLIVAR intends to participate in study of the Austral-Asian monsoon but does not expect to lead the international assault on this key phenomenon. A US Austral-Asian Monsoon Working Group has been formed to develop the way in which the United States can effectively join its international partners to better understand the monsoon s variability and predictability. A plan of action is anticipated by the end of 2001.

3.4.3 Other Climate Regions

Important climate variability is not limited, of course, to the specific regions discussed above. For example, the Indian Ocean sector is significantly affected by ENSO (particularly rainfall over Asia and Australia), and processes in the Indian Ocean may participate in the initiation phases of ENSO. The Austral-Asian monsoon also may be influenced by conditions across the Indian Ocean sector. The Indonesian Throughflow, which carries water into the Indian Ocean from the western tropical Pacific, plays a major role in the Pacific s tropical circulation (see PBECS Plan) and in processes implicated in modulation of ENSO.

Similarly, the Southern Ocean is an important part of the climate engine. It is the major connection between the other oceans and is the site of transformation of deep water to bottom water and formation of intermediate water both of which are major elements in the meridional overturning circulation that is implicated in rapid climate change. Although the Southern Ocean is the least measured ocean, scientists know that it supports climate variability for example, in the interannual Antarctic Circumpolar Wave in SST and sea-level pressure.

Atmospheric conditions over Africa influence the Tropical Atlantic Ocean, as evidenced by the association between Sahelian drought and reduced numbers of Atlantic hurricanes. Dust blowing westward from Africa is modulated by the African climate, and this dust affects radiative fluxes over the Atlantic. Therefore, studies of TAV (Section 3.1.3) may require reliable atmospheric analyses over Africa.

US scientists are examining ways in which they can participate in international CLIVAR efforts in all of these areas. The United States does not anticipate taking a lead in these efforts but looks forward to formulating a program of substantial US involvement to assist the international effort. As more specific projects are being formulated, the highest priority is that sustained observations outside the Atlantic, Pacific, and Pan American sectors should be adequate to provide a basic description of global climate variability. In this respect,

US CLIVAR recommends establishment of the global ARGO array even if it entails somewhat reduced density in the Indian and Southern Oceans and US collaboration in establishing the high-resolution XBT/XCTD lines IX1 and IX15, as well as continuation of AX22 and IX28 (see Figure 2.2).

4. ORGANIZATIONAL ELEMENTS

4.1 MANAGEMENT OF US CLIVAR

CLIVAR is the most ambitious climate-science research program yet envisioned, and the role of the US research community, in conjunction with supporting agencies, will be significant. Consequently, successful development of the US CLIVAR program requires shared responsibility between the scientific community and federal agencies. The process of scientific planning must be open, with input solicited from the larger scientific community as well as agency representatives. When planning is completed and accepted, agencies must work to identify resources required to carry out the plans. The scientific community must accept responsibility for scientific development by setting priorities, sustaining relevant activities, and providing compelling justification for required resources.

Program managers from NASA, NOAA, NSF, and DOE forming the interagency group (IAG) promote and coordinate national interests in CLIVAR. They look for and coordinate opportunities within and across federal agencies to secure resources and develop funding mechanisms. They participate in all aspects of the planning process to ensure program viability. They also approve membership of the SSC and provide support through the US CLIVAR Office for planning and organizational activities. The SSC provides overall scientific and programmatic guidance to ensure that US CLIVAR progresses toward its scientific objectives, including development and approval of implementation plans. The SSC advise agencies on CLIVAR implementation; promote balance within the various elements (theory, modeling, empirical studies, long-term observations, and field campaigns) of the program; and provide oversight and guidance to advisory groups, particularly on the balance and prioritization of activities. Like members of all other US CLIVAR committees, members of the SSC rotate on a regular schedule to ensure fairness and an infusion of fresh ideas.

Three regional implementation panels for the Atlantic, Pacific, and Pan American sectors advise the SSC on required field, empirical, and model studies and appropriate mechanisms (e.g. community meetings, working groups, commissioned studies, etc.) to develop implementation plans. In developing regional implementation plans, these panels cast a wide net through open meetings as well as publicizing planning documents in an effort to develop a comprehensive plan of strongly justified and balanced activities. Together with other national and international groups, they are expected to advise on efficiently coordinating the execution of these plans. The panels also are expected to call for workshops and other meetings that will lead to progress in the implementation phase.

Working groups have been formed to provide focal points for activities and supply the SSC with plans for implementation. The Seasonal-to-Interannual Modeling and Prediction (SIMAP) Working Group organizes and carries out model experiments, intercomparisons, evaluations, and multi-model ensemble experimental variations; it also identifies key scientific questions regarding the predictability of S-I variations and their decadal variations. The Asian-Australian Monsoon Working Group oversees empirical modeling and diagnostic studies of the Asian-Australian Monsoon (AAM) to provide better understanding of the AAM s variability and predictability and its impacts on other climate systems, such as ENSO and global climate. It also promotes interaction with US GEWEX communities. The CLIVAR-PAGES Working Group seeks to facilitate communication between these two programs and actively supports work to understand the implications of the proxy climate record.

Additional panels and working groups are envisioned when there is sufficient national interest from the supporting research agencies and the scientific community and when preliminary planning identifies a cogent research strategy.

The US CLIVAR project office provides the infrastructural glue to bind the organization together. It coordinates the US national program, provides support to the SSC, works with the IAG to develop and analyze budgets, organizes joint activities with other relevant US research programs (e.g., GEWEX), and acts as the liaison to the international CLIVAR effort.

4.2 INFRASTRUCTURE

4.2.1 Computer Resources

Clearly, significant computing resources will be required to carry out the research plan described in this document. The atmospheric and oceanic data-assimilating analyses required to blend together diverse global climate observations involve significant levels of computation, and studies to help design an improved climate observing system will require more. Although many useful modeling studies of climate variability can be carried out with workstation-level resources, the cooperative program of improving seasonal-to-interannual prediction laid out by the SIMAP group will require each participant to allocate substantial resources to the required runs. The program to use knowledge of natural variability to test and improve comprehensive climate models will involve repeated ensemble runs with these models, in addition to the resources required for their main purposes (e.g., forecasting or IPCC runs). Process and modeling teams seeking to transfer understanding from process experiments into comprehensive climate models will require resources. Beyond all these coordinated activities, individual investigators and teams will be using comprehensive models to explore and understand the dynamics and predictability of climate variability.

The success of US CLIVAR depends on significant expansion of the computer resources available for climate research.

4.2.2 Telemetry and Transmission of Data

US CLIVAR s sampling strategies rely on the capability to collect data from remote locations and expendable instrumentation. Data from radiosondes, surface drifters, ARGO floats, VOS, and gliders must be relayed back so that investigators can collect the data. Radiosondes use local radio links to collect data at the ground station, from which the data are transmitted back (inserted on the GTS) for use at NWP centers and for inclusion in CLIVAR databases. Drifters, ARGO floats, gliders, and many surface moorings rely on satellite links to report data. Present technology limits the amount of data that is reasonably transmitted and does not permit two-way communication with remote instruments. Many instrument platforms particularly gliders and floats could benefit from two-way communication to switch sensors; change sampling frequency; or alter depths, waypoints, and stationkeeping on the basis of messages received. US CLIVAR has identified the following telemetry needs:

- Improved satellite data telemetry capabilities, with reduced cost, denser coverage, increased data throughput rates, and two-way communication capabilities
- Improved performance in capturing all available radiosonde data.

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