US CLIVAR Priorities in FY 2000

Below are the priorities for the U.S. Program on Climate Variability and Predictability (CLIVAR) for Fiscal Year 2000. It is the targeted U.S. contribution for this year to the international CLIVAR program and represents a view of research areas that are at once critical to our understanding and prediction of the climate system and scientifically tractable in the near term. The priorities were produced with the recommendations of the CLIVAR Science Steering Committee and supported by the CLIVAR Interagency Group. Agency membership in the Interagency Group includes the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), the National Science Foundation (NSF), and the Department of Energy (DOE). NASA, NOAA, and NSF have identified below those areas of research that they intend to support as a part of their individual agency announcements of opportunity.

This priority list by no means represents the sum of U.S. climate variability and predictibility research. Active programs are underway in climate modeling and prediction (which will incorporate CLIVAR results among others), atmospheric radiation, climate diagnostics, and the carbon cycle, to name a few. It should also be noted that this announcement does not deal with anthropogenic climate change, but development of this scientific focus is underway. Please refer to NSF's Climate Modeling, Analysis and Prediction (CMAP) at http://www.nsf.gov/geo/egch/gc_html for information on NSF interest in high-end climate model development, testing and application for climate change simulations and predictions.

The structure of this announcement consists of a description of desired research areas, followed by links and descriptions of appropriate agency programs where proposals should be submitted. A justification for the choice of these areas follows the description. Proposals should be submitted according to the format and timing given in the particular agency announcement

Areas of Emphasis

A. Process Understanding and Modeling Studies

1. Empirical studies, diagnosis and modeling of the coupled ocean- atmosphere-land system, with emphasis on decadal climate variability.

The U.S. CLIVAR program seeks a better understanding and more realistic simulation of phenomena involving coupled ocean-atmosphere-land processes on seasonal-to-decadal time scales. Of particular interest are studies to elucidate the mechanisms responsible for decadal variability of the climate system and assess their predictability. These studies may seek to enhance our descriptive knowledge of the phenomena (including their interaction with land-surface processes) using historical and paleo-climatic records, develop and compare or test hypotheses regarding the mechanisms of variability using simplified or comprehensive models, or assess the predictability of decadal climate variability. Phenomena of interest include (but are not limited to): decadal variability and predictability of ENSO; tropical Atlantic variability (TAV); mid-latitude phenomena such as the Pacific Decadal Oscillation (PDO); the North Atlantic Oscillation (NAO)/Arctic Oscillation (AO).

NOAA Climate and Global Change Program CLIVAR Program Announcement. For information on NOAA's interest in this research area and guidance on proposal submission see: http://www.ogp.noaa.gov/C&GC/AO/clivar00.htm

NASA Global Modeling and Data Analysis NRA99-OES-04. Several NASA programs have an ongoing interest in development of models, processes and empirical studies related to decadal climate variability. See: http://www.earth.nasa.gov/nra/current/nra99oes04/index.html

NSF Divisions of Atmospheric and Ocean Sciences. It is expected that only a small number of new awards will be possible. For further information on how to submit proposals see: http//www.nsf.gov/geo/egch/gc_clivar.html

2. Diagnosis and modeling of the impact of sea ice and midlatitude SST anomalies on the circulation of the atmosphere.

Studies using atmospheric models to explore the nature and dynamical mechanisms of the atmospheric response to extratropical sea surface temperature (SST) and sea ice anomalies are sought. Emphasis is on interactions that involve synoptic activity and might not be identified in low-resolution climate models. Needed are coordinated experiments with multiple models using a common set of SST anomalies and a common set of diagnostics of model results that are archived at a central location in a common format for comparison. Aside from determining the strength and nature of the response in different models, questions to be addressed are:

* the relationship between the response and model climatology, in particular the position of the model storm tracks relative to the SST anomaly;
* the relationship between the response and the model's internal modes of low-frequency variability;
* the role of transient atmospheric eddies and eddy transport of heat and momentum in determining the model response;
* the role of convective and boundary layer parameterizations in determining the model response; and
* the role of model resolution in determining the model response.

NSF Division of Atmospheric Sciences. It is expected that only a small number of new awards will be possible. For further information on how to submit proposals see: http//www.nsf.gov/geo/egch/gc_clivar.html

3. Enhanced observation, modeling and analysis and of coupled ocean-atmosphere-land phenomena in the Atlantic and Pan American sectors, with emphasis seasonal-to-interannual climate variability.

The U.S.CLIVAR program seeks a better understanding and more realistic simulation of seasonal-to-interannual climate phenomena in the tropical Atlantic and Pan American sectors, and an assessment of their predictability. The specific scientific objectives for FY2000 include improving the understanding of (1) the degree to which land surface feedback processes play an active role in generating coupled ocean-land- atmosphere variability of the Pan American monsoon and tropical Atlantic climate, (2) the effects of remote SST forcing by Pacific climate phenomena (e.g., ENSO and its decadal modulation) in the Pan American and tropical Atlantic sectors, and (3) the interaction of the monsoons and tropical Atlantic variability with extratropical climate modes (e.g. the NAO and North American warm season climate variability).

Proposals for new or continuing research may include empirical studies to explore atmosphere-ocean-land feedback processes, improve the description of Pan American and tropical Atlantic sector phenomena, or assess the limits of predictability; modeling and diagnostic studies to test promising hypotheses or assess predictability; data set development activities to improve the quality and accessibility of historical climate data sets; and studies to accelerate development of the international climate observation and prediction system over the Pan American and tropical Atlantic sectors.

NOAA Climate and Global Change Program CLIVAR Program Announcement. NOAA's CLIVAR Atlantic and PACS foci address much of the research agenda described. For information on specific NOAA emphases see: http://www.ogp.noaa.gov/C&GC/AO/clivar00.htm

NOAA CLIVAR-GEWEX Warm Season Precipitation Initiative Announcement. This Announcement invites projects to test hypotheses regarding the predictability of summer precipitation over North America. See: http://www.ogp.noaa.gov/C&GC/AO/pacs_gcip00.htm

NSF Divisions of Atmospheric and Ocean Sciences. It is expected that only a small number of new awards will be possible. For further information on how to submit proposals see: http//www.nsf.gov/geo/egch/gc_clivar.html

NASA Global Modeling and Data Analysis NRA99-OES-04. NASA is interested in some regional studies utilizing multiple satellite data sets to elucidate processes of seasonal-to-interannual variability. See: http://www.earth.nasa.gov/nra/current/nra99oes04/index.html

B. Observational Design Studies

4. Design studies for ocean observations in support of CLIVAR objectives

A focus of CLIVAR will be a substantially improved ocean observation system feeding data assimilating models in order to diagnose the ocean processes involved in seasonal to decadal climate variability. Satellite altimetry, scatterometry, and SST measurements, along with improved operational satellite surface flux determinations, surface drifters, and Argo profiling floats augmented by XBT/XCTD observations will provide the main broad-scale data sets. CLIVAR seeks assessments of the broad-scale observations and design studies of selected augmentations needed to diagnose the main modes of climate variability. Studies should (a) identify key ocean processes/phenomena and explain their role in climate variability, (b) define what parameters should be observed and how well, (c) define the space-time scales of the signal and noise, and (d) design feasible ways observations might be made over many years and their costs. Investigations of three specific areas are encouraged:

A. Low-latitude western boundary currents of the Atlantic and Pacific;
B. Meridional overturning circulation in the Atlantic; and
C. Complete observing systems over significant portions of the tropical and subtropical Pacific and/or Atlantic.

Studies may be based on theory, analyses of historical observations and/or numerical models. They should take full advantage of the existing in situ and satellite observing networks and of data assimilating models or other analysis methods to extrapolate necessarily limited measurements to give a regional or basin-wide picture. It is important to develop a means to estimate the uncertainty of proposed observations and the scales over which they apply, to address the suitability of available technology, and to assess the robustness of the program given possible data dropouts. Team approaches are encouraged and may be necessary for item C.

NSF Division of Ocean Sciences. It is expected that only a small number of new awards will be possible. For further information on how to submit proposals see: http//www.nsf.gov/geo/egch/gc_clivar.html

NASA Global Modeling and Data Analysis NRA99-OES-04. NASA provides some opportunity for global-scale design studies of integrated in situ and remote sensing observing platforms. See: http://www.earth.nasa.gov/nra/current/nra99oes04/index.html

5. Process experiment design studies: Pacific equatorial upwelling

Design of an observational program to study equatorial upwelling transport in the Pacific is sought. Upwelling is a key link in the shallow meridional overturning cells spanning the subtropical gyres and the equator. The design study may use analyses of historical observations, numerical model results and/or theoretical calculations to justify the need for an upwelling study in the climate context and to define the techniques and sampling needed to adequately observe equatorial upwelling transport and its scales of variability in three-dimensions and time. Of particular interest are the depth to which upwelling extends, its transport and the properties of the upwelled water, since these define the connection between upwelling and the subtropical cells. The design study should address if and how an experiment should distinguish between cross-isopycnal and along- isopycnal flows. Because upwelling is both a local response to equatorial winds and a component of the inter-gyre exchanges in both hemispheres, it is important to establish the connection to both of these elements. Since it will not be possible to fully sample the upwelling process from observations alone, the design study should consider the feasibility of using the observations in assimilation models or other methods of extrapolating the necessarily limited measurements to a basin-wide picture. Methods to estimate the uncertainty of the proposed observations, and the scales over which they apply, are needed. The observing program will occur in the context of the TAO array, satellite observations, and the broadscale observing network (projected to include Argo floats) and should be designed to take full advantage of these resources. The design should address the suitability of present technology to perform the necessary sampling.

NSF Division of Ocean Sciences. It is expected that only a small number of new awards will be possible. For further information on how to submit proposals see: http//www.nsf.gov/geo/egch/gc_clivar.html

6. Strategy for developing surface flux products: design study and proof of concept.

Global fields of surface heat, freshwater, and momentum fluxes and of the supporting surface meteorology are needed to address the fundamental CLIVAR objectives of describing, understanding, and predicting climate variability. High quality in-situ data from a surface moorings, serving as surface flux reference sites, and from upgraded Volunteer Observing Ships (VOS) could provide the foundation for developing accurate surface flux fields. However, the procedures for making best use of such data and the most effective locations for these measurements need to be determined. Specifically, the regions and scales over which sparse accurate in-situ data can be effective in correcting NWP and satellite fields, and the procedures for making those corrections and developing improved global fields must be determined. Proposals from teams of investigators are sought to develop and demonstrate strategies to collect and use such high quality surface data to produce surface flux products. Of particular interest are: (1) the characterization of the spatial and temporal error statistics of NWP surface meteorology and fluxes to facilitate ocean state estimation with such products and (2) the use of new high quality data from moorings and VOS, other in-situ data, gridded fields from NWP analyses, and satellite data, to produce accurate, gridded (6 hourly, 1 degree x 1 degree or better) fields of the surface fluxes of heat, freshwater, and momentum over the world's oceans.

Proposals should address: intercalibration of the in-situ platforms; quality control of in-situ data; development of a working partnership with NWP centers both to increase the amount of high quality in-situ data being assimilated and to improve the ability of the models to produce accurate surface marine and flux fields; development of a working partnership with satellite remote sensing to produce surface marine and flux fields from satellites in near real time and using in-situ observations for calibration; and merging in-situ, NWP, and satellite data to produce improved surface marine and flux fields. The team effort should lead to a determination of the impact of the surface-flux-mooring and upgraded VOS data and include observing system simulation experiments as part of a design study for the global deployment of such platforms. It should also address the use and benefits in CLIVAR of the resulting surface flux fields. The effort should include a proof of concept demonstration of surface flux fields, either using existing or simulated data sets.

NASA Global Modeling and Data Analysis NRA99-OES-04. Development of flux products based on remotely sensed data is a priority interest of the NASA Physical Oceanography Program. See: http://www.earth.nasa.gov/nra/current/nra99oes04/index.html

NOAA Climate and Global Change Program CLIVAR Program Announcement. NOAA's interest in this research area is for *in situ* observations in the tropical Atlantic sector. For more information see: http://www.ogp.noaa.gov/C&GC/AO/clivar00.htm

Agency Announcement Deadlines

NASA – Letters of Intent (LOIs) by August 26, 1999; Proposals by September 27, 1999

NOAA – LOIs by October 15, 1999; Proposals by January 7, 2000

NSF ATM – Proposals may be submitted at any time
NSF OCE – Proposals by February 15, 2000

Justification of Areas of Emphasis

1. Empirical studies, diagnosis and modeling of the coupled ocean- atmosphere-land system, with emphasis on decadal climate variability.

Numerical models of the climate system provide a powerful tool for developing understanding of climate variability. Current global coupled models can be run at relatively high resolution over sufficient time periods to make significant numerical simulations, experiments, and comparative studies. Modeling studies may be divided into two groups: those which seek to simulate the full coupled system and all its variability, and those which seek to isolate key mechanisms. Much of our current theory for climate variability has come from modeling studies of observed phenomena, largely due to the modeler's ability to exclude phenomena, conduct carefully controlled experiments, refine and reduce to seek the essential physics of the process. An example is the development of the delayed action oscillator for ENSO from a simple coupled ocean-atmosphere model that specifically excluded such important features as the annual cycle, mid- latitude coupling, and monsoons. On the other hand, models that are restrictive cannot discover complex inter-relationships the full ocean- atmosphere-land climate system, and do not serve well as the basis for a prediction or reanalysis system. Models with reduced physics exhibit different stability properties, sometimes being more regular, due to a limited number of degrees of freedom, sometimes more unstable, by excluding negative feedbacks inherent in the system. We seek application of a broad range of model types to the problems of climate variability, particularly studies that compare and diagnose the differences between different model classes.

The empirical studies envisioned here are based on retrospective analyses of observational data, including climate data reanalyses based on model- based data assimilation techniques, investigating the nature of climate variations. Many phenomena have multiple candidate mechanisms. Empirical studies can often identify which are most active in nature, or result in the development of new hypotheses when theory and observations diverge. Many theories have specific weak points where empirical studies may provide key evidence for or against the theory. The most important scientific problems include:

Decadal Variability of ENSO

Currently, there are at least four groups of ideas "explaining" decadal variation of ENSO: 1) stochastic, random processes within the tropical ENSO system, 2) a purely tropical air-sea mode of variation, 3) a mode of coupled ocean-atmosphere variability carried through the ocean from the subtropics to the equatorial thermocline, and 4) a stochastic mode coupling the mid-latitude atmosphere with equatorial surface winds, essentially through the atmosphere alone. All of these processes may operate in nature to some extent, some may dominate. Modeling and diagnostic studies are needed to further explore the details of each of these hypotheses. An assessment of the relative role of the different mechanisms can be made, as can specific numerical experiments testing various weak links in the theories.

Decadal Variability of ENSO predictability.

The limit of predictability of El Nino is still largely unknown, although experience with forecasting has given anecdotal evidence of a range of predictability on the order of 1 year. Modeling studies indicate that decadal variation of ENSO can have large effects on its predictability, perhaps showing twice as much predictability in one decade than another. Understanding the interdecadal variation of predictability will be an important advance, since it influences observing system design, prediction model initialization, forecast confidence and theoretical understanding.

Tropical Atlantic Variability.

On interannual to decadal time scale, the dominant mode of variability in the tropical Atlantic is the covarying pattern of the ITCZ and the underlying cross-equatorial SST gradient. This mode of variability has a direct link to rainfall variability in the NE Brazil and Subsaharan West Africa. Climate variability in this region is likely to involve both land- atmosphere-ocean interactions local to tropical Atlantic and remote influence from Pacific ENSO. There are also indications that TAV and NAO may be interrelated. Modeling and diagnostic studies are needed to explore the details of each of these processes and to assess the relative role of the different mechanisms.

Extra-tropical Coupled Ocean-Atmosphere Phenomena

Decadal scale variations of the ocean-atmosphere system outside the tropics have been seen in the North Pacific (PDO) and North Atlantic (NAO)/Arctic Oscillation (AO). Separating these phenomena from tropical variability and obtaining sufficient observational records for analysis is an ongoing effort that remains a challenge for the community. To a large extent we know that the spatial structures of these climate modes of variability are determined by atmospheric internal dynamics. However, the extent to which ocean-atmosphere-land interaction can affect on their temporal structure is not clear. One of the central modeling issues is to determine feedback mechanisms, if they exist, that can give rise to coupled variability in the midlatitudes.

2. Diagnosis and modeling of the impact of sea ice and midlatitude SST anomalies on the circulation of the atmosphere

Communication of climatic signals from the ocean to the atmosphere is through the sea surface temperature. Because interannual to interdecadal memory in the climate system necessarily resides in the ocean, knowing where and how the ocean transmits information to the atmosphere is central to CLIVAR's goal of understanding interannual and interdecadal variability and assessing its predictability. In the tropics, where it is certain that the atmosphere responds robustly to SST anomalies produced by oceanic dynamics, this process is understood at least qualitatively. In middle and high latitudes, however, it is not known how, or even if, SST anomalies have a significant influence on the overlying atmosphere. Atmospheric model studies have produced a variety of mutually contradictory results. Theory has not been helpful, because in those cases in which atmospheric models respond strongly to extratropical SST anomalies, the response differs greatly from that predicted by linear theory. Observational studies have served to expose correlations between the atmospheric flow and the underlying SST field but have been unable to determine whether causality flows into or out of the ocean. In short, this has been a frustrating problem for the community. In the past few years, however, sufficient progress has been made that the midlatitude SST problem deserves a fresh look, taken with the expectation that its resolution is finally achievable.

Clearly the problem is important. If the atmosphere does respond to SST anomalies, the ocean can transmit information about low-frequency atmospheric anomalies both forward in time and across ocean basins. SST anomalies generated by the atmosphere during one winter can be hidden and preserved under the shallow warm-season mixed layer, then reemerge to influence the atmosphere during the following winter (Alexander and Deser 1995). A recent observational analysis by Sutton and Allen (1997) shows that such ocean temperatures can propagate for several years from west to east across the ocean, emerging further east each winter as SST anomalies.

The significance of the midlatitude SST problem for interannual predictability is highlighted by the recent successful simulation of the variability and trend in the North Atlantic Oscillation (NAO) obtained with the Hadley Centre model (Rodwell et al., 1999) when it is forced with the observed record of North Atlantic SSTs over the past fifty years. Similar successful reproductions of the NAO records in atmospheric models forced by observed SST anomalies have been obtained by M. Suarez (personal communication) using the GSFC model and J. Hurrell (personal communication) using CCM3. If, as these results suggest, a significant fraction of the year to year variability in the NAO is determined by the midlatitude SST field, and if, as indicated by Sutton and Allen, the SST field has elements that are predictable on decadal timescales, the potential exists for skillful year to year predictions of important elements of the climate around the North Atlantic basin.

One source of recent progress is the improvements in atmospheric models. In observations the forcing of the atmosphere by signals that are stored in and propagated by the ocean is usually hidden by the stronger local atmospheric generation of SST anomalies. Thus it is necessary to rely on models to expose possible feedbacks from atmospherically generated SST anomalies onto the atmospheric flow. Many models with relatively high resolution (a grid spacing of 4 or less), now show similar responses to SST anomalies in middle latitudes, an equivalent barotropic ridge above and east of a warm SST anomaly. In those few cases for which the dynamics of the response has been carefully analyzed, momentum fluxes by transient baroclinic eddies have been found to play a key role in maintaining the atmospheric response.

Recent work with new theoretical tools (Peng and Whitaker 1999) suggests this eddy feedback may be understood as follows: the linear response to heating associated with the SST anomaly modifies the large scale atmospheric flow in the vicinity of the storm track. These changes in the large-scale flow modify the shape, track, and strength of synoptic eddies in the storm track. This in turn alters the momentum fluxes by the eddies in such a way as to further alter the large scale flow. It has been suggested that because linear responses to extratropical SST anomalies are invariably weak, robust responses are possible only if the response stimulates one of the atmosphere's (or model's) intrinsic modes of variability. In the NCEP GCM Peng (personal communication) has found a close correspondence between the leading modes of month to month wintertime variability in the unforced model, and the model's response to a North Pacific warm anomaly. Furthermore, the dynamics responsible for maintaining the intrinsic modes of variability and the response to the SST anomaly appear to be similar.

Despite these promising developments, the problem is not yet solved. The dynamical mechanism causing the atmospheric response in the recent simulations using observed SST anomalies has not yet been exposed by diagnostic analyses. It is not known which portions or features of the North Atlantic tripole are most responsible for the atmospheric response. In most models that respond robustly to extratropical SST anomalies, including the Hadley Centre model, the anomalous flux of sensible and latent heat between the atmosphere and the ocean is opposite in sign to what is observed in nature - the fluxes damp the SST anomaly in the models (or would, if the SST were allowed to respond), while in nature, in most extratropical regions, the fluxes are the most important factor in generating the anomaly. It appears that these atmospheric model experiments capture only the feedback part of the interaction and not the initial generation of the SST anomalies, though this remains to be sorted out.

Recent experiments with both CCM3 (C. Deser, personal communication) and the French model (T. Schmitt, personal communication) show robust and potentially significant responses to anomalies in sea ice at its equatorward margin. The relative importance of SST and sea ice anomalies in generating an atmospheric response remains uncertain. The relative importance of anomalies in different oceanic regions is similarly unknown, as well as the significance of the atmospheric response in middle latitudes to local SST anomalies in comparison with the influence of tropical anomalies.

Finally, it is not known why some models with relatively high resolution do not respond to SST anomalies (the GFDL model appears to fall in this category - Y. Kushnir, personal communication), whereas in some models the atmospheric response is so strong that the anomalous heat flux at the sea surface reinforces the SST anomaly (Latif and Barnett 1994).

A workshop (Workshop on Extra-Tropical SSTAs, WETS) will be held this June at the Climate Diagnostics Center in Boulder. Results from at least eight different atmospheric models will be presented and compared. While it is possible that all of the above issues will be resolved at WETS, it is more likely that suggestive results will emerge but that the key issues can be settled only by systematic comparisons of the models using a shared set of SST anomaly patterns. WETS will provide a unique opportunity to launch the activity described here.

In summary, it is hoped that research funded under this element of CLIVAR this year will address the following issues:

- What is the relationship between the response of an atmospheric model to an SST anomaly and the model's climatology, in particular the position of the model storm tracks relative to the SST anomaly?

- In which regions do SST anomalies generate the most robust atmospheric responses, and why? In particular, what portion or aspect of the North Atlantic tripole is key to driving the NAO?

- What is the relationship between the response to an SST anomaly and the system's internal modes of low-frequency variability?

- What is the role of transient eddies of heat and momentum in determining the model response to SST anomalies?

- What are the roles of convective and boundary layer parameterizations and model resolution in determining a model's response to midlatitude SST anomalies?

- How does the response to an SST anomaly compare with that to a sea-ice anomaly? How are the dynamics of the response similar? How are they different?

Resolution of these issues will prepare us to move on, in future years, to understanding the dynamics of the coupled atmosphere-ocean system in the extratropics.

REFERENCES

Alexander, M. A., and C. Deser, 1995: A mechanism for the recurrence of wintertime SST anomalies. J. Phys. Oceanogr., 25, 122-137.

Latif. M., and T. P. Barnett, 1994: Causes of decadal climate variability over the North Pacific and North America. Science, 266, 634-637.

Peng, S., and J. S. Whitaker, 1999: Mechanisms determining the atmospheric response to midlatitude SST anomalies. J. Climate, 12, 1393-1408.

Rodwell, M. J., D. P. Rowell, and C. K. Folland, 1999: Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. Nature, 398, 320-323.

Sutton, R. T. and M. R. Allen, 1997: Decadal predictability in Gulf Stream sea surface temperature. Nature, 388, 563-567.

3. Enhanced observation, modeling and analysis of coupled ocean- atmosphere-land phenomena in the Atlantic and Pan American sectors, with emphasis seasonal-to-interannual climate variability.

The U.S. CLIVAR program seeks to understand and improve predictive skill of seasonal-to-interannual climate variability over the Americas by carrying out coordinated research on seasonal-to-decadal climate variability in the Pacific, Pan American and Atlantic sectors. In addition to its value in improving climate prediction, CLIVAR research on the natural variability of the Pan American climate will be crucial to detecting and understanding human impacts on climate. For example, there is growing consensus that the tropics will be an area of great change due to anthropogenic effects on climate. All estimates of projected greenhouse gas emissions and aerosol loading for the 21st century indicate the largest changes will occur in the tropical belt. Emissions of sulfur are projected to be quite large for the Central and South American region. The implications of this for changes in local circulations (e.g. monsoon) are significant. Deforestation and other anthropogenic changes are expected to be large as well.

The research described here focusses on seasonal-to-interannual phenomena in the Atlantic and the Pan American sector. Although empirical and diagnostic studies have described the seasonal shifts and variability of the heat sources and circulation over the tropical regions of Latin America and the mountainous regions of the Sierra Madre and the Andes, much remains uncertain. Inadequate (both in quality and coverage) observations as well as limited availability of historical data have limited progress to a significant degree. Over much of Latin America, model-based climate reanalyses are unconstrained and unvalidated by observed data. The structure of the low level winds that supply moisture from the tropics along the eastern slopes of the Andes, the precipitation patterns and associated divergent circulations, and the energy budgets over the Amazon and the Andean highlands remain largely unvalidated and incompletely understood. Dynamical understanding of seasonal march of rainfall and its variability over Mexico and Central America are incomplete. The meteorological observation and analysis system for Latin America must also be improved to describe and understand the relationship between seasonal- to-decadal climate variability and the nature and frequency of significant weather events such as hurricanes and floods.

The Atlantic warm pool (located off the coast of NE Brazil extending northward into Caribbean region) and the Amazon basin are the regions where major atmospheric heat sources are located in the tropical Atlantic sector. Deep convective activities in these regions exhibit a strong seasonal cycle. Over the ocean the seasonal migration of the ITCZ covaries with the underlying warm water. The monsoon convection over the neighboring continent also contributes to the pronounced seasonal cycle. The strong seasonality in the atmospheric circulation produces a well defined seasonal cycle in oceanic circulation in the region -- the North Brazil Current and North Equatorial Countercurrent both exhibit a strong seasonal variation. Superimposed on this seasonal cycle is a mode of climate variability in which the cross-equatorial SST gradient and the overlying atmospheric flow covaries on a decadal time scale. This mode of variability has a direct and significant influence on rainfall variability in the NE Brazil and Subsaharan West Africa.

Recent atmospheric GCM studies indicate that tropical Atlantic air-sea coupling takes place mainly in the Atlantic warm pool region. Simple coupled model studies show that it is in this region where delay is introduced in oceanic heat transport, setting a time scale for cross- equatorial SST gradient variation. Empirical and modeling studies also indicate that this is the region where the Pacific ENSO exerts the strongest influence on tropical Atlantic variability. More recent modeling studies suggest that feedback processes involving continental heating over the Amazon may also play a crucial role in cross-equatorial SST gradient variability. Although these preliminary studies point to the importance of land-atmosphere- ocean interactions over the Amazon basin and Atlantic warm pool, detailed mechanisms have not yet been fully explored.

This is an opportune time to accelerate research on the Pan American monsoon. A CLIVAR effort has been developing within the NOAA Office of Global Programs and NSF over the past four years. Plans for CLIVAR research activities in the Atlantic sector are at an advanced stage as the result of community meetings over the past two years (ACVE meetings in Dallas and Florence and COSTA in Miami). Rapid progress is being made through CLIVAR VAMOS and other international programs to coordinate research among Latin American academic and governmental organizations that observe and study climate. New satellite data sets are becoming available and model-based reanalyses of existing climate data are becoming more routine.

For FY2000, empirical, modeling and diagnostic studies are encouraged in the following areas:
* the dynamical processes responsible for the onset, demise and character of the continental scale monsoon over South America, especially the role of land surface processes,
* the dynamical and physical links between the seasonal march of atmospheric heat sources over Mexico and Central America and air-sea interactions over the Pan American warm pool region,
* cause-and-effect relationships for monsoon modulation on time scales from seasonal to interdecadal, including teleconnection patterns that span the Pan American region,
* the dynamical and climatic effects of the South American low level jet, and whether the system is similar to that over the U.S. Great Plains,
* the dynamical and physical mechanisms that organize atmospheric mesoscale convective systems on climatic space and time scales,
* the role of land surface processes in the seasonal changes of the monsoon and its variability on seasonal-to-decadal time scales.

The diagnostic studies envisioned here for the study of coupling between the Atlantic warm pool and the Amazonian region include retrospective analyses of observational and reanalysis data. The focus of diagnostic studies will be on the investigation of atmospheric boundary layer processes, convective structure over the warm pool and the Amazon basin, dominant processes in surface heat flux, land and ocean processes that control heat balance. Diagnostic studies of fully coupled model simulations are also needed to examine the models' ability in simulating tropical Atlantic mean state and climate variability and to determine potential causes of models' shortcomings. Furthermore, stand-alone and coupled modeling studies are envisioned to identify key feedback loops in the coupled land-atmosphere-ocean system and to formulate and test hypotheses.

The quality and coverage of the climate observing system over data sparse areas of the tropical Atlantic and Pan American sectors is a concern for the success of CLIVAR research. There is clear empirical evidence that climatic variability over Latin America is related to SST and mechanisms for evolution of tropical Atlantic SST have been advanced. Parts of the tropical Atlantic Ocean are just now instrumented with an array of surface moorings (PIRATA), satellite altimetry and surface winds are measured, limited observations with VOS XBTs continue while surface drifters and profiling floats are deployed sporadically. It is likely that more needs to be done to establish a tropical Atlantic observing system if the dynamics of the ocean-atmosphere-land connections are to be understood. Over the last two years a number of community meetings (ACVE meetings in Dallas and Florence and COSTA in Miami) have suggested modifications of the observing array including modifications of PIRATA to provide valuable information about the spatial extent of off-equatorial SST anomalies, moorings instrumented with high quality flux sensors to provide correction to large- scale NWP flux fields, instrumenting VOS-XBT lines with high quality flux sensors to measure the scales over which corrections apply, deploying drifters to monitor upper ocean heat and fresh-water storage, drifters to measure SST and surface currents, moorings and/or floats to monitor advection of ocean heat, measurements to better understand the quality of remotely sensed SST and to blend these measurements with in situ data and many more observational enhancements. If interaction of the climate over the tropical ocean and land are to understood we must measure the capabilities and costs of these different observing system elements and rationally design an appropriate combination.

The existing atmospheric sounding network over South America is less than adequate (in both coverage and quality) to study the atmosphere-ocean-land interaction. PACS and GEWEX LBA working through VAMOS have made some effort to temporarily increase the network. It is important to develop a path toward maintaining this extension and to take advantage of opportunities to contribute to the design and implementation of a permanent climate observing network for South America.

4. Design studies for ocean observations in support of CLIVAR objectives

A. Low latitude western boundary currents (WBCs) are important as links in the subtropical cells that bring water subducted in the subtropics to the equatorial thermocline where they can affect the close tropical air-sea coupling. In a zonal average, these cells consist of Ekman outflow from the tropics, subduction in the central subtropical gyres, equatorward geostrophic flow at thermocline level, and equatorial upwelling. The cells help determine equatorial SST, the amount of tropical heat exported to the subtropics, and thermocline stratification throughout the region. In the Pacific, anomalous advection in the cells has been hypothesized to modulate evolution of the ENSO cycle.

The zonal average picture, however, oversimplifies the three-dimensional nature of this circulation, in which (especially in the northern hemisphere), a great deal of the equatorward transport occurs not in mid- basin but in the narrow western boundary currents (the Mindanao Current in the north and the New Guinea Coastal Undercurrent in the south). The western concentration of the flow is due to the same Sverdrup dynamics that produces the midlatitude poleward WBCs, but to the north is enhanced by the thermocline ridge under the ITCZ forcing equatorward flow all the way to the west. Thus, low-latitude WBC transport of mass, heat and salt is a key process that needs to be observationally quantified to enable diagnosis and prediction of climate variability in the Pacific.

A number of considerations complicate the picture and make designing and observing strategy for these flows difficult. The North Equatorial Current (NEC) splits at a mean latitude of about 14^{o} N at the Philippine coast, feeding both the poleward Kuroshio and the equatorward Mindanao Current. This bifurcation is modulated by both local (east Asian monsoon winds) and remote effects (Rossby waves generated by basinwide winds). Because the (time-varying) latitude of the bifurcation helps determine how much NEC water ends up at the equator it is desirable to observe it. The spatial coverage required to do this argues against moored current meters. Also, the very strong current speeds and steep bottom topography make moored measurements especially challenging. Satellite altimetry is less useful here than in mid-basin because the strong flows occur so near the coasts and ageostrophic flow is a concern. A further complication is that a substantial fraction of the western boundary current flows depart the Pacific via the Indonesian throughflow. Some model studies suggest that most of the throughflow is fed from the South Pacific but this remains controversial and needs observational confirmation. A design study will evaluate the parameters needed to disentangle these questions and determine the appropriate mix of new instrumentation and the utility of the existing observational networks.

In the Atlantic, the low-latitude WBCs are a key aspect of the exchange and heat transport between the North and South Atlantic. Previous studies have shown that they exhibit substantial annual and semiannual variability which is probably larger than the anticipated interannual variability. This poses a serious challenge to the design of a boundary current observing system. The source water of the equatorial thermocline are believed to be largely of South Atlantic origin. Thus changes in the subduction rates or water mass properties in the subtropical South Atlantic may significantly alter the equatorial circulation while subduction variability in the subtropical north Atlantic might have a lesser effect. Recirculation gyres associated with the low-latitude WBCs pose an additional observational challenge.

B. Variability of the meridional overturning circulation (MOC) is directly linked to the upper ocean (warm water) transport, and hence to part of the gyre-gyre exchanges and the trans-equatorial flow, as well as to deep flows, such as those through inter-basin choke points and in deep western boundary currents. On decadal and longer time scales, changes in the MOC can influence the climate over the adjacent continents and may result in large scale climate change. Most coupled climate models suggest that the MOC will be weakened in the next few decades as a result of increasing CO2 concentration in the atmosphere. They predict a dramatically decreased oceanic heat transport in the Atlantic sector with global scale climate impacts. While there is considerable uncertainty in such projections, it is very likely that the existing ocean observing system is unable to directly measure the meridional overturning circulation on interannual time scales.

Modeling and diagnostic studies are needed to design a cost effective pilot MOC observing system capable of documenting the anticipated circulation change over the next decades. Emphasis should be placed on the Atlantic sector with a more modest effort on the global scale. Of particular interest is to quantify which of the existing observing networks and methods such as (SST, altimeter, floats, VOS, cable transports, hydrographic time series stations, mooring arrays, hydrographic sections, etc.) should be enhanced and what would constitute an optimal observational mix.

C. Complete observing systems over significant regions of the tropical and North Pacific and/or Atlantic.

Topics A and B above address specific aspects of the ocean circulation that planning studies have suggested are important to studying climate variability and may not be well described by the anticipated broad-scale ocean observing system. There are, of course, many other ocean processes and phenomena that may play a role in climate variability. For example subtropical WBCs, mixed layer mixing and entrainment, equatorial undercurrents, Rossby waves, subtropical subduction, west-wind drifts, coastally trapped waves, mesoscale eddy fluxes and coastal upwelling have all been implicated in theoretical, modeling or observational studies of climate variability. It is not clear what needs to be known about these phenomena to establish their roles in climate variability. Neither is it clear how well the anticipated broad-scale observing system, existing observations and data assimilation can quantify the aspects of these phenomena that are important to diagnosing climate variability. It is not yet clear how best to combine different kinds of data (e.g. altimetry and profiles, high-resolution XBT/XCTD sections and broad-scale profiles), what the trade-off between different types of observations and analysis errors are, or how much data assimilation modeling can substitute for observational density. Answers to these questions, particularly as the apply to the tropical and North Pacific and Atlantic would allow more effective analysis of the existing arrays, support refinement of the design of the anticipated broad-scale arrays, and support augmentation of these arrays with other observations.

5. Process experiment design studies: Pacific equatorial upwelling

Equatorial upwelling is, first, a key link in the subtropical cells (STCs) that bring the water that forms the equatorial thermocline from its surface ventilation in the subtropical gyres. Second, upwelling and the resulting heat flux is probably the largest and the least-known term in the heat balance of the surface layer of the equatorial Pacific.

The subtropical cells are the circulation in the vertical-meridional plane of the upper Pacific. The zonal winds of the tropics produce two basin- scale effects: first, Ekman divergence advects surface water away from the equator; and second, the thermocline tilts down to the west to balance the wind stress, and this tilt produces equatorward geostrophic currents in both hemispheres at thermocline level. This circulation is completed by subduction of surface water into the thermocline in the subtropical gyres, and by equatorial upwelling of thermocline water to the surface. All the water that participates in the STCs upwells on the equator, and therefore this is a chokepoint for the entire STC system, and an essential place to observe the variations of the cells and their connection to equatorial and basinwide winds.

Recent modeling studies of decadal modulation of the ENSO cycle have shown that quite small changes in the slowly varying background equatorial thermocline depth and slope can have significant implications for predictability. The sensitivity to the background arises because of the positive feedback between zonal wind and SST gradient on the equator. Observations suggest that changes in water properties advected around the STCs may be able to produce such small equatorial changes (though this has not been observed directly), and therefore that flow through the STCs may contribute to the decadal modulation of the ENSO cycle. Such modulation could come through variations of upwelling transport, or its depth of penetration, or through variation of the properties of the upwelled water. Observations of the spatial pattern and temporal modulation of equatorial upwelling, will therefore be an important link in the understanding of the influence of the gyre-scale variations on ENSO.

In addition to its role in the STCs, equatorial upwelling is the unsampled 800-lb gorilla of virtually all studies of the near-equatorial heat balance in the Pacific. While impossible to quantify with present observations, it is clearly the largest term in the regional heat budget, and appears as the largest uncertainty in such calculations. Without an adequate understanding of upwelling transport and its variations, we will not be able to quantify the flux of heat near the equator with any degree of confidence. Since this heat transport is thought to be a key aspect of seasonal and interannual variability, observations of upwelling and the fluxes associated with it is a key parameter for CLIVAR.

Because of its importance to our understanding of equatorial processes, numerous studies over three decades have sought to measure or estimate the magnitude and effects of equatorial upwelling. Most have relied on various indirect or inverse techniques. Estimates of the mean have been made from wind observations based on Ekman divergence, and from geostrophic constraints based on thermocline tilt. There has been only one attempt to measure (through the continuity equation) upwelling velocity in the central Pacific (during the TIWE experiment), which produced a vertical profile of upwelling speed at one location. However, the large-scale effects on SST, and from there to the coupled system, depend on the transport and its three-dimensional spatial pattern, not just the speed at one location.

To progress beyond existing results, an observational array will need to efficiently use sparse instrumentation to develop a three-dimensional picture that can be extrapolated to the larger region. This will likely involve taking advantage of the other observed fields from the TAO array and the broadscale network, including VOS XBT and ARGO profiles and buoy and satellite winds and SST. How can an array be sited to best do this? A design study will evaluate the necessity and utility of simultaneously sampling other parameters in various locations: temperature, and possibly salinity, and their gradients, and the local winds. Ultimately, the full impact of the observations and the most useful extrapolation may come through the use of an assimilating ocean model to produce complete fields. But it is not known at present how the necessarily sparse velocity observations can be appropriately assimilated into the models, so this must also be a subject for research.

6. Strategy for developing surface flux products: design study and proof of concept.

Significant progress has been made in obtaining accurate, in-situ, surface marine and air-sea flux measurements. It is now possible to make the observations on surface moorings needed to obtain accurate (~10 W m-2) for monthly values of net heat flux) surface fluxes and also to greatly improve the quality of surface marine and surface flux measurements made from Volunteer Observing Ships (VOS).

These improvements have come from developing new sensors and methods and also from improved understanding of how best to use data collected on the VOS that regularly transit much of the world's oceans. Work in WOCE and TOGA confirmed that surface moorings equipped with the new sensors are capable of collecting accurate time series of surface meteorology and of the air-sea fluxes of heat, freshwater, and momentum with high temporal resolution at fixed sites. It has been found that the deficiencies of surface marine observations made from VOS can be greatly mitigated by documenting the sensors, understanding their performance and determining the air flow around each ship. Further, these VOS can be instrumented with the new sensors to make their observations better and more complete. These VOS provide spatial coverage that complements the time series that can be obtained from the surface moorings.

Deployments of surface moorings instrumented to measure the air-sea fluxes in process studies in recent years have proven their capabilities. Monthly mean net heat flux observations have been compared to independent shipboard flux observations and net heat flux estimates averaged over several weeks have shown to be accurate to 5-10 W m^-2. With that accuracy, these moorings have been used in some of these experiments as the basis for adjusting marine observations and fluxes from other sources and thus to guide production of gridded flux fields. With this use in mind, some have labeled these moorings as surface flux reference sites.

Using the surface mooring data as a reference, it has been shown that improvements can be made to the VOS-based flux fields for the region immediately surrounding the site where the mooring is deployed. The VOS- based flux fields are derived using the observables (wind, SST, air temperature, humidity, pressure, rain, and observer's estimates of cloud cover and type) together with formulae that parameterize the air-sea fluxes in terms of these observables. These formulae, particularly for shortwave and longwave radiation, are empirical and sometimes based on observations made in a particular region of the world's oceans. The time series from the surface flux reference sites guide the choice of the regionally correct formulae to be used with the VOS and to provide the basis for correcting other biases in the ship-based data. The deployments of well-equipped surface moorings in TOGA and WOCE also documented the large errors possible in surface fluxes from the analysis fields of numerical weather prediction (NWP) models and in historical data sets such as the past ship-based climatologies. Monthly mean net heat fluxes have been found to have the wrong sign and to be up to 100 W m-2 in error. Such fields are inadequate for forcing ocean models and in diagnosing ocean's response to atmospheric forcing or the ocean's role in driving atmospheric variability. Comparisons of the buoy observations with the NWP surface fields (wind, SST, air temperature, humidity, rain) indicate that some of the surface quantities (wind, pressure, SST, air temperature, humidity) show better agreement, pointing to errors in the model's flux parameterizations. (Some models do produce large biases in quantities such as air temperature.) The largest errors in the NWP fluxes are often found in the fields influenced by the model's clouds (shortwave radiation, rainfall, and longwave radiation) or by the model's boundary layer parameterizations (latent heat flux). Performance of NWP models varies from region to region, pointing to the need for regional calibration/validation sites.

Satellites provide global coverage, and the rainfall, shortwave radiation, and surface wind fields they provide are of particular value as an alternative to those fields from NWP models or in conjunction with NWP fields. It is desirable to have surface flux fields in near-real time (within the month) for use in process studies and ocean data assimilation; however, the production of some fields from satellite data now has delays of up to 5 years. Because of aerosols and regional differences in the atmosphere, it is anticipated that quality of many uncalibrated, satellite- sensed fields will vary regionally.

Discussions among the various groups have led to a suggested strategy for obtaining surface flux fields. Surface flux reference sites (well-equipped surface moorings measuring wind speed and direction, air and sea surface (1 m depth) temperature, relative humidity, barometric pressure, incoming shortwave and longwave radiation, and rainfall every minute) would be established at select sites in the world's oceans. They would provide accurate time series for regional calibration/validation of the data from VOS, of the NWP analysis fields, and of satellite data. They would also be incorporated in ongoing atmospheric and coupled model intercomparison projects (AMIPS, CMIPs) to judge the success of these models in producing realistic surface fluxes and in diagnosing model problems and motivating model improvements.

The high quality time series obtained at select points by the surface flux reference sites would be extended spatially using the VOS, NWP, and satellite fields. However, because the spatial representativeness of the regional corrections indicated by the surface flux reference sites to these other data sets is not known; an additional in-situ element is suggested. This would be the installation on select VOS lines of improved sensor sets (adding incoming shortwave and longwave and rain as well as better SST, air temperature, barometric pressure, humidity, and wind speed and direction sensors). The data from these high quality VOS would be used to verify and perhaps change the regionally specific choice of flux formulae and error corrections made based on the surface flux reference sites.

The data from the surface flux reference sites, high quality VOS, and satellite-derived surface winds can be used to guide the choice of which NWP fields (several different models should be examined, including NCEP, ECMWF, BMRC, JMA) and use of wind speed and direction, SST, air temperature, and humidity is anticipated) are most useful in generating the global surface flux products and also to make corrections to those fields. These fields would be used with bulk formulae to produce wind stress, latent heat flux, and sensible heat flux. It is anticipated that the NWP radiation and precipitation fields may not be usable due to large errors and unrealistic spatial variability. Thus, a method is needed to either use bulk formulae alone or in conjunction with satellite data to produce the shortwave and longwave radiation fields and the rain field. In doing this, the surface flux reference sites and high quality VOS provide a check on the success of such procedures. At present, satellite surface radiation and precipitation products are difficult to obtain in a timely fashion and may be available only after such space/time averaging that they are less frequently sampled than the desired 6 hourly, 1 degree grid. An alternative approach would be to develop a blend of data from various sources with appropriate recognition of the errors in the in-situ, NWP, and satellite data in the manner, e.g., of Atlas, R. , Hoffman, R.N., and Bloom, S.C. (Surface wind velocity over the oceans, In Atlas of satellite observations related to global change, R. J. Gurney, J. L. Foster, and C. L. Parkinson (eds.)).

At present, 6 hourly, 1-degree surface flux fields have been produced in support of several WOCE and TOGA process studies. The goal for CLIVAR is to do this globally on a routine basis. In doing so, great benefits would be derived from ongoing partnerships among those collecting the in-situ data and the NWP and satellite groups. It is felt that more of the in-situ data could be assimilated by NWP models once its quality and reliability established and that an ongoing intercomparison of high quality in-situ fluxes and those produced by the models would lead to improvement in the models and greatly ability to base the desired flux fields on NWP gridded fields. Partnership with those seeking to derive and deliver surface marine and flux fields from satellites is essential. The present production of the MCSST fields is a good example of ongoing use of in-situ data to calibrate satellite fields and of near real time delivery of the resulting global fields. This would serve as a model for developing satellite-based shortwave radiation, wind speed and direction, and precipitation fields for use in producing the global surface flux fields for CLIVAR.