THE PACIFIC BASIN EXTENDED CLIMATE STUDY

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1 - INTRODUCTION

Largely as the result of modeling efforts and an intensive observational network established under the internationally coordinated TOGA program, the basic physics of the El Niño/Southern Oscillation (ENSO) cycle are becoming understood. Because their evolution depends mostly on equatorial thermocline depth variations that are controlled by tropically trapped planetary waves, individual El Niño events can be described, diagnosed and predicted largely based on conditions in the tropics alone. Based on observations made by the ENSO observing system that continued after TOGA, predictions are now routinely made of tropical Pacific sea surface temperature (SST) and the associated atmospheric climate variability. In addition to changes in the tropical Pacific associated with the ENSO cycle, progress has been made towards understanding and predicting the ENSO time-scale atmospheric teleconnections from the tropics to mid-latitudes, making possible skillful seasonal climate predictions over significant portions of the globe.

The remote atmospheric circulation patterns associated with ENSO also modify wind and cloud forcing of the midlatitude Pacific Ocean, which leads to a dynamical adjustment of the subtropical and subpolar gyres on interannual to decadal time scales. Such atmospheric responses to remote forcing potentially impact gyre circulation, watermass formation, thermocline stratification, along with mixed layer and SST variability in the subtropical gyres and subarctic North Pacific, but these effects are much less well understood. At the same time, patterns of mid-latitude climate variability, such as the Pacific Decadal Oscillation, may affect the way that the ENSO cycle evolves by modulating ocean properties, providing atmospheric triggers for ENSO and/or generating oceanic thermal patterns that precondition the tropical ocean state for ENSO variations.

In addition to the ENSO cycle, the Pacific is observed to exhibit climate variability on interannual to decadal time scales. On decadal time scales, large-scale SST variability of the northern hemisphere is maximum in the mid-basin North Pacific Current but is correlated with tropical SST. This basin-scale SST variability can be well described by an antiphase relation between the North Pacific Current and an equatorially centered pattern that resembles an ENSO anomaly. This Pacific Decadal Oscillation (PDO) is well correlated with an atmospheric pattern with structure similar to the Pacific/North American pattern that dominates shorter-term sea level pressure anomalies. Leetmaa reports that half of the skill of NCEP seasonal forecasts depends on knowledge of decadal variability in the Pacific, knowledge that is now derived mainly from persistence.

How much of the PDO, and other less energetic midlatitude decadal variability, is a remote response to decadal modulation of the ENSO cycle and how much is due to internal mid-latitude dynamics is a subject of active debate. Several distinct coupled ocean-atmosphere mechanisms for Pacific decadal variability have been proposed (see below), some involving teleconnection from the tropics and others with dynamics internal to the North Pacific ocean-atmosphere system. In all those theories in which the ocean plays an active role it is lateral advection that is key. Until the mechanisms for decadal variability are understood it is unlikely that decadal climate predictability can be assessed, let alone realized. An observational basis for improved understanding of this climate variability (and related oceanic biological and biogeochemical phenomena) must be developed and incorporated into improved models.

There is significant variation in how different ENSO events develop and in how well different prediction systems forecast each event. Coupled model predictability experiments suggest that the character of the ENSO cycle is quite sensitive to the background state of the equatorial thermocline because this determines how efficiently equatorial upwelling cools SST. There is, therefore, great interest in understanding the processes that modulate the background state of the tropical Pacific. Among the most important processes are subduction and oceanic advection, working slowly on decadal time scales, that could potentially carry mid-latitude-generated anomalies to the equator.

The general ocean circulation in the tropical Pacific and the tropical limbs of the subtropical gyres is intimately connected to the prevailing easterlies. These produce surface Ekman outflow from the tropics and (by tilting the thermocline down to the west) a geostrophic inflow below. The northern and southern cells are completed by equatorial upwelling and subtropical subduction. (This simple zonal average picture of the subtropical cells (STC) is complicated by the ITCZ, which lifts the thermocline and pushes the equatorward return flow to the western boundary current.) As a result of this shallow overturning, water that flows into the equatorial undercurrent and rises into the east Pacific cold tongue originated at the surface in the subtropical gyres. This pathway potentially provides a way for the subtropics to modulate the tropics and, thereby, affect evolution of the ENSO cycle. Therefore, relatively small variations of either the speed of the circulation in the STCs or of the properties of the advected water may modulate the ENSO cycle.

The Pacific Basin Extended Climate Study (PBECS) is proposed to describe, understand and model climatic variability within and over the Pacific Ocean north of the Southern Ocean. Within today's understanding, the climate phenomena of interest are ENSO, especially its poorly-understood advective and mixing processes, decadal variability like the Pacific Decadal Oscillation, and the decadal modulation of ENSO and its predictability. It would also not be surprising if similarly important signals are revealed when more observations become available in the less-explored South Pacific.

The primary goal of the PBECS is to develop the observational basis to quantitatively test, and thereby improve, models of the ocean processes that affect variability of SST and the upper ocean budgets of heat and freshwater. Specific objectives are:

* to obtain a quantitative description of the low-frequency, three-dimensional circulation and

associated thermohaline structure of the upper Pacific Ocean with sufficient accuracy to measure advective fluxes and their divergences;

* to understand the processes that couple the tropical and subtropical Pacific oceanic gyres on climatic time scales and to test hypotheses about the role of the ocean in basin-scale variability on a broad range of climate time scales; and

* to test models of the circulation of the Pacific Ocean and its intrinsic modes of variability and coupling with the atmosphere.

2 - PROCESSES AND HYPOTHESES TO BE STUDIED

Despite remarkable progress during TOGA, many questions remain to be answered to establish a quantitative description of the climatically important oceanic processes in the tropical Pacific beyond the relatively straightforward equatorial waves. Of particular relevance are the dynamics of heat flow in the eastern Pacific equatorial cold tongue and the tropical freshwater/salt budget. The zonal gradient of equatorial SST is determined in part by the rate at which water in the cold tongue is warmed as it flows westward toward the warm pool. Active processes include upwelling, zonal advection, meridional advection, diapycnal and lateral mixing, and warming by air-sea fluxes. The same processes determine the very sharp meridional gradients of SST and sea surface salinity found in the eastern tropical Pacific. The relationship between variability of thermocline depth, which is driven by ocean dynamics, and changes of equatorial SST, which affects the atmosphere, is set by the cold-tongue heat budget so it is crucial to model it correctly. All models simulate cold-tongue warming during El Niños, but the balance of terms differs among them and, consequently so do their responses to differing atmospheric forcing and to slow modulation of the ocean background inside of which the ENSO cycle evolves.

Southern Oscillation and equatorial SST indices show that the period and amplitude of the ENSO cycle varies on decadal time scales, and this is not yet understood. Interest in this longer-term variability has increased considerably since 1990, as the tropical Pacific appears to have remained in a warm state for several consecutive years during half of the decade and especially with the occurrence of the very strong 1997-98 El Niño. This recent behavior contrasts markedly with the 1970s and 1980s, when warm events occurred fairly regularly with a period of about 4-5 years. Such nonstationarity has challenged the prediction skill of coupled models of ENSO and raised the question of how the low-frequency behavior of other aspects of Pacific climate might be interacting with the ENSO cycle.

Over the past few years, the realization that the physical processes important to the development of individual El Niño events are not sufficient to describe the slower evolution of Pacific climate has inspired a wide variety of theoretical and model calculations, and diverse hypotheses have been (and continue to be) emerging. Fundamental to many of these is the idea that the next step in understanding climate variability beyond the ENSO cycle involves more than the tropics: longer time scales allow the influence of broader meridional scales to be felt. For decadal variability of the ENSO cycle, there is also a contrary hypothesis: that low-frequency modulation may be due to noise in the equatorial system; for example debris from one El Niño might leave the equatorial background slightly different for the next. However, at least four hypotheses have appeared in the recent literature suggesting mechanisms for low-frequency (decadal) coupled ocean-atmosphere climate variability that extends at least through the subtropical gyres.

Very brief summaries suggest the range of plausible processes:

* Latif and Barnett (1996). A delayed-negative feedback is provided by extratropical wind-driven Rossby waves in the North Pacific Ocean that take five to ten years to alter the transport of the subtropical gyre. This changes the poleward transport of heat by the Kuroshio and thereby changes the sign of SST anomalies along the west-central subarctic frontal zone. The SST pattern alters the prevailing westerly winds and wind stress curl, forcing extratropical Rossby waves of opposite sign.

* Zhang, Wallace and Battisti (1997). A delayed-negative feedback is provided by extratropical wind-driven Rossby waves that take 5-10 years to propagate pycnocline depth anomalies from the eastern ocean to the western boundary, where they provide a weak but steady influence upon equatorial pycnocline depth and SST anomalies via reflected Kelvin waves, followed by an immediate-negative feedback changing the sign of extratropical wind stress curl anomalies (i.e., driving Rossby waves of opposite sign) via meridional atmospheric teleconnections.

* White and Cayan (1997). A delayed-negative feedback is provided by the equatorward propagation of extratropical covarying SST and SLP anomalies into the tropics that takes 5-10 years to change the sign of equatorial SST anomalies, followed by an immediate-negative feedback changing the sign of extratropical SLP and SST anomalies via meridional atmospheric teleconnections.

* McCreary and Lu (1994), Gu and Philander (1997). A delayed-negative feedback is provided by the subduction of extratropical upper ocean temperature anomalies that take 5-10 years to advect along isopycnal surfaces to the equator, where subsequent entrainment into the equatorial mixed layer changes the sign of equatorial SST anomalies, followed by an immediate negative feedback changing the sign of extratropical wind and upper ocean temperature anomalies via meridional atmospheric teleconnections.

The recent emergence of this variety of plausible (mostly not mutually exclusive) hypotheses that have emerged from model experiments makes it fruitful to begin testing specific ideas against observations.

3 - NEEDED OBSERVATIONS

The concept of the Pacific Basin Extended Climate Study is to observe enough of the forcing, internal structure and transport of the Pacific Ocean that, when combined in data-assimilating models, it will be possible to discriminate among various hypotheses for decadal climate variability and decadal modulation of seasonal-to-interannual variability. This is the conception of many process experiments but has never been employed over the scale of a basin or the decade time-scale of the phenomena of concern for PBECS. It is necessary to cover the entire Pacific north of the Southern Ocean because this is the region in which the variability of interest is observed and which hypotheses suggest is connected by oceanic processes that feedback to sustain that variability. It is necessary sustain the observations for at least the decadal time scale of the phenomena of interest.

Much of the sustained observational basis needed to investigate and substantiate, modify or dismiss the various hypotheses above is the same. These include observations of:

* air-sea fluxes of momentum, heat and freshwater - these will probably be best made by combining improved operational NWP initialization models with satellite measurements of surface winds, clouds and radiation, and with isolated high-quality observations of surface parameters to correct and verify procedures for assimilating all available data into the needed flux fields;

* near surface conditions that describe the ocean's immediate response to, and forcing of, air sea interaction - variables to be measured include sea-surface temperature, near-surface salinity, properties of the mixed layer and a census of newly formed water masses and are most likely to be made from a combination of surface and profile observations yet to be determined;

* changes in the storage of heat and freshwater - these include satellite observations of sea level elevation supplemented by in situ profiles of temperature and salinity to describe the vertical structure associated with altimetry signals and separate the contributions of temperature and salinity;

* advective and eddy transports of mass, heat and freshwater in the interior ocean - surface altimetry supplemented by profiles of ocean temperature and salinity and direct measurements of flow below the surface layer (to define the barotropic current contribution to sea level elevation). ARGO plus expendables can provide this in the ocean interior but high resolution measurements will be needed in some narrow currents, along the equator where geostrophy fails and in the wind forced layer.

* high temporal and spatial resolution sampling of surface wind and ocean temperature, salinity and velocity in the equatorial zone - continuation and adaptation of the existing TAO array and ENSO observing system.

* transport processes in the Kuroshio and its extension - repeated sections or moored observations along the length of the Kuroshio including continuation of the repeated section southeast from the Shikoku island; repeated hydrographic and expendable sampling of the high air-sea flux region around the Kuroshio and its extension.

The vision of the PBECS observing system grows from the success of the ENSO observing system, both practically, in relying on many of the same methods, and conceptually, in being based on a broadscale sustained observing network with embedded process studies that is integrated inside assimilating ocean models. The elements of the proposed in situ network function in synchronism with each other to develop a three-dimensional picture of the evolution of the tropical and subtropical ocean and the processes that cause its variation.

In order to observe the ocean circulation and processes in the heat/freshwater/momentum balance with sufficient accuracy and resolution to achieve the PBECS objectives, something like the following in situ observational network will be required. As the description above makes clear, the in situ network depends on satellite observations. AVHRR or microwave SST, scatterometer winds, and altimetric sea surface height are needed and time series of remotely-sensed precipitation and cloud coverage/type are extremely desirable. Similarly the discussion assumes that the needed surface and high-temporal-resolution profiles from the TAO array that are needed in the rapidly responding equatorial zone will be continuously available.

The proposed in situ observing elements include:

A. A broad-scale sustained network of temperature and salinity profiles. The ARGO array of profiling floats is the heart of the broadscale sampling for PBECS. The purposes of these measurements in PBECS are to i) describe the state of the ocean for assimilation into models; ii) provide subsurface data to complement and amplify the interpretation of altimetric sea surface height; iii) measure mixed layer depth as a parameter in estimating the effects of surface fluxes; iv) allow diagnosis of ocean properties along isopycnals for studies of gyre-scale advection; v) illustrate the mid-depth circulation through float motion at their parking depth. The ARGO goal of one float per 3-degree square reporting every 10-14 days is believed adequate for broad-scale coverage although as data becomes available this density needs to be reevaluated. Further the tradeoff between XCTD/XBT coverage (where it is possible) and floats must be reevaluated as technology develops.

B. Repeated high-resolution XBT/XCTD sections from voluntary observing ships (VOS), occasionally supplemented with hydrographic sections sampling a full range of properties, across the Pacific will be needed to monitor time variations of geostrophic transport by both large-scale flows and mesoscale features. ARGO floats will not have the spatial density to compute geostrophic flows with sufficient accuracy. The time series of transport of heat, freshwater and selected water types through sections will be primary data for deducing the transport associated with various modes of climate variability in the central ocean and in concentrated boundary currents. The same VOS should support accurate SST measurements and high-accuracy measurements of the surface parameters associated with air-sea fluxes. It may someday be possible to combine altimetry and lower density ARGO profiles to infer these transports but years of high-resolution sections will be needed to train and verify the procedures to do this. It may also be possible someday to supplement VOS sections across boundary currents with sections gathered by small autonomous vehicles operated from shore.

C. Direct velocity measurements of both low-latitude western boundary currents, that feed the equatorial undercurrent, and the equatorial currents themselves. Because these are not geostrophic, they are not well-sampled by profiling floats, satellite altimetry or VOS sections. Direct measurements of the equatorial currents, sufficient to resolve their zonal, meridional and vertical scales and variability will be needed. The boundary currents are crucial links by which subtropical water reaches the equator, central elements in the tropical-subtropical overturning by which subducted anomalies can reach the equatorial zone and can be modulated by cross-basin Rossby waves generated in the subtropics. Of particular interest is the bifurcation of the North Equatorial Current at the Philippine coast where it feeds both the Kuroshio and the tropical return to the tropical gyre in the Mindanao Current. This bifurcation is known to vary substantially from year to year and this variation can not only affect both the tropical and subtropical ocean variability but also the water exchange between the Pacific and Indian Oceans.

D. Direct measurements of the Kuroshio and its extension. Although one of the most extensively observed ocean currents, our knowledge of variability of the Kuroshio system is still limited. This is mainly because most sampling to date has been widely separated hydrographic sections and systematic continuous observations are lacking. The mechanisms behind variation of Kuroshio, such as its large meander and its relation to other inter-annual variations like ENSO or its decadal variation, need to be established. Since it is clear that bottom topography plays an important role in the Kuroshio, observations of detailed current structure and bottom pressure may be required. The Kuroshio extension is an area of extreme heat and moisture exchange with the atmosphere and is an area where the ocean affects the atmospheric circulation most effectively. At the same time, this cooling forms subsurface, low potential-vorticity waters, like subtropical mode water or the central mode water, that can subduct and alter the density structure in the tropical region.

E. Measurements of the spatial pattern of equatorial upwelling transport and its variability. All the water that participates in the subtropical- tropical exchange reaches the surface via equatorial upwelling, yet this has been one of the most difficult processes to observe or infer indirectly. Diagnosing the effects of upwelling will require knowing the depth from which upwelling draws and the properties of the upwelled water, since these speak to the sources in the subtropics. Because upwelling is both a local response to equatorial winds and a component of the inter-gyre exchanges in both hemispheres, it will be important to establish the connection to both of these elements. Since a field study to observe upwelling must span a relatively short duration and limited area, it should lead to the development of parameterizations so that longer-term and more widely-spread platforms (e.g. the TAO array and remotely-sensed SST and sea surface height) can be inverted to infer the complete upwelling circulation.

F. Measurement of the air-sea fluxes throughout the basin to determine the processes that lead to changes in SST and formation of new water masses. This includes the central subtropical gyres where there is a need to diagnose the processes forming the winter mixed layer and eventually establishing the characteristics of the equatorial thermocline as these water masses subduct and are advected through the subtropical cells. Fluxes of heat and freshwater, and the mixing that produces the winter mixed layer are needed. Similarly, throughout the tropics fluxes are needed to diagnose the causes of anomalies that appear there and potentially affect the atmosphere directly or are advected to the equatorial zone. At present, surface fluxes are among the most poorly-determined fields in NWP models, so the object of these necessarily-sparse in situ observations is to use a few well-chosen reference sites to improve the models' parameterization of the surface fluxes and radiation fields. Needed observables are wind, SST, air temperature, humidity and rainfall, net short- and long-wave radiation together with simultaneous vertical upper-ocean profiles to diagnose the rate and penetration of mixing.

4 - MAKING A COHERENT WHOLE: INTEGRATION OF OBSERVATIONS AND MODELING

Understanding the mechanisms of climate variability will require integrated observational, process and modeling studies by oceanographers that have been coordinated with analogous studies by meteorologists and hydrologists. Any conceivable basin-wide network of sustained observations will be too thin to support, by themselves, the detailed quantitative studies of specific climate modes that are required to understand them. Concentrated field studies can elucidate specific processes that are key to climate variability, but they do not last long enough to study the variability itself. What is needed are observations that span the time and space scales of routine observations, but which are designed to describe specific processes and accomplish effective tests of model simulation as is usual in process experiments. Without the kind of basin-wide, long-term observational effort that TOGA conducted in the study of ENSO, climate model testing will be ambiguous, leading to numerous publications on how things might work but providing little confidence that we do understand the mechanisms of climate variability.

What is proposed is a new type of study that integrates sustained observations and modeling into a single examination of the phenomena of basin-scale climate variability that is designed with the philosophy of a process experiment. Separate, even if coordinated, studies are not enough. Additional well designed long-term observations, model development and sensitivity studies, and well designed processes studies of the processes affecting climate variability will all be needed. But quantitative understanding of the large-scale phenomena that are coupled to the atmosphere on seasonal to decadal time scales can only be gained by observing and diagnosing them on their own scales. Inevitably this will require developing new methodologies to closely link observations and modeling on basin- and climate-scales. This lesson was made clear by the TOGA experience where basin-wide observations were involved with data assimilation and predictive modeling in a productive feedback loop.

The focus of this integrated study will be quantitative diagnosis and prediction of upper ocean heat and freshwater transports and transformations. The approach will involve using an economically efficient observing system with significantly greater coverage and density than present routine observations to develop a time series of basin-scale analyses of the upper Pacific Ocean. These will be assimilated into, and in large measure analyzed inside, a comprehensive modeling effort using a range of model sophistication and assimilation methods. It is this focus on model assimilation of a coordinated and sustained data set that defines PBECS.

With the exception of lateral advection, many ocean processes can be reasonably well dealt with by low resolution, quasi-linear models. For a class of short-term phenomena, mixing is important only in the surface mixed layer where it can be parameterized. Indeed, early successes in predicting the ocean dynamics of ENSO were based on quasi-linear, low-resolution models in which all the pertinent mixing that changes SST were simply related to the depth of the tropical thermocline. As we turn to decadal variability, like the modulation of ENSO or the Pacific Decadal Oscillation, the balance of terms changes. Time derivative terms in balance equations become less important while advection and mixing become more important. For example, in the meridional circulation that links subtropical and tropical gyres on decadal time scales, mixing is important all along a parcel's advected path which carries it through both broad currents like the

NEC and confined currents like the Mindanao Current and the Equatorial Undercurrent. At lower frequencies mixing cannot be treated as confined to the mixed layer; improved parameterizations will be needed before models can adequately simulate these processes and observations of water mass transformation will be needed to initialize and test these models. Similarly, because advection is a fundamentally nonlinear process, high model resolution will be needed to accurately represent advective fluxes and, consequently, higher resolution observations will be needed than might suffice for assimilation into ENSO models.

A number of assimilation efforts have been developed for ENSO prediction. Some of these systems routinely perform analyses for the regions under consideration here, but they need to be enhanced and extended for PBECS. Present OGCMs have several inadequacies that simple assimilation will overcome. Consequently, much of the information content of in situ observations is now used up in correcting gross model errors, and the more subtle signatures of interest to decadal climate can be swamped. Therefore we envision an interactive process in which analysis of the broadscale observations, improved air-sea flux measurements and intensive process studies described above are used to improve model physics and parameterizations, making the models more able to produce realistic gridded fields from the broadscale observations.

5 - SUMMARY

The network of existing long-term observations has disclosed decadal variation of the ocean/atmosphere climate in the Pacific basin and decadal modulation of the evolution of ENSO and its predictability. Decadal variability is already a significant factor in climate predictability and modulation of the ENSO cycle seriously affects seasonal-interannual climate prediction. Various models have been advanced to explain the observed low-frequency phenomena and many of these models centrally involve oceanic advection of heat as a mechanism for delayed feedback to the atmosphere.

The present observational network and analysis methods are inadequate to discriminate among the proposed mechanisms for decadal phenomena. It is proposed to augment existing long-term observations (particularly satellite altimetry, the ENSO observing system, and repeated high-resolution expendable and hydrographic sections) with sufficient new observations to constrain data-assimilating models well enough that the processes affecting decadal variability and decadal modulation of ENSO can be studied in detail. This Pacific Basin Extended Climate Study (PBECS) is an extension of the process-study methodology to phenomena with basin scales and decadal periods. Expansion of some of the existing observations plus the ARGO array of profiling floats, sustained observations of boundary currents and other special regions, selected time series of high-quality surface meteorological measurements and a sequence of imbedded process experiments are the main new observational elements of PBECS. The key will be using these observations in an active effort to improve data assimilation, which will necessarily involve improving the dynamical models upon which assimilation is based, and sustaining this process long enough to carefully study the decadal phenomena of concern.