Prospectus for a Pacific Basinwide Extended Climate Study

By R. Lukas, R. Davis, W. Kessler, et al.

Version 3.1
September 1998

Prospectus for a Pacific Basinwide Extended Climate Study

Overview

It is proposed to put in place in the Pacific Ocean a long-term process experiment to test and improve dynamical models of the ocean processes that participate in climate variability. This project is based on the belief that the best hope for climate prediction and assessment lies in models that have sound approximations of important physics and that are initialized with numerous accurate observations. Certainly successful climate prediction will require models of, and data from, the atmosphere, land, cryosphere and ocean. Nevertheless, the models of each medium must be accurate and well understood before coupling them will be very useful. The proposed project represents the conjunction of three thrusts in modern oceanography: the rapidly developing ability to combine ocean models with observations, the ability to make long-term broad-scale observations of the ocean using new techniques and the intense interest in the Pacific Ocean as an important element in potentially predictable climate variability. By combining data from a relatively dense array of long-term observations with modern ocean models and assimilation techniques we believe the research community can (a) develop greatly improved understanding and models of the ocean processes of climate, (b) provide intensive and high quality observations of ocean and surface meteorological variables that will be useful in multi-disciplinary CLIVAR studies of climatic air-sea interaction, (c) both improve understanding of what ocean observations are needed to initialize ocean models and begin collecting them, and (d) develop a dynamically consistent description of the ocean region studied that will be useful in other multi-disciplinary studies of biological and/or chemical ocean variability.

Energetic large-scale variability in the upper Pacific Ocean exists on time scales from roughly seasonal through decadal, much of which is not well measured, not yet well-tested in models and not utilized in climate predictions. This oceanic variability has strong relationships with the tropical and extratropical atmosphere, through ENSO and the dominant atmospheric teleconnection patterns (principally the PNA), both of which have significant influence over North American climate fluctuations. These atmospheric modes exhibit broadband variability in this range of time scales. The adiabatic aspects of advection in the shallow tropical ocean that play a central role in ENSO on time scales of up to a year or two fairly well explored. However, neither the oceanic connections to the extratropical oceans nor the diabatic processes below the surface layer have received adequate attention because they become important only on longer time scales.

The role of equatorially trapped waves in affecting anomalous sea surface temperature (SST) is understood but the full mechanism by which a shallow thermocline causes cold SST is not well-modeled. Tying down the relative roles of varying upwelling, meridional advection, lateral mixing, and changing air-sea fluxes in the maintenance of SST in the tropical Pacific is important because there appears to be a decadal modulation of the predictability of ENSO using today's models.

While the seasonal variability in the extratropical ocean is initiated by the atmosphere, slower feedbacks onto the atmosphere are able to modify its subsequent evolution. Local feedbacks can result from stored heat or local surface layer entrainment while remote feedbacks can involve oceanic advection of heat or wind-induced wave motions that alter thermocline depths. Present observations have not permitted adequate testing of the emerging spectrum of theories and models of decadal climate variability and a long term effort combining *in situ* and remote observations with data assimilating models is needed.

Thus, we propose a Basinwide Extended Climate Study (BECS) in the Pacific Ocean to describe, understand and model climatic variability within and between the tropical and subtropical Pacific Ocean. Within today's understanding, the climate phenomena of interest are ENSO, decadal variability like the Pacific Decadal Oscillation, and the decadal modulation of ENSO and its predictability.

Perhaps the most immediate payoff of a Pacific BECS will be in testing ideas about the processes of decadal variability of ENSO. An underlying hypothesis of the project is that this variability results from changes in the strength of the Pacific Subtropical Cells (STCs). These meridional cells carry cool thermocline water from the subtropics to the equator, where it upwells in the eastern equatorial Pacific to form the cold tongue. Variations in either the strength or temperature of the STCs may alter SST in the cold tongue, providing a feedback to the atmosphere in a way that affects ENSO. Recent work has indicated that STC strength is determined by off-equatorial winds located near the boundaries of the tropical ocean (the Trade Winds), and that temperature anomalies in this circulation feature are influenced by subduction at even higher latitudes. Thus, STC variability results from quite different processes than the largely wind-driven, adiabatic mechanisms responsible for ENSO. It also connects the subtropics where decadal SST variability is largest with the tropics where ENSO is centered.

The scientific objectives of this proposed Pacific BECS are to measure this oceanic variability, to test existing models of it, and from this testing improve the models and our understanding of the processes. Activities along this way will be to identify the principal three-dimensional space-time patterns of temperature and salinity anomalies and their circulation pathways; assess the controlling dynamical processes; compare existing models of these processes with improved observations; develop the ability to simulate them in ocean and climate models, both independently from the observations as well as through data assimilation and forecasts; and to determine the Pacific Ocean's coupling and feedback with the atmosphere and thus its role in climate variability. Practically, the Pacific BECS will cooperate with various other studies which are dealing with related processes in the Pacific (especially CLIVAR) and provide the physical framework for understanding related climate-scale biogeochemical variability.

While the CLIVAR program is organized to take separate multi-disciplinary views of seasonal-to-interannual and decadal climate variability, the practical aspects of field work and modeling studies motivate a single ocean study that is focused on seasonal to decadal time scales and closely coordinated with other CLIVAR studies. The reasons for this crosscut are twofold. First, it appears from the ocean components of present comprehensive models that the quantitative tests needed to improve these models cannot be carried without more extensive and intensive observations extended over many years. Neither the models nor the needed data differs much between seasonal-to-interannual and decadal studies. Second, the difficulties of augmenting the present observing array are largely logistical and do not differ significantly between time scales. Thus the Pacific BECS is intended to address parts of CLIVAR projects G1 (Extending and Improving Predictions Based on ENSO) and D4 (Pacific and Indian Ocean Decadal Variability).

The purpose of this Prospectus is to develop the concept of a Pacific BECS by summarizing the key scientific questions and outlining how these questions would be addressed with extended basin-scale observational and modeling studies. Another purpose for this prospectus is to begin a dialog with other projects addressing climate variability in the Pacific and other oceanographic projects that could benefit or contribute to the near-real-time picture of the tropical and subtropical Pacific we hope to develop. A third purpose is to suggest the infrastructure required to advance the concept of P-BECS.

I. Introduction

The basic physics of the El Niño/Southern Oscillation (ENSO) are understood and predictions are routinely made of tropical Pacific sea surface temperature (SST) and associated atmospheric climate variability. ENSO involves a readjustment of the tropical oceans through planetary wave processes initiated by wind stress changes. The resulting ocean circulation changes the SST that the atmosphere senses, leading to an unstable coupled interaction. Progress has been made towards understanding the atmospheric connections between midlatitudes and the tropics on ENSO time scales. The atmospheric circulation patterns associated with ENSO also produce a variable forcing of the midlatitude Pacific Ocean which leads to a dynamical adjustment of the subtropical and subpolar gyres on interannual to decadal time scales. The most prominent pattern is the Pacific-North American (PNA) teleconnection pattern. Such atmospheric responses to remote forcing potentially impact the process of water mass formation, thermocline stratification, and SST variability especially in oceanic frontal regions. 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 (Philander and Gu, 1997), provide atmospheric triggers for ENSO (Pierce et al., 1998) and/or generate oceanic thermal patterns that precondition this triggering (Oberhuber et al., 1998).

Despite the remarkable progress during TOGA, questions remain about the quantitative description of important oceanic processes in the tropical Pacific. Of particular oceanographic 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. The active processes are upwelling, zonal advection, meridional advection, diapycnal and lateral mixing, and warming by air-sea fluxes. The relationship between thermocline depth variability, which is driven by ocean dynamics, and changes of SST, which affects the atmosphere, is set by this heat budget so it is crucial to model it correctly. All models simulate cold-tongue warming during ENSO, but the balance of terms differs between them and, consequently so do their responses to differing atmospheric forcing and to slow oceanic modulation of the ocean background inside of which ENSO evolves. Southern Oscillation and equatorial SST indices show that the period and amplitude of ENSO 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 throughout the first half of the decade and especially with the occurrence of the very strong 1997-98 ENSO. This recent behavior contrasts markedly with the 1970s and 1980s, when ENSO occurred fairly regularly with a period of about five years. Such nonstationarity has also challenged the prediction skill of some coupled models of ENSO.

Modes of climate variability other than ENSO are now being explored, including those involving the midlatitude North Pacific Ocean. Robust decadal variations of the midlatitude North Pacific, and decadal modulations of ENSO, have been documented, and coupled ocean-atmosphere mechanisms which also involve the PNA have been proposed. The observational basis for improved understanding of these modes of climate (and related oceanic biochemical) variability must be developed and incorporated into improved models.

We propose the Pacific Basinwide Extended Climate Study (P-BECS) to describe, understand and model climatic variability within and between the tropical and subtropical Pacific Ocean. Within today's understanding, the climate phenomena of interest are ENSO, decadal variability like the Pacific Decadal Oscillation, and the decadal modulation of ENSO and its predictability.

The primary goal of the P-BECS is 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 test models of this circulation and its intrinsic modes of variability as well as those due to coupling with the atmosphere;
- 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.

This document provides the framework for achieving these objectives. Background for the challenge to ocean science to deliver a substantial increment of improved understanding of the role of the Pacific Ocean in seasonal-to-decadal climate variability is provided in section II. The concept and strategy of a P-BECS are given in sections III and IV, respectively. The programmatic context for conducting the Pacific BECS is discussed in section V, and the next steps needed to advance planning for this project are pointed to in section VI.

II. Background

Dominant modes of SST variability on both interannual and decadal time scales in the North Pacific are associated with the PNA atmospheric teleconnection, and thus with temperature and rainfall over North America. Interannual variations of the PNA are mainly forced by anomalous atmospheric heating in the tropics during ENSO events (Horel and Wallace, 1981). Although there are distinct interannual SST variations in the North Pacific, they are weaker than in the tropics and are dominated by local atmospheric forcing associated with the PNA pattern. The tropical oceans dominate interannual SST variability and play a fairly direct role in shaping interannual climate evolution, largely because oceanic planetary waves in the tropics are relatively rapid, allowing the tropical ocean to couple more strongly with the short time scales of the atmosphere. However, the strongest *decadal* SST variations are in the midlatitude North Pacific, not the tropics, and they are linked with the PNA (Figure 1; Latif and Barnett, 1994; Zhang et al., 1997). Oceanic planetary waves appear to play an important role in the evolution of these patterns, as do trade wind variations, midlatitude storm track variations and cross-frontal advection (Nakamura et al., 1997). Internal planetary waves and currents are slow in midlatitudes so the influence of the midlatitude ocean on interannual variability is weak [Davis, 1976].

Nevertheless, anomalous heat content resulting from the ocean's ability to integrate atmospheric forcing can feedback with some delay to produce subtle but persistent forcing of the atmosphere (Namias, 1951, 1963, 1966, 1978; Davis, 1978; Lau, 1988; Lau & Nath, 1990). Interaction of the tropics and subtropics within the North Pacific Ocean also has a potentially important role in climate variability including the decadal modulation of ENSO. ENSO signals propagate to the subtropics via eastern boundary oceanic Kelvin waves as well as through atmospheric teleconnections. There are clear signatures of ENSO over North America and the ocean's role in propagating these signals is unclear. The North Equatorial Current and Kuroshio form a major pathway for meridional heat transport whose variability may be a source for decadal change in the subtropics. Conversely, processes in the subtropics are believed to influence tropical stratification and consequently decadal modulation of ENSO evolution.

A. The ocean processes of ENSO

The 1997-98 El Niño has demonstrated again that we have realized significant skill in forecasting the evolution of the tropical Pacific 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 several models predicted the evolution over the next six months quite realistically. This ability is a clear application of the scientific successes made possible by a concen-

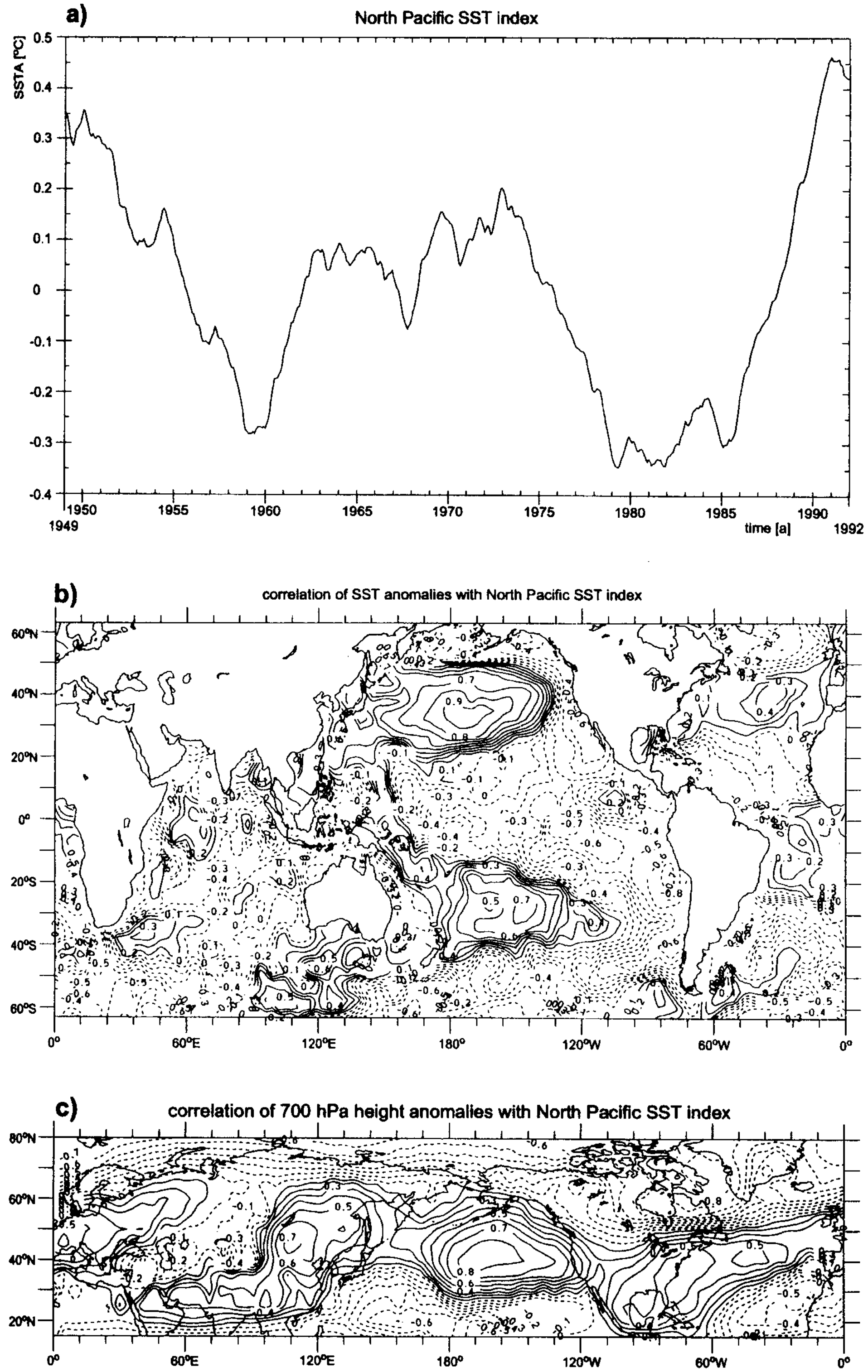

Figure 1 — Time series of North Pacific SST anomalies averaged over the regions 25°-40°N, 170°E-160°W (a) and spatial distributions of correlation coefficients of observed SST anomalies (b) and observed 700 hPa height anomalies (c) with the index time series shown in (a). All data were detrended and smoothed with a five-year running mean filter prior to the correlation analysis. (After Latif and Barnett, 1996).

trated effort combining 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 foresee the onset of the 1997 event and none predicted the extremely large-amplitude event. For conditions less dramatic than the growth stage of a large El Niño, our skill at predicting the smaller variations of tropical Pacific SST is relatively weak. We still apparently are unable to recognize the conditions that presage El Niño, in fact are unable to say with any confidence to what extent the oceanic state is a necessary element, what a precursor oceanic state might be, or whether the onset is perhaps initiated by essentially random wind patterns or some other influence.

Interpretations of the ENSO cycle have evolved from the early idea that the trade winds build up a strong zonal sea level gradient that provides the potential for an eastward reversal when the winds relax (Wyrtki 1975). Two ideas which are at the heart of subsequent El Niño oscillator models were first suggested by McCreary (1983): that ENSO-like time scales can be due to a time-lagged negative feedback through reflection of Rossby waves from the western boundary, and that wave-mediated thermocline depth variations would affect east Pacific SST and then feed back to modify the strength of the trade winds. Later models that demonstrated "delayed oscillator" physics (Zebiak and Cane, 1987; Schopf and Suarez, 1988; Battisti, 1988; Battisti and Hirst, 1988) proposed additional elements of the coupled interaction. A coupled instability develops in the central basin in which a depressed thermocline produces anomalously warm SST due to upwelling acting on a weakened vertical temperature gradient, then the warm SST results in anomalous westerly winds over and to the west of the warm patch, which further lowers the thermocline and adds to the growing anomaly. Kelvin waves carry the downwelling eastward, but propagation of the coupled anomaly is slower than the free Kelvin speed. The delayed oscillator models showed that the slow ENSO time scale can be produced solely within the equatorial waveguide. One no longer expects a warm event to be triggered directly by Rossby to Kelvin reflection; rather, the reflected wave lowers the equatorial thermocline and sets up the coupled instability in mid-basin, which then grows with its own time scale, generates its own westerly winds, and produces additional Kelvin waves that reinforce the growing, slowly moving, anomaly.

The delayed oscillator models had important successes in predicting the 1986-87 and 1991-92 El Niño events almost a year in advance, but have largely failed to explain the unusual behavior of the ENSO cycle since then. In particular there has been little evidence that Rossby wave reflection played a major part in the initiation of the mid-1990s warm events, and this absence probably contributed to the lack of forecast success by delayed oscillator models. The focus of attention on the ENSO cycle is shifting from wave dynamics towards the more difficult problems of the heat balance in the upper tropical Pacific and how it interacts with the overlying atmosphere.

Numerous observational and modeling studies have shown that the largest influences on the heat balance of the near-surface equatorial Pacific are those that we don't measure very well: upwelling and vertical entrainment, surface fluxes and horizontal mixing. The Subtropical Cell (STC; see II.B) interacts with equatorial dynamics through wind-driven upwelling, which can be seen as a choke point through which all water involved in the STC must pass. Upwelling speed varies annually and interannually with the local zonal winds (Qiao and Weisberg, 1996) with typical values of a few meters/day, but the effect of upwelling on SST depends on the depth of the thermocline (Kessler and McPhaden, 1995), which can be mediated by remotely forced waves.

In the eastern and central Pacific, upwelling results in a strong SST front just north of the equator. During the second half of each year, the trade winds strengthen, and the entire upper equatorial circulation quickens: the westward South Equatorial Current and eastward North Equatorial Countercurrent are strong, as is upwelling. All three of these advective tendencies strengthen the SST front, while at the same time the shears between the currents are largest. This stronger SST front and increased shear contribute to the development of tropical instability waves through barotropic and baroclinic mechanisms respectively (Philander, 1978; Yu et al., 1995). Tropical instability waves mix across the SST front, warming the equator. Therefore the June-December quickening generates opposing SST advective tendencies (upwelling versus eddy mixing) and the effect of total ocean advection on cold tongue SST is smaller than the individual terms would indicate. The result is that the annual SST cycle appears to follow the air-sea flux tendencies, but this appearance should not be interpreted as a one-dimensional balance (Kessler et al., 1998). In the east, vast stratus cloud decks cover the cool water from the coast of Peru to about 120°W, producing a positive feedback with SST, as cool surface temperatures chill the lower atmosphere, enhancing the formation of stratus which blocks incoming shortwave radiation, further cooling the SST. Quantification of this feedback is difficult, not least because the AVHRR satellite observations that are a primary source of SST data for this poorly sampled region do not see through clouds, and stratus coverage as measured by satellite can be more than 80% of the observed pixels over wide areas during the cool time of year.

Further west, near the dateline, a front separates the warm fresh water of the west Pacific warm pool from the cooler, saltier water under the trades. West of the front, the thermocline is deep enough that upwelling cannot be a large cooling term, and the surface layer heat balance is dominated by heavy rainfall (3-5 m/yr) that often controls vertical exchanges of heat and momentum by establishing a shallow halocline under weak mean wind conditions (Lukas and Lindstrom, 1991; Webster and Lukas, 1992; Godfrey et al., 1998). Episodic westerly wind events of as much as one month's duration (the Madden-Julian Oscillation; Madden and Julian, 1971) extend to the east edge of the warm pool (Kessler et al., 1995) accompanied by deep atmospheric convection. When the warm pool is advected eastward it rides over the denser eastern water and can result in relatively saline subsurface layers above the deep thermocline (Vialard and Delecluse, 1998)). Under strong westerly wind events, the equatorial zonal pressure gradient and velocity vertical structure can set up rapidly (less than 10 days) as the mirror image of the usual trade wind profile, with a westward-directed undercurrent driven by the pressure gradient below an eastward surface downwind current. During the stronger events the salinity stratification can rapidly mix away. McPhaden et al. (1988; 1992) examined moored velocity time series during several of these wind bursts and estimated from the shear profiles that vertical eddy viscosities were O(100 cm/s), an order of magnitude higher than found in the central Pacific from microstructure measurements. This suggests that once the halocline is removed, the thick nearly isothermal upper layer can efficiently mix to at least 100 m depth. Since such strong wind events occur several times a year, particularly strongly during El Niños, this intermittent mixing contributes importantly to the large-scale climatology of heat, salt and momentum in the warm pool (Webster and Lukas, 1992; Godfrey et al., 1998).

B. Pathways for shallow overturning cells

The zonally averaged circulation in the Pacific reveals a shallow meridional overturning cell that connects the tropics and subtropics [Figure 2; Hirst et al., 1996; Lu et al., 1998]. This overturning involves equatorial upwelling, poleward flow near the surface, subduction in the subtropics and equatorward return flow in the upper thermocline. Forced by both Ekman pumping and thermohaline fluxes [McCreary and Lu, 1994; Liu et al., 1994], this cell helps determine equatorial SST, the amount of tropical heat exported to the subtropics and thermocline stratification throughout the region. Variability of each of these processes is likely on all time scales and over large spatial scales.

Zonal averaging oversimplifies this tropical/subtropical connection which depends on the circulations in the wind-driven tropical and subtropical gyres and their strong western boundary currents (Figure 3). The North Equatorial Current (NEC) is the northern limb of the tropical gyre

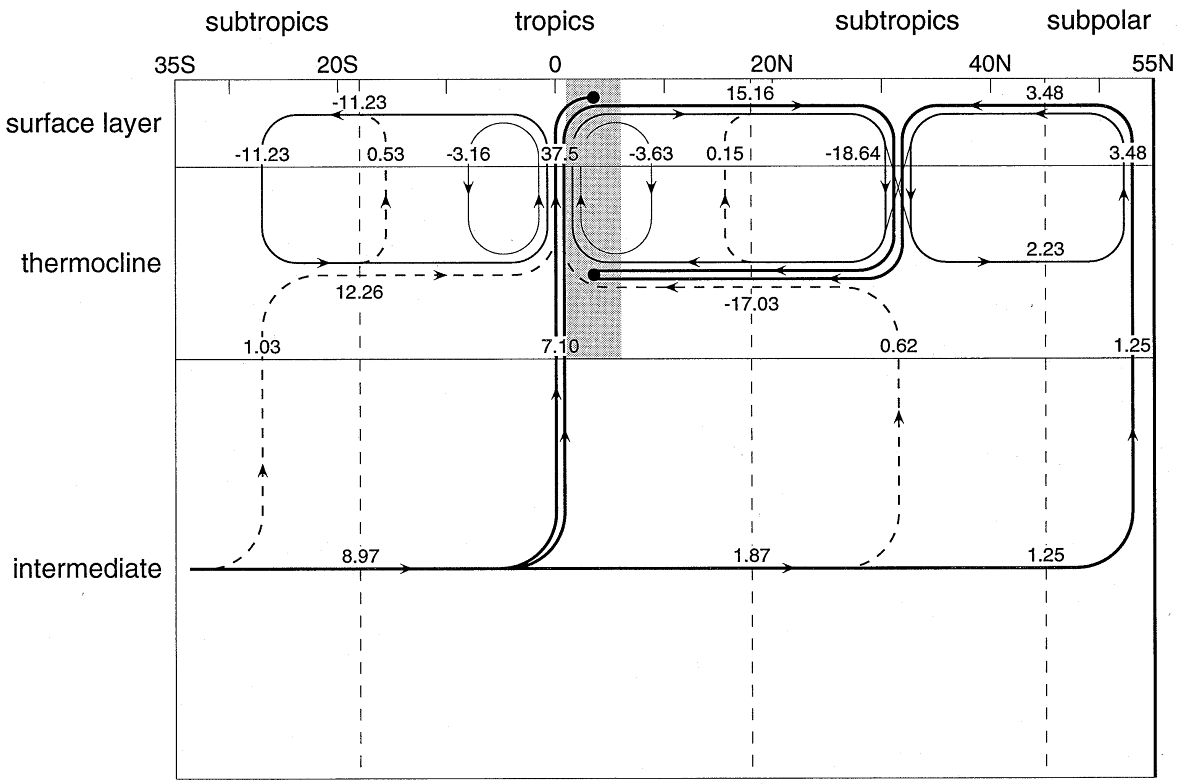

Figure 2 — Schematic illustrating zonal mean meridional circulation cells in the three-layer model of Lu et al. (1998). Numbers on different branches of the overturning circulation are transports in Sv. Shaded area indicates the mass sink associated with the Indonesian Throughflow.

and the southern limb of the subtropical gyre, fed in the east by the confluence of the California Current and the North Equatorial Countercurrent. Variability of this confluence is due to regional wind stress variations, to poleward propagating Kelvin waves, and to their radiation of Rossby wave energy westward; it is dominated by ENSO. In the interior, anomalous exchanges across the NEC are due to advection of anomalies by the mean circulation, to quasi-geostrophic flows in the thermocline and to anomalous Ekman transports in the surface layer. The NEC splits as it approaches the coast of the Philippines, feeding the Kuroshio and Mindanao Current along the western boundary. This NEC bifurcation is controlled remotely by Rossby waves from the east and coastal Kelvin waves from the north, and locally by the east Asian monsoon (Qiu and Lukas, 1996). The mass and heat transports of the western NEC are subject to pronounced seasonal, interannual and decadal variations and these likely have impacts downstream in the Kuroshio, the Mindanao Current, the North Equatorial Countercurrent and the Indonesian Throughflow. Models and observations suggest that the downstream impacts of NEC variability are complicated by the processes controlling the splitting of the NEC at the coast of the Philippine Islands [Lukas et al., 1996], and by the details of the topography of the western boundary and marginal seas (Metzger and Hurlburt, 1996).

A number of theoretical studies using simple ocean models (2-1/2 layer systems) have investigated the pathways by which subtropical thermocline water flows to the equator to complete the subsurface branch of the STC. Pedlosky

(1987, 1988) and Pedlosky and Samelson (1989) obtained solutions by matching the geostrophic interior flow field of Luyten et al. (1983) to an equatorial, inertial boundary layer, thereby explicitly pointing out the close connection that exists between the subtropical and equatorial oceans. McCreary and Lu (1994) extended this work by finding solutions in a closed basin, showing that the subsurface, equatorward flow was one branch of a closed circulation cell, the STC; in this cell, water subducts in the subtropics, flows equatorward as thermocline water, upwells in the eastern equatorial basin, and returns to the subtropics in the surface layer. Lu and McCreary (1995) and Lu et al. (1998) determined further that much of the subtropical water flows to the equator via tropical western boundary currents, rather than in the interior ocean. Indeed, in their solutions nearly all of the North Pacific thermocline water moves equatorward in a western boundary current (the Mindanao Current) because of a "potential vorticity barrier" generated by Ekman pumping associated with the ITCZ; this property is consistent with observed tracer distributions, which also appear to be blocked near the latitude of the ITCZ at 10°N (see Wyrtki and Kilonsky, 1984, for example). Solutions to general circulation models (GCMs) also develop STCs (Bryan, 1991; Liu et al., 1994; Blanke and Raynaud, 1997; Hirst et al., 1996; Rothstein et al., 1998). However, the GCM solutions tend to allow considerably more flow to the equator in the interior ocean than the layer-model solutions do. The reason for this different behavior is not yet clear, but it is likely due either to the GCMs having greater vertical resolution, thereby allowing the flow of thermocline water to have greater shear, or to their having stronger vertical mixing,

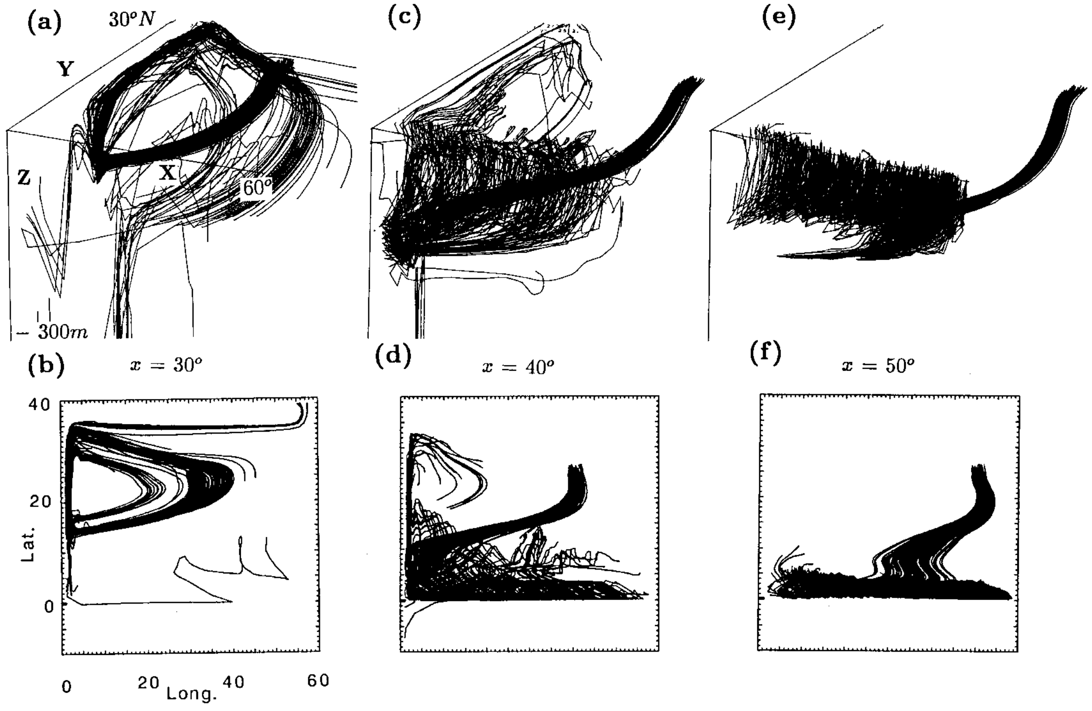

Figure 3 — Three-dimensional and plan views of decade-long trajectories of groups of particles released at the surface along 26°N in an ocean GCM. Particles released in mid-basin (a, b) mostly recirculate in the subtropical gyre. Particles released 10° of longitude further east (c, d) travel to the equator along the western boundary after subducting, and are upwelled along the equator. Particles released closer to the eastern boundary (e, f) flow to the equator along a more direct path where they are upwelled. (After Liu et al., 1994).

which can break the potential vorticity constraint caused by the ITCZ. How much vertical mixing actually occurs in the extra-equatorial tropical Pacific is not known. Probably, vertical mixing is too weak in inviscid layer models and too strong in the GCMs.

The basic reason for the existence of STCs is divergence of surface water out of the tropical ocean: By mass conservation, this divergence must be compensated for by an equatorward transport of subsurface water. McCreary and Lu (1994) derived a simple expression for the upper-layer divergence in their analytic model, showing that it was determined almost entirely by the Ekman transport across the boundaries of the tropics. STC strength is not determined by midlatitude windstress curl, as might be expected. It is true that an increase in midlatitude wind curl does increase subduction by a proportionate amount, but the additional subducted water can recirculate within the subtropical gyres, and need not flow into the tropical ocean. On the other hand, the temperature and salinity of the STC water that moves to the equator can be affected by diabatic processes within the midlatitude subduction zones.

Variations in the strength and temperature of the STC are determined respectively by off-equatorial wind anomalies located near the edges of the warm pool and by diabatic processes within the midlatitude subduction zones. Because the speeds of off-equatorial Rossby waves are considerably slower than those of equatorially trapped waves, we expect the STC mechanism to generate lower-frequency variability than the ENSO mechanism does. These variations may feedback onto the atmosphere in at least two ways. In response to weaker or warmer STCs, less cool subsurface water flows into the tropics, hence less cool water upwells in the eastern Pacific and the cold tongue weakens. A weaker cold tongue will allow atmospheric convection in the western Pacific to shift eastward more easily, thereby increasing the likelihood of ENSO warm events. Conversely, stronger and colder STCs lead to a strengthened cold tongue, which increases the likelihood of ENSO cold events and helps to maintain the easterly anomalies. Some of the water that subducts in the subtropics of the Pacific joins the oceanic gyre that includes the Kuroshio Current. The subduction of unusually cold (or warm) waters could influence sea surface temperatures that in turn affect the winds and their curl that drive the gyre. These are the elements of decadal climate fluctuations, explored by Latif and Barnett (1996), in the midlatitudes of both the Pacific and Atlantic Oceans. These phenomena depend on poorly understood issues some of which were raised above and discussed below. Of particular interest are the mechanisms of subduction, the influence of changes in the thermocline on surface conditions, and the nature of interactions between the ocean and atmosphere in midlatitudes.

C. Decadal modulation of ENSO

The easterly winds that prevail in the tropics drive poleward Ekman flow in the surface layers and also cause the thermocline to slope down to the west, thus creating an eastward pressure force which is associated with equatorward geostrophic motion in the thermocline. Upwelling at the equator and subduction in the subtropics close this meridional circulation which has been inferred from the distribution of transient tracers such as tritium and C^{14}. Because of this circulation, which has been studied by means of oceanic models (Liu et al., 1995, Lu and McCreary, 1995), a change in the properties of the extratropical surface waters will, in due course first influence the equatorial thermocline and then the surface conditions in low latitudes. Sea surface temperatures in the tropics affect the global atmospheric circulation and, in particular, affect conditions over the region where oceanic subduction occurs. These rapid atmospheric links between the tropics and subtropics, and the slow oceanic links in the reverse direction can result in continual, decadal climate fluctuations (Gu and Philander, 1997). The evidence that makes these arguments plausible include the documentation of the initial equatorward path of a mass of unusually cold waters that subducted in the central subtropical North Pacific Ocean in the late 1970s (Deser et al., 1996), and the demonstration, with a realistic oceanic GCM, that decadal variations in the equatorial thermocline have their origin in the surface layers of the extratropics (P. Chang, personal communication, 1996).

However, a number of important issues still have to be addressed:

1) The process of subduction appears to filter out seasonal and interannual variations so that only decadal fluctuations penetrate to the depth of the thermocline and participate in the subtropical-tropical exchange. It is likely that the "Stommel demon" (Stommel, 1979; Marshall et al., 1993; Huang and Qiu, 1994; Williams et al., 1995) that rectifies the seasonal cycle, by biasing the T/S properties of the thermocline to that of the winter mixed layer, also operates on longer time scales, biasing the properties of the thermocline not only to the colder season but to colder decades. Is this true and can models simulate this filter?
2) For a climate model to reproduce subduction, does its atmospheric component have to resolve individual storms and the tracks they follow? To what extent do changes in storm tracks depend on changes in sea surface temperatures, as suggested by Lau (1988).
3) The oceanic models indicate that, whereas water parcels that subduct in the southern hemisphere in the Pacific follow a relatively straightforward route to the equator, those in the northern hemisphere follow a more circuitous path because the ridge of the thermocline at 10°N is at least a partial barrier. Is that the case in reality? The analyses of Tsuchiya et al. (1989), Johnson and McPhaden (1998), and Liu and Huang (1998) support this view for the mean circulation, but it is not known whether this is true for the variable circulation. If so, how do changes in the thermocline north of 10°N affect local sea surface temperatures? Do answers to these questions explain why sea surface temperature anomalies have a larger north-south scale on interdecadal than on interannual time scales? (See Zhang et al., 1997.)

If the above scenarios are correct, the dynamics of ENSO decadal variability are very different from the dynamics of ENSO itself, which appears to be determined by equatorial wind anomalies. That is, diabatic processes are not of secondary importance compared to adiabatic dynamics.

D. North Pacific decadal variability

Namias (1970, 1972) showed that temperatures in the midlatitude North Pacific varied on interannual and decadal time scales, and on spatial scales comparable to the width of the Pacific basin. Namias (1951, 1963, 1966, 1978) used these variations to forecast seasonal and longer-term anomalies of atmospheric circulation over North America. The underlying hypothesis that the thermal inertia of the midlatitude ocean persistently forces the atmosphere (cf. Namias, 1970) motivated the NORPAX program of the 1970s, but observations and models proved unable to provide a convincing test of the hypothesis. This was largely because of the strong forcing of the ocean by the atmosphere on the synoptic weather time scale, which obscures any slower, less energetic feedbacks from the ocean (Davis, 1976). Since that time, enhanced observations and improved models have begun to reveal more subtle features of ocean-atmosphere coupling in the North Pacific, though nonlinearities still challenge our linear statistical tools.

Fragmentary evidence has accumulated which suggests there is at least one coupled ocean-atmosphere mode of variability on decadal time scales which is intrinsic to the midlatitude North Pacific. A maximum of SST variability in the region of the Kuroshio extension (and subarctic front; Figure 4) is apparently a locus of unstable air-sea interaction. The subtropical front in the eastern North Pacific is another region of maximum SST variability on decadal time scales (Nakamura et al., 1997). SST anomalies are shown to propagate with direction and speed consistent with advection by the mean flow (Michaelson, 1982); expansion and intensification of these anomalies suggest coupling with atmosphere and positive feedback. Yamagata et al. (1985) showed the coherent variation of the North

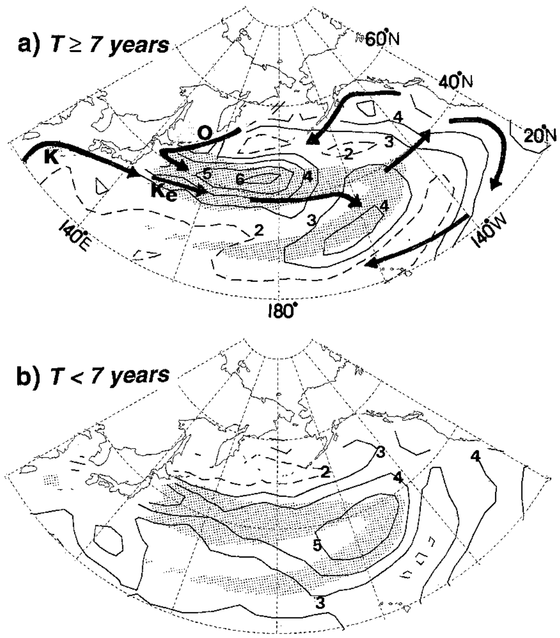

Figure 4 — (a) Decadal SST standard deviation (x 0.1°C, contoured), and two major oceanic fronts (stippled) where the mean meridional SST gradient in winter is great than 0.7°C per 100 km. Superimposed is a schematic of the ocean surface currents (K: Kuroshio; Ke: Kuroshio Extension; O: Oyashio). (b) As in (a) but for SST variability with periods less than seven years. (After Nakamura et al. 1997).

Equatorial Current, the Kuroshio, and Kuroshio Extension on interannual and longer time scales, suggesting a gyre-scale readjustment. Subtropical mode waters to the south of the Kuroshio extension may provide the dominant source of thermal inertia (Yasuda and Hanawa, 1997). This is consistent with the interpretation by Namias (1970) of the dynamical impact of thermal anomalies on the Kuroshio. Decadal variability of the North Pacific appears to be associated with the South Pacific. Evidence for quasi-periodic, meridionally symmetric modes of climate variability on sub-ENSO frequencies has been accumulating (e.g., Folland et al., 1984; Mann et al., 1995; Mann and Park, 1996; Lau and Weng, 1995; White et al., 1997). Global patterns of variability in sea surface temperature (SST) and sea level pressure (SLP) extending over the past 100 years are dominated by decadal (8-13 year) and interdecadal (15-35 year) signals, the latter larger than the former by a factor of two or so. Global, meridionally symmetric patterns have been observed in EOFs of interdecadal-filtered SST and upper ocean temperature anomalies by White et al. (1997), Zhang et al. (1997), White and Cayan (1998), and Tourre et al. (1998). Moreover, global interdecadal patterns in SST have been observed in association with corresponding global interdecadal patterns in SLP and associated trade wind and westerly wind systems by Mann and Park (1996), Zhang et al. (1997), and White and Cayan (1998).

Meridionally symmetric modes in the Pacific basin have been related to meridional atmospheric teleconnections (Zhang et al., 1997; White and Cayan, 1998) with intense extratropical westerly winds in both hemispheres associated with warm tropical SST anomalies on both ENSO and interdecadal time scales, consistent with meridional atmospheric teleconnections (Graham, 1994). These reflection symmetries and associated phase relationships between oceanic and atmospheric variables make a compelling argument that the quasi-periodicity of interdecadal variability in the Pacific basin derives from extratropical influences producing a delayed-negative feedback on equatorial SST anomalies, the latter providing an immediate-negative feedback to the extratropics through meridional atmospheric teleconnections.

Interdecadal upper ocean temperature anomalies above the main pycnocline are approximately out of phase with those in the main pycnocline over tropical and eastern oceans (White and Cayan, 1998). Warm (cool) SST anomalies are generally associated with shallow (deep) pycnocline depth anomalies, yielding cool (warm) heat content anomalies. Subduction and advection along isopycnal surfaces contribute to these cool (warm) temperature anomalies in the tropical pycnocline (Watanabe and Mizuno, 1994; Deser et al., 1996). This is consistent with modeling experiments conducted by McCreary and Lu (1994) and Gu and Philander (1997).

One principal subduction region is along the western-central subarctic and SubAntarctic frontal zone (SAFZ) in both hemispheres, where SST and pycnocline temperature anomalies fluctuate generally in phase. In this domain, Tourre et al. (1988) have observed SST anomalies continuing to intensify and propagate slowly eastward while pycnocline temperature anomalies propagate directly equatorward. They find equatorward propagation of pycnocline temperature anomalies occurring at an average speed of 0.01-0.04 m/s, taking eight to 10 years to transit from the west-central SAFZ to the tropics in both hemispheres. A portion of this propagation appears to stem from advection along isopycnal surfaces, while another portion stems from the equatorward propagation of isopycnal depth anomalies, in quasi-stationary Sverdrup balance with a slow equatorward propagation of overlying wind stress curl anomalies (Miller et al., 1997). The latter occurs in association with equatorward propagation of covarying extratropical SST and SLP anomalies (White and Cayan, 1998), which in the North Pacific extend from the central-eastern SAFZ to the latitude of Hawaii but in the South Pacific extend from the western-central SAFZ onto the equator and the ITCZ. Based upon the similarities between interannual and interdecadal SST and SLP anomaly patterns, Zhang et al. (1997) have proposed that the quasi-periodicity of interdecadal variability arises from a delayed negative feedback provided by wind-driven extratropical Rossby waves in the same way that wind-driven equatorial Rossby waves provide a delayed negative feedback responsible for the quasi-periodicity of El Niño (Graham and White, 1988).

Earlier, Latif and Barnett (1994) simulated interdecadal variability in a coupled general circulation model of the global ocean-atmosphere system, proposing that wind-driven extratropical Rossby waves provide a different delayed-negative feedback responsible for the quasi-periodicity of interdecadal variability. In their model, wind-driven extratropical Rossby waves alters the transport of the subtropical gyre, which in turn alters the poleward transport of heat that changes the sign of SST anomalies along the western and central SAFZ, the latter altering the overlying westerly winds and associated wind stress curl in such a way as to change the sign of the wind-driven Rossby waves and, subsequently, the strength of the subtropical gyre. In both cases, delayed-negative feedbacks accrue from the 5-10 years that extratropical Rossby waves take to traverse the Pacific ocean. Evidence for the slow westward phase propagation of extratropical Rossby waves has been provided by Jacobs et al. (1994).

Westward propagating sea level anomalies in TOPEX/POSEIDON data exhibit propagation speeds that are systematically higher than linear theory by amounts that range from nearly negligible to more than a factor of two depending mainly on latitude (Chelton and Shlax, 1996). This exposes an obvious gap in our theories concerning Rossby waves and the various adjustment processes they bring about. A modified theory obtained by linearization about a vertically sheared zonal mean velocity field yields faster free-wave phase speeds with nearly a factor of two speed-up for realistic profiles (Killworth et al., 1997). Alternatively, Qiu et al. (1997) ascribe the faster phase speed to the mix of free and forced Rossby wave excited by the ambient wind stress anomalies. A resolution of this issue awaits better quantification of the forcing and response, as well as consideration of possible ocean-atmosphere coupling. Important implications of the observations are that basinwide annual baroclinic adjustment may occur at higher latitudes than in the standard Rossby wave theory. The faster propagation speed might imply a faster basinwide baroclinic adjustment to wind and eastern boundary forcing. As a consequence, the midlatitude, interior ocean response to El Niño may be quicker than predicted by the standard theory. Improved ocean models will have to take these evolving findings into account.

In summary, two hypotheses grounded in observations have been formulated to explain the quasi-periodicity of decadal variability, characterized by the following delayed-negative feedbacks:

- A delayed-negative feedback is provided by the subduction of extratropical upper ocean temperature anomalies that take five to 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 (e.g., Gu and Philander, 1997).
- A delayed-negative feedback is provided by the equatorward propagation of extratropical covarying SST and SLP anomalies into the tropics that takes five to 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 (e.g., White and Cayan, 1998).

Two hypotheses obtained from consideration of coupled models have been formulated to explain the quasi-periodicity of interdecadal variability, characterized by the following delayed-negative feedbacks:

- A delayed-negative feedback is provided by extratropical wind-driven Rossby waves that take five to 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 (e.g., driving Rossby waves of opposite sign) via meridional atmospheric teleconnections. (e.g., Zhang et al., 1997).
- A delayed-negative feedback is provided by extratropical wind-driven Rossby waves in the North Pacific ocean that take five to 10 years to alter the transport of the subtropical gyre, the latter altering the poleward advection of heat by the Kuroshio and changing the sign of SST anomalies along the western-central SubAntarctic frontal zone (SAFZ), the latter altering westerly winds and associated wind stress curl that force extratropical Rossby waves of opposite sign (Latif and Barnett, 1994; Jin, 1997). This hypothesis also has some observational evidence to support it (Yamagata et al., 1985; Kutsuwada, 1988; Nakamura et al., 1997).

Recent analysis and theoretical work (Zhang and Liu, 1998; Liu, 1998) suggest that both the subduction mode and the wave mode of decadal Pacific Ocean variability are active, and that they may be phase-locked by the atmospheric variability which force them.

E. Coupled thermodynamics, dynamics and the hydrological cycle

The western tropical Pacific warm pool and the intertropical convergence zones are regions of substantial net freshwater flux into the ocean, while the subtropical gyres of the Pacific Ocean are source regions for this moisture (Figure 5). Meteorological analyses (e.g., Trenberth and Solomon, 1994) show that there is a direct atmospheric connection, with the trade winds extracting moisture from the ocean and releasing it back in regions of convergence and deep convection. In order to achieve a climatological balance, there must be an oceanic counterpart to the Hadley circulation, and the STCs discussed above provide that circulation. Subtropical and equatorial subduction of saline waters is an important process to maintain the climatological balance of the warm pool (cf. Lukas and Lindstrom, 1991; Shinoda and Lukas, 1995), but imbalances of the freshwater budget on seasonal to decadal time scales may be important aspects of climate variability.

The hydrological cycle is closely linked to the upper ocean thermodynamics in the warm pool (cf. Anderson et al., 1996; Vialard and Delecluse, 1998), but it is not clear how the heat and moisture budgets of the subtropical gyres are linked and on what time scales. The “tightness” of the coupling must depend on the strength of adiabatic processes relative to diabatic processes,

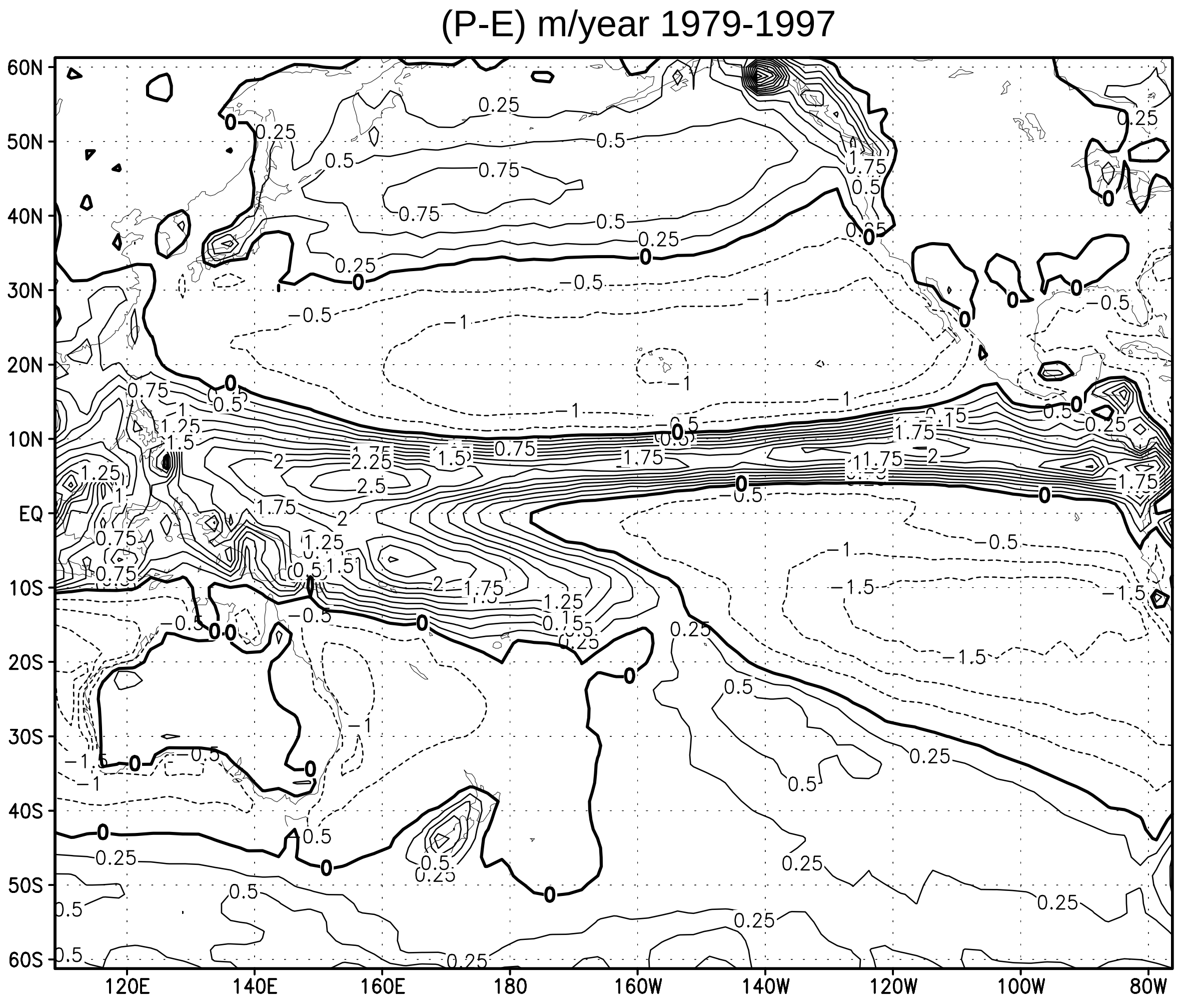

Figure 5 — Annual mean (1979-1997) net freshwater flux (m yr^{-1})computed from CMAP rainfall (Xie and Arkin, 1997) and evaporation from NCEP reanalysis. Salty waters subducted in the subtropics must ultimately arrive beneath the fresher surface waters in regions of net rainfall and mix with the overlying waters to produce a climatological salinity balance.

and the time scale on which heat which is sequestered below the ocean surface layer is recovered by the atmosphere. During the ENSO cycle, there are substantial modifications of the equatorial Pacific stratification associated with salinity (Delcroix and Henin, 1991; Webster and Lukas, 1992; Delcroix et al., 1992; Roemmich et al., 1994; Picaut and Delcroix, 1995; Picaut et al., 1996; Ando and McPhaden (1997); Delcroix and Picaut, 1998; Vialard and Delecluse, 1998a,b), which suggests a strong linkage between the hydrological cycle and the thermal balance of the tropical Pacific Ocean.

Clearly, the development of the hypothesis that the oceanic limb of the hydrological cycle is active in interannual and decadal ocean climate variability requires observations of the time-varying distribution of salinity in the upper Pacific Ocean. Any tests of this hypothesis will require substantially improved coupled ocean-atmosphere models with an active hydrological cycle in both components of the model, and which can reproduce the observed variability of salinity in addition to the upper ocean thermal structure.

For the overall understanding of air-sea coupling the greatest utility of the oceanic freshwater budget may be the diagnosis of low-frequency variability of latent heating of the atmosphere. The total amount of water that can be stored in the atmosphere is relatively small. Consequently, at climate frequencies the air-sea flux of water is an accurate proxy for the internal heating of the atmosphere by latent heat release and thus it provides a key verification of models of the atmosphere.

III. The Scientific Challenge

The hypotheses concerning the role of the Pacific Ocean in interannual to decadal climate variability discussed above involve slow processes that span large parts of the Pacific Ocean. It is impractical to marshal enough resources to test such hypotheses solely with observations or to wait for time series to become long enough. Paleoceanographic records may help, but their interpretation is not straightforward. It will be necessary to make efficient use of the observations by employing dynamic models in their analysis. Basin-scale observations and analyses will be needed to gain the quantitative description of the Pacific Ocean evolution needed to first carefully test models which will then be used to test these hypotheses and develop others. The robustness of conclusions based on numerical experiments depends on the quantity and quality of the observations against which the models are tested, so it is essential that the dynamical analyses not depend strongly on model physics. This requires a “critical mass” of observations, but that is a function of the type of observations and is relative to the physics of a particular model. A major element of the P-BECS research program will be to determine this critical mass of observations.

There has been remarkable progress in recent years in the methodology (loosely called data assimilation) for combining dynamical models with observations to test the ability of models to simulate ocean evolution and to determine whether the disagreements of simulations and observations result from inadequate model dynamics or inadequate observations for model initialization and forcing. The BECS concept is a response to four perceptions: (1) successful coupled models will need accurate oceanic and coupling components; (2) improvement of models requires testing simulations against observations that have enough acuity to describe the crucial processes; (3) even with the remarkable achievements of the TAO observing system, present routine ocean and air-sea observations are not adequate for this testing; and (4) testing model representations of processes like advection or mixing will require a density higher than today’s routine observations that span a significant part of the Pacific Ocean, including its boundaries and the fields forcing it, and that extend for the order of a decade.

The main questions raised by the discussion of processes in Section II involve large parts of the Pacific Ocean basin and span years to decades:

- Is evolution of decadal variability in the subtropics associated with ocean advection of heat content anomalies and a coupled interaction of SST and the atmosphere in midlatitudes (Latif and Barnett, 1994)?
- Do the subtropics respond on decadal time scales to tropical SST and atmospheric convection through the same teleconnections that drive the PNA on interannual time scales (Graham et al., 1994)?
- What is the role of variable Kuroshio volume and heat transport in the climate-scale SST variability of the North Pacific (Michaelson, 1982; Yamagata et al., 1985)?
- Are low-frequency thermal anomalies propagated downwards by isopycnal advection in subduction processes (Watanabe & Mizuno, 1994; Deser et al., 1996) or by vertical displacements driven by Ekman pumping forced by anomalous atmospheric circulation (Tourre et al., 1998)?
- Does the shallow overturning circulation carry subsurface temperature and salinity anomalies to the tropics where they can affect ENSO evolution (Gu & Philander, 1997)?
- What are the roles of western boundary currents in the shallow overturning circulation?
- What are the detailed upper ocean heat and freshwater budgets in the tropical Pacific?

How do these change on decadal time scales? Is cold tongue SST variability influenced by variability of lateral warming processes as it is by thermocline depth variability modulating the cooling processes of mixing and upwelling?

- How must surface layer processes be parameterized to adequately model evolution of upper ocean temperature, salinity and velocity on seasonal, interannual and decadal time scales?
- What oceanic mechanisms dominate tropical-subtropical gyre interactions? What are the roles of subtropical gyre processes in maintaining the tropical upper ocean thermal structure? How is the tropical thermocline maintained and perturbed by subtropical subduction?
- What are the pathways by which heat is exported from the tropical ocean to the extratropical North Pacific? How do wind and buoyancy forcing determine these pathways?

As these suggest, the role of the Pacific in climate variability depends on a large number of processes. More importantly, it depends on the interaction of these processes in complex and nonlinear ways. The only feasible way to deal with these interactions is inside fairly comprehensive numerical models that are constrained by adequate observations. Because of the large space and time scales involved, an innovative approach must be taken to meet the scientific challenge of observing and understanding the role of the Pacific Ocean in global climate variability.

A. The concept of the Pacific BECS

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. The global network of sustained observations are too thin to support the detailed quantitative studies of specific climate modes that are required to well 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 in process experiments. Without the kind of basinwide, 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 needed 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 with 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 basinwide observations were involved with data assimilation and predictive modeling in a productive feedback loop.

It is proposed that an integrated program of observation and modeling be started for the tropical and North Pacific Ocean and **sustained over a decade at least**. The challenge of understanding the decadal modulation of ENSO argues for extending the observations as far south as is feasible, perhaps even to a symmetric distribution of observations between the hemispheres and if there are sufficient resources this would be desirable. It is, however, central to the P-BECS philosophy that observations are dense enough that advective processes are resolved and there are several reasons to begin with the tropical and North Pacific. There is a greater historical base of observations to work from in the North Pacific than in the south. The decadal mode of variability in the North Pacific is more robust than in the South Pacific (this may be due to paucity of observations, but we cannot be sure; Harrison and Larkin, 1996, 1998). Thus, it should require fewer new *in situ* observations to obtain a favorable signal-to-noise ratio in the North Pacific. An overarching motivation for concentration in the North Pacific is that the two nations with the greatest resources that could be directed to quantitatively understanding these challenging climate signals are located on either side of the North Pacific basin, and their governments are most concerned with the climate variability that most directly influences their citizens. We argue, however, that the numerical representation of the physics of interannual to decadal climate variability in the South Pacific Ocean will be more likely improved by concentrating sufficient observational resources in the midlatitudes of the North Pacific, than by dispersing the resources over the entire Pacific Ocean. In addition, we note that powerful space-based measurements of the South Pacific Ocean will be more effectively used to constrain the analyses there given the effort in the North Pacific.

The focus of this integrated study will be quantitative diagnosis and prediction of upper ocean heat and freshwater transports and transformations. The phenomenological focus will be oceanic influences in the PNA mode and ENSO. 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 a BECS.

With the exception of lateral advection, most 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 adequately 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.

Observing the Pacific well enough for the increased demands of the models needed for elucidating decadal scale phenomena would be impossible were it not for a number of technical advances over the last few years. Most important are the remarkable abilities of satellite altimetry and wind measuring satellite scatterometers. These developments change the strategy for *in situ* observations from a stand-alone framework to one of making maximum use of the high density of satellite coverage by extending the utility of these measurements to observe subsurface properties and processes not easily visible at the surface. Thus, for example, the altimeter responds to some combination of geostrophic barotropic currents and the vertically integrated density of the ocean and does this globally with a frequency and spatial density that cannot be matched by *in* *situ* observations. The strategy of ocean observations in P-BECS will be to extend this information downward by observing the structure and components of vertical stratification, to extend it into boundary current regions where altimetry may be inadequate, and to extend the interpretability of altimeter inferences of currents by observing the ageostrophic component of near-surface flow and of low latitude flows where the geostrophic link is weak. Additionally, *in situ* observations will be needed to observe tracer fields that cannot be measured from space. The observational density for these fields cannot approach that from satellites so greater emphasis will be placed on using property-property relations and model assimilation to infer their unmeasured parts.

The model-synthesized observations that P-BECS will produce will provide the basis for testing some hypotheses of climate variability. They will also provide an analysis of the evolving ocean in relation to climatic variations that is unparalleled in completeness and could become a central part of numerous other studies. These include processes studies of ocean phenomena relevant to climate dynamics, examination of atmospheric phenomena influenced by the ocean and of the processes coupling the two media, and research programs that seek to understand the role of ocean biogeochemistry in climate and the impacts of climate variability on fisheries. The precise scope of the P-BECS will depend on how these associated studies develop and an important purpose of this document is to sketch what oceanographers think might be done in order to initiate dialogues with the various communities.

The P-BECS will take the form of a pilot operational analysis system that will develop the active dialogue between observers and modelers that is needed to carry both approaches forward. This is appropriate because an important objective of both the GOALS and Dec-Cen components of CLIVAR is to identify and exploit incremental elements of climate predictability provided by modes of ocean-atmosphere variability beyond ENSO. A program such as P-BECS will be required in order to hope to achieve this objective.

B. Objectives of the Pacific BECS

The primary goal of P-BECS is 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 an accurate, quantitative description of the low-frequency, three-dimensional circulation and associated thermohaline structure of the upper Pacific Ocean including those processes that link the tropics and subtropics;
- to test models of this circulation and the intrinsic modes of variability as well as those due to coupling with the atmosphere;
- to test basin-scale hypotheses about the role of the North Pacific Ocean in climate variability on a broad range of time scales.

While the goal of P-BECS will be to test and improve models of climate variability, a significant test of these models will come from their ability to reproduce the lowest frequency, or mean, behavior of the ocean and its coupling to the atmosphere. Can the observed heat budget of the ocean (or ideally of the ocean and atmosphere) be closed on seasonal time scales and longer? Can the general distributions of temperature and salinity be reproduced by models while faithfully representing surface fluxes and volume transports? Do models transport heat and freshwater by the same processes as nature does? Properly simulating the mean may not be a prerequisite to explaining climate variability, but for some time this will be the only unambiguously interpretable test of models abilities to simulate the important ocean processes on decadal time scales. Furthermore, the flux corrections typically required to limit climate drift in coupled ocean-atmospheric models are a sign that the mean heat budget of at least one medium cannot be faithfully modeled. The P-BECS will seek to determine the true heat and freshwater budgets, allowing us to find the regions where coupled models are in error and how to fix them.

There are good reasons to focus on the upper-ocean heat and freshwater budgets. First, these are the ocean variables whose air-sea fluxes drive the atmosphere. Heat is directly involved in setting SST and freshwater is a direct indicator of the latent heating in the atmosphere. Second, observing the elements of the upper ocean heat budget at the needed high temporal and spatial density is easier than observing the full column or tracking other variables that are harder to measure economically. Indeed, practicality will probably limit freshwater budget observations to a smaller area, more limited sampling and reliance on the relatively slow evolution of T-S relations below the surface layer. Third, upper layer heat budgets, which intimately involve air-sea fluxes of heat and water, provide the most direct support to complementary studies in the atmosphere.

Specific process experiments will be imbedded inside the P-BECS, taking advantage of the observational and analysis support provided, and contributing to them. This is critical because so many of the important modeling questions involve not just individual processes but their interactions with others. Of potentially greater impact, while P-BECS can be designed as a self-contained test of ocean climate models, P-BECS observations and analyses could also serve as the ocean side of comprehensive ocean-atmosphere studies of sensible and latent heat. An experiment of this sort, CAGE, was proposed in the late 1970s but was abandoned because atmospheric observations capable of measuring lateral fluxes with sufficient accuracy were not then feasible. Remote sensing and atmospheric models have improved substantially since then and it may be time to reconsider the possibility of a major test of both ocean and atmospheric models on the basin scale.

IV. An Integrated Strategy

The broad attack required to improve understanding of the ocean's role in climate includes sustained observations, model development, process experiments and, we propose, a coordinated long-term observational and modeling study of climatic phenomena. There are a small number of long-term observations that have provided the basis for our present view of climate variability and these should, on there own merits, be sustained. Models of climate phenomena are rapidly improving as is our understanding of their behavior. This progress should be continued whether there is a BECS or not. There are key processes (e.g., subduction, equatorial upwelling, SST influence on stratus decks, fluctuations of ocean gyre strength in response to winds, etc.) that must be better understood before descriptions of climate phenomena can be completed. Focused studies on these processes will be required whether there is a BECS or not. While these different types of study each benefit from, and influence, each other, it is feasible and perhaps more efficient, to organize each separately. Communication between these lines of work is slow enough to be carried out through normal publications and meetings and they are not strongly linked by common logistical requirements. A BECS is meant to be the smallest logical unit that can effectively operate to improve and test climate models. A BECS will require unusually close coordination among groups of observers and among modelers and also between these groups. Such close cooperation would be very inefficient, and might not even be possible, if P-BECS were made comprehensive enough to include all mutually related elements of Pacific climate studies. The P-BECS will be a building block in the larger CLIVAR, carefully coordinated with others at the program level.

The P-BECS strategy is to integrate multivariate ocean observations with an assimilation/analysis system to construct periodic analyses (and reanalyses) of climate-scale evolution of the Pacific and to test different models through their ability to explain that evolution. To begin with at least, atmospheric forcing would likely be derived from quasi-operational analyses which might have been augmented by specific surface observations of the P-BECS experimental plan. Fields for initializing and verifying the ocean model would be developed from a combination of existing quasi-operational observations (like those from satellites, the TAO array, drifters and Volunteer Observing Ships), observations and analyses from separately organized research programs (like the PACS and Consortium on the Ocean's Role in Climate programs), and from new P-BECS observations required to make adequate the observed fields pertinent to models. These observations would be combined using methods ranging from empirical approaches based on field statistics and the simplest kinematic constraints through reduced-state-space data assimilating models and on to the most sophisticated assimilation systems. For the P-BECS to succeed the resultant analyses must be capable of describing the coherent patterns of upper ocean variability and the processes that cause them - processes like isopycnal advection; subduction; mixing and entrainment; Ekman divergence; air-sea fluxes; Rossby and Kelvin wave propagation and reflection; and upper layer transport by the major current systems.

It is not sufficient to simply obtain observations sufficient to describe the patterns of variability and processes. These must be made dynamically consistent, which will require a faithful model with appropriate representations of the key processes. In part this means adequate parameterizations of sub-grid processes but it also means using models with sufficient resolution that the fluxes supported by the resolved field are accurately computed. At the same time, models must be realistic enough that they are directly comparable with observations without uncertainty about what physical variable various model parameters represent. Thus models based on thick homogeneous layers will be less useful than will models that involve realistic stratification. Finally, the observational sampling must be dense and comprehensive enough to reduce analysis error to the point that high resolution models can be accurately initialized and critically tested. The importance and nonlinear nature of advection will make its accurate observation the factor that determines the observational density in most places.

There is a tension between achieving sufficient observational density to really initialize and test assimilating models and covering enough of the Pacific basin to observe all of the important phenomena. The P-BECS concept is closely tied to exploiting assimilating models, so the strategy of first obtaining a sufficient concentration in a high-priority region and then working outward to other regions is dictated. There are several reasons to suggest the Pacific BECS should begin with a focus on the tropics and its connections to the subtropics:

- There is great intellectual interest in the processes of the tropical air-sea coupling;
- Interannual prediction has great potential societal value;
- There is presently a considerable instrumentation investment in the tropical Pacific;
- Advances in understanding interannual variability are expected to be more rapid than for decadal variability;
- There is an expressed Japanese focus on the Kuroshio and North Pacific subpolar gyre which could lead to an integrated international effort.

The relatively rapid dynamical connection with the tropics along the eastern and western boundaries suggest extension to higher latitudes there than in the central ocean. Coverage of eastern and western boundaries is critical but the meridional domain could be expanded farther into the subtropics as resources allow. The appropriate focus of the Pacific BECS is on the upper 300-1000 m of the ocean and the processes that lead to seasonal through decadal anomalies of SST, upper ocean heat transport, and stratification. The biggest uncertainties here are the inter-gyre connections made either along the boundaries or in the shallow meridional overturning circulation and the diabatic processes that have been largely avoided in seeking ENSO predictability. ENSO development and the associated mechanisms (the connection of thermocline depth to SST, heat budget of the cold tongue, apparent off-equator sea-level and SST precursors) are of interest although the TAO observing system and ENSO modeling efforts already provide much in this area already.

Because ocean variability is the focus of the P-BECS, accurate surface forcing fields are a necessity. It is important to note that some climate scale processes, such as subduction, are forced by synoptic scale atmospheric variability. Fortunately, the North Pacific Ocean is reasonably well sampled by volunteer observing ships. Estimates of forcing functions are available from analysis of surface observation data sets. The best forcing fields will come from operational atmospheric models that assimilate these surface observations along with the full suite of *in situ* and remote atmospheric measurements. The P-BECS approach to surface fluxes, like that to altimeter data, will be to improve the accuracy of climate-scale averages of analyzed flux fields so that their spatial-temporal coverage can be exploited for climate studies. Two approaches will be followed simultaneously. The P-BECS should include augmented surface observations to diagnose errors in the analyses and, by closing climate time scale upper ocean heat and salt budgets, should provide the strongest tests on the net fluxes.

Key elements of P-BECS are likely to include:

- A focus and coordinating mechanism for the improvements of models and assimilation methods for use with BECS data. This would coordinate needed computer resources with the scientists who need them. The same mechanism would serve as the focus for dialogue between modelers and observers in developing an understanding of observed climate variability.
- Focused analyses of existing observations from TOGA, WOCE and quasi-operational monitoring are required to better understand what can be accomplished from past observational arrays and what augmentation will be needed.
- Increased temperature/salinity measurements within the upper ocean. Since important observed salinity changes are of the order 0.2 psu, salinity must be measured to better than 0.05.
- Altimetry/sea level measurements and analyses. This would include analyses of the subsurface conditions associated with sea-level anomalies and direct velocity observations. This will require continued high-quality altimetric coverage.
- Direct velocity observations. High-resolution is needed in boundary currents while extensive observations would be needed to observe potentially ageostrophic surface flows and the weaker flows associated with the meridional overturning circulation.
- Special surface observations are needed to test and improve model-based analyses of heat, moisture and momentum fluxes.
- Tracer studies. These will clarify the adiabatic and diabatic processes in the water-mass formation and subduction branches of the meridional overturning system.
- Specific instrument development will be needed for the above items, particularly sensors capable of accurate long-term *in situ* measurements of salinity.

In addition to general upper ocean climatic variability and the changes in circulation that accompany or cause them, these elements, and perhaps others, should be focused on some key processes such as:

- A focused study of upper layer processes that govern upper layer heat and freshwater transport and mixing such as subduction out of the mixed layer, entrainment, convection, frontogenesis, and diabatic and ageostrophic processes occurring below the surface mixed layer.
- A study of subducted waters within the subtropical gyre including tracking water mass anomalies in the upper layer, the diapycnal and isopycnal mixing that modifies them, and the advection that carries these anomalies around the Pacific in the upper pycnocline.
- A specific western boundary current study to understand confluences, bifurcations, Rossby wave reflection and the resultant transport variability.
- An examination of the heat budget of the equatorial cold tongue including upwelling, meridional and zonal advection, vertical and lateral mixing and their relationship to surface forcing.

A. Long-term observations

In the context of P-BECS, “long-term” means 10 years or longer. Only through quantitative model-data comparisons spanning the basinwide scales of interest and extending over years can the physics of ocean climate models be improved and validated. It is impossible to imagine a single research program supporting observations of sufficient number and diversity to provide the needed observations. Thus the BECS observations must be designed to gain maximum advantage both from present *in situ* observing systems and from the global satellite observations which have recently come online.

The strategy for the long-term observations in P-BECS is to rely on continuation of the Pacific Ocean component of the "global climate observing system" and to enhance that selectively to achieve the observational mix and density required. The observational domain would initially be focused in the tropics and subtropical North Pacific, say from 20°S to 40°N, but could be enlarged over time as the value of the BECS strategy is demonstrated and additional resources are identified, either from other national or international programs (see section V).

Continuing TOGA and WOCE observations, such as the TAO array of moorings, broadscale and high-resolution XBT networks, surface drifter and ALACE float arrays provide a substantial base on which to build. In addition to satellite SST and wind measurements, the dynamically revealing measurements of sea surface height from altimeters will be crucial.

The long-term observational objectives of P-BECS overlaps those of the proposed Global Ocean Data Assimilation Experiment (GODAE). Many of the needed *in situ* observations will be designed to define the subsurface features associated with sea level perturbations. These perturbations describe anomalies of surface geostrophic currents and represent some combination of changes in vertically integrated heat content, salinity variability and barotropic currents. The mean surface currents, the ageostrophic current component, the partition of baroclinic and barotropic currents and the vertical thermohaline structure must all be determined with *in situ* observations. To the extent that this can be done the spatial and temporal coverage of the satellite observations will apply to these fields as well.

Observations will be needed not only in the ocean interior, but also along both the eastern and western boundaries. Given the planned programs under GLOBEC, CoOP, PACS and VAMOS in the eastern Pacific it may be relatively easy to observe the primarily wave-like phenomena along the eastern boundary. It will be more difficult to observe the western boundary well, particularly variability in the bifurcation of the NEC at the Philippines, the effect this has on the Kuroshio and the Mindanao Current, and how this variability is related to the reflection of Rossby waves and to equatorward-propagating Kelvin waves.

1. The ongoing global observing system

The fledgling global climate observing system includes the following ocean variables and observational techniques:

- sea surface temperature - AVHRR, surface drifters
- thermal structure - XBT (high resolution + broadcast), TAO + TRITON buoy arrays
- sea level - altimeter, island and coastal tide gauges
- velocity - surface drifters, floats, CM moorings
- salinity - XCTD, repeat hydrography
- surface forcing - VOS, moored buoys, scatterometer, ISCCP, GPCP, Numerical Weather Prediction analyses

Unfortunately, not all of these components have achieved routine operational status because their funding is provided through research projects, and the distribution of the observations is extremely sparse for some components such as salinity. This prospectus provides motivation for their sustained funding through transition to operational status or through community-based research projects. It is unfortunate that some of those elements which have been considered routine for many years are also subject to funding problems, but recent efforts to develop the Global Climate Observing System and Global Ocean Observing System have begun to receive wider support.

Despite the recent successes with satellite oceanography, the community needs to think ahead to ensure continued availability of the required sensors. It takes about a decade to plan a new mission. (Note, however, that NASA is now considering smaller, cheaper, faster missions that can be planned and launched in less than five years.) Another consideration is that NASA's charter is technology development, not ocean monitoring. Thus, once the technology is proved, responsibility for maintenance of the required ocean observational capability must be placed within an appropriate funding agency context.

At present, altimetric measurements seem assured through 2005 thanks to TOPEX/ Poseidon and the follow-on mission, JASON. The recent mishap to NSCAT has severely affected scatterometer operations as the data from the ERS satellites are not as good; however, the NSCAT recovery mission (QuikSCAT) is likely to go ahead in 1998, with SEAWINDS missions planned for 2000 and 2003. Thus scatterometer data should be available through 2006. Missions after 2005 or so will depend to a large degree on progress with NPOESS, which is considering the convergence of military and civilian satellite use.

2. Enhanced measurements

Present understanding indicates that P-BECS will require enhanced long-term measurements of:

- Upper ocean thermal and salinity structure; these can be provided by a mix of XBTs, XCTDs, profiling floats, salinity-sensing surface drifters, moorings, gliders, repeat hydrography (including time series stations), and thermosalinographs on VOS.
- Boundary flows such as the Kuroshio; techniques include current moorings, repeat hydrography including ADCP, VOS ADCP, regional tomography.
- Upper ocean advection; methods include surface drifters, subsurface floats, VOS ADCP.
- Surface forcing; this requires both air-sea interaction buoys and increased quality/ quantity of VOS surface meteorological observations.

These are needed to enhance the spatial coverage and resolution available from existing observations and to provide coverage of additional variables. The distinctive aspect of P-BECS is the focus on velocity, advection of heat and salt, and the need for improved air-sea fluxes.

Present planning assumes that the majority of the enhanced observations will be carried out by academic scientists from universities and both private and government laboratories. The scope of observation is not so much greater than these groups have undertaken in the recent past. The needed instruments are either available or require the kind of technical advances that can be counted on. P-BECS would, of course, embrace new technologies that provide more cost effective or more scientifically useful observations as these become available.

The rub in this plan to piece a basin-scale, long-term observing system together from contributions by academics is organizational. Research grants and the interests of researchers are too short to plan on the same groups making the observations throughout P-BECS. It is intended that different observational tasks would be shared by several groups and these would rotate over time. To make this work well, some form of central management structure will be required to oversee coordination of the various observational components, to provide quality control, and to adapt to the inevitable changes that occur over years. Finding an appropriate management structure and a way for it to appropriately inform and/ or mediate the relationship between funding sources and the groups doing the work will be a major challenge. Of course, this is also a challenge for development of a mature operational ocean climate observing system.

B. Modeling and data assimilation

TOGA's success resulted from applying to the ENSO phenomenon a hierarchy of models ranging from the relatively simple to complex coupled general circulation models (CGCMs). This allowed a broad community of scientists to participate in unraveling the ENSO processes and developing experimental prediction systems. It was only by the end of the TOGA decade that some of the sophisticated CGCMs achieved the same levels of forecast skill as the simpler models. One can anticipate that a similar paradigm will apply for the P-BECS. Some of the basic adjustment processes are robust and can be dealt with in models that isolate simple physics. However, one must anticipate that CGCMs will be required to deal with all the interacting complexities.

Despite their shortcomings, ocean GCMs (OGCMs) have achieved a sufficient degree of realism that they can now be employed actively both as tools for synthesizing diverse oceanic observations into "best estimates" of the quantities of interest (e.g., to estimate the freshwater divergence from the array of observations) and in answering experiment design questions (e.g., to what extent is the oceanic heat flux divergence sensitive to the observed flow field in some particular region at a particular time?) An active program in data-model synthesis must be a component of the P-BECS to interpret and analyze the observations and to help plan improvements of the observational array. The combination of model and data fields, presuming that both contain elements of the same variability, provides a better definition of oceanic evolution than either by itself. Once the extent of predictability has been established, these same analyses then serve as the initial conditions for experimental forecasts of the coupled system.

1. Model development

Today's OGCMs tend to underestimate oceanic variability. This variability is the result of eddies and oceanic adjustment to highly variable surface forcing. Deficiencies in the ability of models to propagate information accurately will be a severe handicap in understanding oceanic adjustment processes. Hence this is one category of model improvement that is necessary. Another is the treatment of mixing. Model physics need improvement in key ways to be useful for describing subduction. On longer time scales one cannot believe model studies of the dispersion of active or passive tracers until the mixing parameterizations are improved. It is likely that this will require specialized process studies to help develop the appropriate parameterizations. Another aspect of model performance that needs to be improved are the transports and variability in western boundary currents.

Many OGCMs tend to develop spurious internal variability in the western boundary current separation region and this must be fixed before real variability can be studied. The P-BECS will provide an opportunity to develop links between the ocean-modeling and coupled-modeling communities. The coupling processes in the extra-equatorial regions are more subtle than those near the equator, so coupled model studies need to be an integral part of research to help determine the specifics of the phenomena and study its potential predictability. If the meteorological community chooses to take advantage of P-BECS to mount similarly enhanced observation in the atmosphere the needed collaboration of modelers will follow naturally.

Genuine model development requires dedicated scientists willing to invest long periods of time without the kind of scientific payoffs upon which most academic careers are judged. As the National Center of Atmospheric Research was formed to facilitate academic research to improve atmospheric and climate models (among other meteorological needs), so the ocean community must encourage ocean model development and provide the substantial computer resources to support this development. This may require centralized facilities or, in this age of rapid electronic communication, mainly a coordinating and funding mechanism. The strategies for encouraging ocean model development are beyond the scope of P-BECS, but much of the intent of this project is to improve models and that will require entraining productive model developers.

2. Data assimilation studies

An active program in data assimilation is central to a BECS. Because any comparison of models and data must deal with errors in both, the most effective testing of ocean models is done within an assimilation context. The combination of model and data fields allows a better definition of what took place (a better analysis) than either by itself. The same process, when based on realistic measures of measurement error and sampling noise, allows quantitative testing of the model, identifications of model deficiencies, and experimentation that leads to model improvement. Once predictability has been established, these analyses then serve as the initial conditions for the forecasts.

A number of assimilation efforts have been developed for ENSO prediction; the use of *in situ* and remote observations for initialization clearly improves the skill of the forecasts. Some of these systems routinely perform analyses for the regions under consideration here, but they need to be enhanced and extended for P-BECS. This includes a) focusing on tests and improvement of model representations of climate processes over longer time scales, (b) extending the analysis domain to consider climate variability in the subtropics, and (c) designing an array of observations specifically designed to test model representations of key climate processes. The basic infrastructure developed for operational ENSO analyses, such as acquisition and active management of ocean data and forcing fields, could benefit P-BECS researchers. As recently completed for the atmosphere, ocean reanalyses will be done for regions of interest. Since the North Pacific is one of the best sampled areas of the ocean for the past 40 years, having retrospective analyses over this time period will be a key element for diagnosing the sources and mechanisms for past climate variability. At the same time, P-BECS improvements in data, data management, models and assimilation techniques could be incorporated into operational climate forecasts.

Data-sensitive modeling uses ocean dynamics to add to the information content of observations by constraining the analysis of them to evolve according to known physics. One approach is corrective data assimilation, such as employed by NCEP. In this scheme, a dynamical model is initialized with data and run in a predictive mode with observed forcing. The result is then corrected, using a non-physical form of forcing, to match new data and the model run forward again. The objective is prediction and internal dynamical inconsistency due to the corrections is not a primary issue. An alternative approach, more appropriate in the P-BECS context, is to seek initial and forcing fields that are consistent with ocean observations and which allow the dynamical model to evolve continuously and consistently with subsequent observations. This is a form of inverse problem, where the a priori guess (with known error variance) of initial and forcing fields is adjusted so that the model reproduces the data. Model testing hinges on whether the model can be made to reproduce the observations within their error bars by altering the initial and forcing fields within their error bars. Clearly, the ability to test the model depends on the amount and quality of constraining data. If the fit is successful, then the resulting dynamically consistent evolution is a 4-D interpolation of the observations, using the dynamical constraints to contribute additional information beyond what is contained in the observations.

Sampling studies are needed to help determine effective and efficient observational networks. The rigorous framework of data assimilation provides the possibility to develop objective criteria for assessing sampling alternatives. A central theme of our observational and analysis frameworks will be to develop a predictive relation between sea surface height and subsurface density structure so that altimetric information can be propagated downward through the water column. The primary task of broadscale profiling then becomes estimating this relation, rather than the far more demanding task of mapping the subsurface fields directly. Without such powerful advantages as are accorded by present *in situ* observations and satellite sensors, any feasible observing system we might implement would be too sparse for its objectives. With them, a substantial fraction of the variance in subsurface density and velocity structure can be recovered.

As with model development, special provisions will be required to enlist academics into the complex and long-term task of P-BECS assimilation studies. While the expected substantial scientific advances will attract first-rate scientists, the substantial load of routine work in preparing data sets, carrying out model sensitivity studies, and performing reanalyses will be daunting. Presently, computational resources are an important limitation on the development and improvement of ocean data assimilation techniques. A coordinated ocean data assimilation activity (perhaps even a center) that provides some of the common functions and infrastructure needed by various research efforts and that helps coordinate all the groups involved in various aspects of ocean modeling and data assimilation would seem the most effective approach, if not the easiest to organize. Fortunately, such an activity could naturally support BECS activities in multiple oceans and other studies in ocean ecology, biology and chemistry needing either the associated modeling expertise or regular analyses of the evolving ocean.

C. Process studies

The Pacific BECS will need supporting process-oriented studies. These studies would have, among others, the purpose of hypothesis development and testing and would help improve the representations of specific processes in OGCMs. Prominent deficiencies in models are related to the parameterization of upper ocean physics (especially entrainment and subduction) and the transfer (mixing) of the ocean eddy field. Resolved processes in models can be verified in process experiments and the parameterization of unresolved processes can be tested. Effective data assimilation also requires estimation of parameters (such as covariance structures) that can only be determined by oversampling to capture all relevant scales. Process studies are also important for observing system development, for their ability to determine minimum appropriate sampling density of a particular process or region, and to advance both *in situ* and remote observational technology development.

Present planning assumes that CLIVAR (and other major ocean programs) will conduct process studies to regionally enhance observations with the objectives of improving models used for assimilation and prediction, and to further develop the climate observing system. Indeed, a BECS is itself such an experiment that addresses a larger scale over a longer time than traditional process experiments but uses the same methodological approach. Other focused experiments, aimed at specific processes and spanning shorter periods than a BECS, would be sited inside P-BECS where those processes are most apt to affect the basinwide dynamics under study. Multiple-process studies are needed to understand complex linkages between processes, since these are the likely source of climate feedbacks. Effort should be made to coordinate these efforts whenever it is possible and useful to do so.

An example of such a potential process study is the effort, to be conducted under the auspices of PACS/VAMOS, to study the annual cycle and variability in the cold tongue. Another process deserving focused study is bifurcation of the North Equatorial Current and the atmospheric and oceanic factors controlling the partition of mass, heat and salt between the Kuroshio and Mindanao Current in relation to the seasonal-to-decadal variations of the Asian-Australian monsoon system and the ENSO related heat budget of the warm pool. Variable thermocline ventilation involves processes covering a broad range of time and space scales, and this is certainly a candidate for development of a process study embedded in P-BECS. Additionally, the process of upwelling and downwelling that so directly affect tropical SST may be the subject of a focused study. Specific attention must also be paid to improving surface forcing fields derived from numerical weather prediction analyses and from space-based platforms.

V. Programmatic Context

A. International programs

1. CLIVAR [http://www.dkrz.de/clivar/hp.html]

The Pacific BECS is intended to be a U.S. contribution to the WCRP Climate Variability and Predictability (CLIVAR) program and is intended to involve collaboration with other participating nations. The CLIVAR implementation plan includes a Pacific BECS in its strategy for studying Indo-Pacific decadal variability and P-BECS should contribute to GOALS research on improved predictability of ENSO. The CLIVAR Upper Ocean Panel is concerned with sustaining and enhancing long-term observations in support CLIVAR research. The Numerical Experimentation Groups -1 and -2 of CLIVAR are concerned with the improved modeling and potential prediction (on seasonal-to-interannual and on decadal-to-centennial time scales respectively) of the coupled ocean-atmosphere-land system. The Pacific BECS should be of great value to their efforts and vice versa. The Asian-Australian Monsoon Panel of CLIVAR is concerned with the influence of the western Pacific Ocean on seasonal-to-decadal variability of the monsoon system. The American Monsoon Panel has been set up to address variability of that monsoon system, and the international VAMOS project has been organized to conduct process research in that regard; the eastern tropical Pacific Ocean is an important region for VAMOS.

EPIC (http://www.cdc.noaa.gov/~ajr/epicwksh.html) is the first process-oriented study of the VAMOS element of CLIVAR. Its focus is on the eastern Pacific Ocean, specifically the cold tongue-ITCZ region and the stratus deck region. Its goal is to understand coupled ocean-atmosphere processes in these regions with the intent of building toward better models and prediction. EPIC is interested in time scales from diurnal to several years.

2. U.S.-Japan cooperation in Global Change Research

Japan has allocated new resources for global change research, and there appears to be a willingness to initiate partnerships with U.S. scientists to carry out research into climate problems. The existing U.S./Japan bilateral agreement on natural resources has supported the TYKKI program, which may be enhanced in the future. CLIVAR provides a useful scientific framework for enhanced cooperation in climate research including ocean observations and analysis. Recently, the International Pacific Research Center has been established in Hawaii to support enhanced cooperative research between Japan and the US on Pacific climate variability through modeling and data analysis.

Among likely observational programs are: JAMSTEC will take over the western part of the TAO array and has begun a moored measurement program for Pacific low-latitude western boundary currents and the inflow to Indonesian seas; JMA and MSA will continue monitoring along 137°E, 155°E and 165°E; a Kuroshio Extension experiment is planned for 1999-2004; JHA will continue with repeat hydrography lines along 134.7°E and 144°E; Kyushu University has initiated current monitoring along an ADCP line from south of Japan to the Indonesian throughflow; Japan Fisheries Institute will be working hydrographic lines in a triangle between Japan, 180° and the Aleutian Islands; Hokkaido University will continue monitoring along 155°E, 175°E and 180°.

In addition, XBTs will be provided to support continued sampling in the TRANSPAC region, a sub-arctic gyre experiment (SAGE) is in the planning stage, and there is the possibility that work will be expanded east of the Philippines in terms of moored observations, repeat hydrography and tomography.

3. GODAE/GCOS/GOOS (Global Observing System) (http://WWW.BoM.GOV.AU/bmrc/mrlr/nrs/oopc/godae/homepage.html)

The Global Ocean Data Assimilation Experiment (GODAE) has been proposed to provide a convincing demonstration of real-time assimilation systems, to be carried out 2003-2005 on a global basis, under the auspices of GCOS/GOOS. The aim is to assimilate data on scales of O(days, 100km), and produce integrated analyses that can be used for initializing model runs and for local-scale studies. This has been received enthusiastically by the WCRP. The plans call for a multi-node operation, with different groups focusing on different oceans, although all will use a common model and format so as to produce consistent products. At present, it appears that the weakest link will be a lack of subsurface ocean observations. There are also various technical problems to solve, e.g., that of constraining assimilation schemes with sparse data, how to make the prior estimates of error covariances etc.

4. PICES [http://pices.ios.bc.ca]

PICES, the North Pacific Marine Science Organization, is an intergovernmental scientific organization that was established and held its first meetings in 1992. Its present members are Canada, People's Republic of China, Japan, Republic of Korea, Russian Federation, and the United States of America. The purposes of the Organization are as follows; Promote and coordinate marine research in the northern North Pacific and adjacent seas especially northward of 30 degrees North; Advance scientific knowledge about the ocean environment, global weather and climate change, living resources and their ecosystems, and the impacts of human activities; Promote the collection and rapid exchange of scientific information on these issues.

5. GLOBEC [http://www.igbp.kva.se/globec.html]

International GLOBEC (now an official IGBP program) has a planning activity for an effort called Small Pelagics and Climate Change (SPACC). The planning has involved Japan, US, Mexico, Peru and Chile, hoping for similar activities as found in US GLOBEC - retrospective studies, monitoring, modeling and process studies.

B. US programs

1. PACS [http://tao.atmos.washington.edu/pacs]

The Pan-American Climate Studies (PACS) aim to improve the skill of operational seasonal-to-interannual climate prediction over the Americas, with the emphasis on forecasting warm season rainfall. PACS is the US component of VAMOS. Pilot studies have been funded for the region 95°W-140°W; these include ATLAS moorings within 8°N-8°S, current meter deployments along the equator, wind profilers, and IMET systems and shipboard Doppler radar within the cold tongue. Focal points include the relationship between boundary forcing and climate variability; processes governing SST variability in the tropical Atlantic and Pacific; and the development of the mixed layer. Products will include data on cloud cover, E-P, heat fluxes, and 2- and 3-dimensional models of the relative importance of mixing and advection.

2. CORC

The Consortium on the Ocean's Role in Climate (SIO/LDEO supported by NOAA) is conducting a program of observations and assimilation in the eastern tropical Pacific (20°N-20°S from the western American coast to 165°W). The program includes deployment of drifters, profiling floats, high-resolution XBTs, and VOS-mounted meteorological observations. These data together with routine XBT observations, surface flux analyses and altimetry will be inserted in dynamical models. Meteorological data will be used to identify errors in the surface flux estimates from various routine NWP analyses.

3. GLOBEC [http://www.ccpo.odu.edu/Research/globec_menu.html]

The Northeast Pacific GLOBEC program is based on anticipated ENSO variability, so the monitoring program will look for close connections to the equatorial system through oceanic and atmospheric pathways. Quarterly sampling will be carried out along transects off central Oregon and Alaska. MBARI is beginning more extensive transects off Monterey Bay, CalCOFI continues quarterly surveys in the Southern California Bight and a new program will begin CalCOFI-like sampling off Baja California. Canada will continue surveys along a line out to Station PAPA and add a line north to Alaska. The PICES program is trying to establish similar quarterly transects from Korea around the basin. Off South America, the Peruvians have been quite active in sampling, and sampling off Chile at 23°S, 30°S, and 37°S may be established. So the margins of the basin may be sampled along transects extending out 200 km or more with moderately good alongshore spacing (from a basin perspective). The GLOBEC program will intensify around 2000, both in these monitoring transects (California Current and Coastal Gyre of Alaska) and process studies within several 100 km of the coast. A major motivation is to examine covariability between the subarctic gyre and the subtropical gyre along the eastern margins over a five-year period, so monitoring is expected to continue to 2004 or so, with a scaled down system left in place.

As part of the GLOBEC work, at least one numerical model will be run from south of the equator to the northern boundary of the Pacific. Along the margins, regional models will be nested or run with open-boundary conditions. Very high resolution models will be nested inside these regional models at a few locations, and the research effort will be coordinated with CoOP. Cooperation between this effort and those supported by P-BECS is highly desirable. The GLOBEC implementation plan also discusses the utility of seeding the North Pacific with an array of Profiling ALACE floats to monitor the density structure and as inputs for data assimilation models. Again cooperation with the Pacific BECS could increase the effectiveness of both programs.

4. CoOP [http://www.hpl.umces.edu/CoOP/index.htm]

Coastal Ocean Processes (CoOP) is a program that seeks to plan and implement multi-investigator, interdisciplinary research in the coastal ocean. CoOP encompasses the disciplines of Biological, Chemical, Geological and Physical Oceanography, plus Marine Meteorology. For planning purposes, CoOP defines the coastal ocean as extending from the surf zone to the edge of the continental rise, an area generally ranging from 100 to 1000 km offshore. Together with US GLOBEC, CoOP is conducting The Northeast Pacific Study: Coordinated Coastal Research (http://www.hpl.umces.edu/CoOP/NEPacific.htm). Presently, phase I is in progress, consisting of modeling, retrospective analysis and pilot observing projects

VI. Next Steps

There are essentially four steps required to design and implement an effective Pacific Basinwide Extended Climate Study. First is coordination with CLIVAR and the numerous other climate studies and oceanographic programs that might benefit from a well designed P-BECS and might contribute to it. This will define the scope of the BECS itself and define other specific process experiments, model developments or sustained observations that may be required to complement it. Second is commitment by the community and funding agencies to the concept and scope of a P-BECS. Because a BECS will be made up of many essential and coordinated elements that must continue for years, it cannot be developed without a steering entity to ensure that the essential elements are in place. A commitment to put such an entity in place must precede the third step, which is establishment of a coordinating mechanism to plan implementation and oversee integration of the various P-BECS elements. The last step is the detailed planning, funding, and implementation of specific elements of the study.

Effective development of a P-BECS will require a degree of coordination that is unprecedented in oceanography, but which has been accomplished by the atmospheric sciences. While a successful study could be carried out by close collaboration between observing and modeling oceanographers, the effort will have vastly greater impact if it is combined with a comparable effort in the atmosphere. Thus, it is desirable to engage in a discussion between oceanographers and meteorologists to determine the feasibility of coordinating their Pacific Ocean efforts, presumably under the umbrella of CLIVAR. At the same time there are other oceanographic studies, notably GLOBEC and any JGOFS follow-on, that might benefit from a P-BECS and might influence how that study develops.

After the general elements and scope of the P-BECS are determined, it will be necessary to devise a mechanism for planning and coordinating the complex of elements that will make it up. Both the observational and assimilation modeling aspects of a BECS will depend on unprecedented coordination of academic researchers. However it is organized, this coordinating function will require considerable time and effort from specific scientists and an institutional commitment that will allow coordination to continue as these scientists change. Before these can be established, it will be necessary for a critical mass of scientists to commit to the process and funding agencies to agree to treat the BECS as a group of interrelated elements rather than individual investigations.

The necessarily long duration of a BECS will require unusual attention to how the coordinating activity is established. On one hand, it is essential that the best individual scientists be selected to carry out the work of the study and that this selection be reevaluated as the study progresses. On the other, it is important that all the necessary scientific elements continue effectively for the duration of the study. One approach is for the steering group to define the specific BECS elements (e.g., XBTs, surface flux fields, model sensitivity studies) and help funding agencies to select appropriate groups to carry out this work. To insure continuity, maintaining the steering group might be the function of a consortium of institutions that operate under contract. Hopefully systems experts in the agencies can devise an effective mechanism for coordinating all of the needed scientific activity, oversight functions and the differing goals of the agencies themselves. It will require the greatest sensitivity to establish an oversight mechanism that both maintains the community's confidence in its fairness while exercising the control necessary to keep the BECS components effective and coordinated.

The last stage of planning will be defining the specific components of the P-BECS. If, in fact, the study is organized as a network of separately contracted functions, description of these functions will be the key planning step and the basis for ongoing management.

References

Anderson, S.P., R.A. Weller, and R. Lukas, 1996: Surface buoyancy forcing and the mixed layer of the western Pacific warm pool: Observations and 1-D model results. *J. Climate*, 9, 3056-3085.

Ando, K. and M.J. McPhaden, 1997: Variability of surface layer hydrography in the tropical Pacific Ocean. *J. Geophys. Res.*, 102, 23,063-23,078.

Battisti, D.S. and A.C. Hirst, 1988: Interannual varability in the tropical atmosphere/ocean system: Influence of the basic state and ocean geometry. *J. Atmos. Sci.*, 45, 1687-1712.

Battisti, D.S., 1988: The dynamics and thermodynamics of a warming event in a coupled tropical atmosphere/ocean model. *J. Atmos. Sci.*, 45, 2889-2919.

Blanke, B., and S. Raynaud, 1997: Kinematics of the Pacific Equatorial Undercurrent: An Eulerian and Lagrangian approach from GCM results. *J. Phys. Oceanogr.*, 27, 1038-1053.

Bryan, K., 1991: Michael Cox (1941-1989): His pioneering contributions to ocean circulation modeling. *J. Phys. Oceanogr.*, 21, 1259-1270.

Chelton, D.B., and M.G. Schlax. 1996: Global observations of oceanic Rossby waves. *Science*, 272, 234-238.

Davis, R.E., 1976: Predictability of Sea Surface Temperature and Sea Level Pressure Anomalies over the North Pacific Ocean. *J. Phys. Oceanogr.*, 6, 249-266.

Davis, R.E., 1978: Predictability of sea level pressure anomalies over the North Pacific Ocean. *J. Phys. Oceanogr.*, 8, 233-246.

Delcroix, T. and C. Henin, 1991: Seasonal and interannual variations of sea surface salinity in the tropical Pacific Ocean. *J. Geophys. Res.*, 96, 22,135-22,150.

Delcroix, T., and J. Picaut, 1998: Zonal displacement of the western equatorial Pacific “fresh pool”. *J. Geophys. Res.*, 103, 1087-1098.

Delcroix, T., G. Eldin, and M.-H. Radenac, 1992: Variation of the western equatorial Pacific Ocean, 1986-1988. *J. Geophys. Res.*, 97, 5423-5445.

Deser, C., M.A. Alexander, and M.S. Timlin, 1996: Upper-ocean thermal variations in the North Pacific during 1970-1991. *J. Climate*, 9, 1840-1855.

Folland, C. K., D. E. Parker and F. E. Kates, 1984: Worldwide marine temperature fluctuations 1856-1981. *Nature*, 310, 670- 673.

Frankignoul, C., P. Muller, and E. Zorita, 1997: A simple model of the decadal response of the ocean to stochastic forcing. *J. Phys. Oceanogr.*, 27, 1533-1546.

Godfrey, J.S., R.A. Houze, Jr., R.H. Johnson, R. Lukas, J.-L. Redelsperger, A. Sumi and R. Weller, 1998: Coupled Ocean-Atmosphere Response Experiment (COARE): An interim report. *J. Geophys. Res.*, 103, 14,395-14,450.

Graham, N. E., 1994: Decadal-scale climate variability in the 1970’s and 1980’s: Observations and model results. *Clim. Dyn.*, 10, 135-162.

Graham, N.E. and W.B. White, 1988: The El Niño cycle: a natural oscillator of the Pacific ocean-atmosphere system. *Science*, 240, 1293-1302.

Gu, D. and S.G.H. Philander, 1997: Interdecadal climate fluctuations that depend upon exchanges between the tropics and extratropics. *Science*, 275, 805-807.

Hanawa, K., S. Ishizaki and Y. Tanimoto, 1996: Examination of the strengthening of wintertime mid-latitude westerlies over the North Pacific in the 1970s. *J. Meteor. Soc. Japan*, 74, 715- 721.

Harrison, D.E. and N.K. Larkin, 1998: El Niño/Southern Oscillation: surface temperature and wind anomalies, 1946-1993. *Rev. Geophysics* (in press).

Harrison, D.E. and N.S. Larkin, 1996: The COADS sea level pressure signal: A near-global El Niño composite and time series results, 1946-1993. *J. Climate*, 9, 3025-3055.

Hirst, A.C., D.R. Jackett, and T.J. McDougall, 1996: The meridional overturning cells of a world ocean model in neutral density coordinates. *J. Phys. Oceanogr.*, 26, 775-791.

Huang, R.X., and B. Qiu, 1994: Three-dimensional structure of the wind-driven circulation in the subtropical North Pacific. *J. Phys. Oceanogr.*, 24, 1608-1622.

Jacobs, G.A., H.E. Hurlburt, J.C. Kindle, E.J. Metzger, J.L. Mitchell, W.J. Teague and A.J. Wallcraft, 1994. Decade-scale trans-Pacific propagation and warming effects on an El Niño anomaly. *Nature*, 370, 360-363.

Jin, F.-F., 1997: A theory of interdecadal climate variability of the North Pacific Ocean-Atmosphere system. *J. Climate*, 10, 1821-1835.

Johnson, G.C., and M.J. McPhaden, 1998: Interior pycnocline flow from the subtropical to the equatorial Pacific Ocean., *J. Phys. Oceanogr.*, submitted.

Kessler, W.S., L.M. Rothstein and D. Chen, 1998: The annual cycle of SST in the eastern tropical Pacific, diagnosed in an ocean GCM. *J. Climate*, 11, 777-799.

Kessler, W.S., M.J. McPhjaden, and K.M Weickmann, 1995: Forcing of intrasesasonal Kelvin waves in the equatorial Pacific. *J. Geophys. Res.*, 100, 10,613-10,631.

Killworth, P.D., D.B. Chelton, and R.A. deSzoeke, 1997: The speed of observed and theoretical long extratropical planetary waves. *J. Phys. Oceanogr.*, 27, 1946-1966.

Kutsuwada, K., 1988: Interannual correlations between sea level difference at the south coast of Japan and wind stress over the North Pacific. *J. Oceanogr. Soc. Japan*, 44, 68-80.

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

Latif, M. D. Anderson, T. Barnett, M. Cane, R. Kleeman, A. Leetmaa, J. O'Brien, A. Rosati and E. Schneider, 1998: A review of the predictability and prediction of ENSO. *J. Geophys. Res.*, 103, 14,375-14,393.

Latif, M., 1998: Dynamics of interdecadal variability in coupled ocean-atmosphere models. *J. Climate*, 11, 602-624.

Latif. M., and T.P. Barnett, 1996: Decadal climate variability over the North Pacific and North America: Dynamics and Predictability. *J. Climate*, 9, 2407-2423.

Lau, K.-M., and H. Weng, 1995: Climate signal detection using wavelet transform: How to make a time series sing. *Bull. Amer. Meteor. Soc.*, 76, 2391-2402.

Lau, N.-C. and M.J. Nath, 1990: A general circulation model study of the atmospheric response to extratropical SST anomalies observed in 1950-79. *J. Climate*, 3, 965-989.

Lau, N.-C., 1988: Variability of the observed midlatitude storm tracks in relation to low-frequency changes in the circulation pattern. *J. Atmos. Sci.*, 45, 2718-2743.

Liu, Z. and S.G.H. Philander, 1995: How different wind stress patterns affect the tropical-subtropical circulations of the upper ocean. *J. Phys. Oceanogr.*, 25, 449-462.

Liu, Z., 1998: Forced planetary wave response in a thermocline gyre. *J. Phys. Oceanogr.*, submitted.

Liu, Z., and B. Huang, 1998: Why is there a tritium maximum in the central equatorial Pacific thermocline? *J. Phys. Oceanogr.*, 28, 1527-1533.

Liu, Z.Y., S.G.H. Philander and P.C. Pacanowski, 1994: A GCM study of tropical-subtropical upper-ocean water exchange. *J. Phys. Oceanogr.*, 24, 2606-2623.

Lu, P., and J.P. McCreary, 1995: Influence of the ITCZ on the flow of thermocline water from the subtropical to the equatorial Pacific Ocean. *J. Phys. Oceanogr.*, 25, 3076- 3088.

Lu, P., J.P. McCreary, and B.A. Klinger, 1998: Meridional circulation cells and the source waters of the Pacific Equatorial Undercurrent. *J. Phys. Oceanogr.*, 28, 62-84.

Lukas, R. and E. Lindstrom, 1991: The Mixed Layer of the Western Equatorial Pacific Ocean. *J. Geophys. Res.*, 96(suppl.), 3343-3357.

Lukas, R., T. Yamagata, and J. McCreary, 1996: Pacific Low-Latitude Western Boundary Currents. *J. Geophys. Res.*, 101, 12,209-12,216.

Luyten, J.R., J. Pedlosky, and H. Stommel, 1983: The ventilated thermocline. *J. Phys. Oceanogr.*,13, 292-309.

Madden, R.A., and P.R. Julian, 1971: Detection of a 40-50 day oscillation in the zonal wind in the tropical Pacific. *J. Atmos. Science*, 28, 702-708.

Mann, M.E. and J. Park, 1996: Global scale modes of surface temperature variability on interannual to century time scales. *J. Geophys. Res.*, 99, 25, 819-25,833.

Mann, M.E., J. Park, and R.S. Bradley, 1995. Global interdecadal and century-scale climate oscillations during the past five centuries. *Nature*, 378, 266-270.

Marshall, J., G. Nurser, and R. Williams, 1993: Inferring the subduction rate and period over the North Atlantic. *J. Phys. Oceanogr.*, 21, 1315-1329

McCreary, J.P. 1983: A model of tropical ocean-atmosphere interaction. *Mon. Wea. Rev.*, 111, 370-387.

McCreary, J.P., and P. Lu, 1994: On the interaction between the subtropical and the equatorial oceans: The subtropical cell. *J. Phys. Oceanogr.*, 24, 466-497.

McPhaden, M. J., F. Bahr, Y. Du Penhoat, E. Firing, S. P. Hayes, P. L. Richardson P. P. Niiler, and J. M. Toole. 1992. The response of the Western Equatorial Pacific Ocean to westerly wind bursts during November 1989 to January 1990. *J. Geophys. Res.*, 97, 14,289-14,303.

McPhaden, M.J., H. Paul Freitag, S. P. Hayes, and B. A. Taft. 1988: The response of the equatorial Pacific Ocean to a westerly wind burst in May 1986. *J. Geophys. Res.*, 93, 10589-10603.

Metzger, E.J. and H.E. Hurlburt, 1996: Coupled dynamics of the South China Sea, the Sulu Sea and the Pacific Ocean. *J. Geophys. Res.*, 101, 12331-12352.

Michaelson, J., 1982: A statistical study of large-scale, long- period variability in North Pacific sea surface temperature anomalies. *J. Phys. Oceanogr.*, 12, 694-703.

Miller, A. J., D.R. Cayan, and W.B. White, 1998: A decadal change in the North Pacific thermocline and gyre-scale circulation. *J. Climate* (in press).

Miller, A.J., W.B. White, and D.R. Cayan, 1997: North Pacific thermocline variations on ENSO timescales. *J. Phys. Oceanogr.*, 27, 2023-2039.

Nakamura, H., G. Lin and T. Yamagata, 1997: Decadal climate variability in the North Pacific during the recent decades. *Bull. Am. Met. Soc.*, 78, 2215-2225.

Namias, J., 1951: The great Pacific anticyclone of winter 1949- 50: A case study in the evolution of climatic anomalies. *J. Met.*, 8, 251-261.

Namias, J., 1963: Large-scale air-sea interactions over the North Pacific from summer 1962 through the subsequent winter. *J. Geophys. Res.*, 68, 6171-6186.

Namias, J., 1966: Nature and possible causes of the northeastern United States drought during 1962-65. *Mon. Wea. Rev.*, 94, 543-554.

Namias, J., 1970: Macroscale variations in sea-surface temperatures in the North Pacific. *J. Geophys. Res.*, 75, 565-582.

Namias, J., 1972: Space scales of sea-surface temperature patterns and their causes. *Fish. Bull.*, 70, 611-617.

Namias, J., 1978: Multiple causes of the North American abnormal winter 1976-77. *Mon. Wea. Rev.*, 106, 279-295.

Oberhuber, J.M., E. Roeckner, M. Chrisoph, M. Esch and M. Latif, 1998: Predicting the ’97 El Niño event with a global climate model. (submitted to *Nature*).

Pedlosky, J., 1987: An inertial theory of the equatorial undercurrent. *J. Phys. Oceanogr.*,17, 1978-1985.

Pedlosky, J., 1988: Entrainment and the termination of the equatorial undercurrent, *J. Phys. Oceanogr.*,18, 880-886.

Pedlosky, J., and R.M. Samelson, 1989: Wind forcing and the zonal structure of the equatorial undercurrent, *J. Phys. Oceanogr.*, 19, 1244-1254.

Philander, S.G.H., 1978. Forced oceanic waves. *Rev. Geophys. Space Phys.*, 16, 15-46.

Picaut, J. and T. Delcroix, 1995: Equatorial wave sequence associated with the warm pool displacement during the 1986-1989 El Niño and La Niña. *J. Geophys. Res.*, 100, 18,393-18,408.

Picaut, J., M. Ioualalen, C. Menkes, T. Delcroix, and M.J. McPhaden, 1996: Mechanism of the zonal displacements of the Pacific warm pool, implication for ENSO. *Science*, 274, 1486-1489.

Pierce, D. W., Barnett, T. P., and Latif, M., 1998: Connections between the tropics and midlatitudes on decadal time scales. *J. Climate*, submitted.

Qiao, L., and R.H. Weisberg. 1997: The zonal momentum balance of the Equatorial Undercurrent in the central Pacific. *J. Phys. Oceanogr.*, 27, 1094-1119.

Qiu, B. and R. Lukas, 1996: Seasonal and interannual variability of the North Equatorial Current, the Mindanao Current and the Kuroshio along the Pacific Western Boundary. *J. Geophys. Res.*, 101, 12,315-12,330.

Qiu, B., W. Miao and P. Muller, 1997: Propagation and decay of forced and free baroclinic Rossby waves in off-equatorial oceans. *J. Phys. Oceanogr.*, 27, 2405-2417.

Roemmich, D., M. Morris, W.R. Young and J.R. Donguy, 1994: Fresh equatorial jets. *J. Phys. Oceanogr.*, 24, 540-558.

Rothstein, L.M., R.-H. Zhang, A.J. Busalacchi and D. Chen, 1998: A numerical simulation of the annual-mean water pathways in the subtropical and tropical Pacific Ocean. *J. Phys. Oceanogr.*, 28, 322-343.

Schopf, P.S., and M.J. Suarez, 1988: Vascillations in a coupled ocean-atmosphere model. *J. Atmos. Sci.*, 45, 549-566.

Shinoda, T. and R. Lukas, 1995: Lagrangian mixed layer modeling of the western equatorial Pacific. *J. Geophys. Res.*, 100, 2523-2541.

Stommel, H., 1979: Determination of watermass properties of water pumped down from the Ekman layer to the geostrophic layer below. *Proc. Natl. Acad. Sci. U.S.*, 76, 3051-3055.

Tanimoto, Y., N. Iwasaka, K. Hanawa and Y. Toba, 1993: Characteristic variations of sea surface temperature with multiple time scales on the North Pacific. *J. Climate*, 6, 1153-1160.

Tourre, Y.M., Y. Kushnir and W. B. White. 1998. Evolution of quasi-cyclic interdecadal variability in the Pacific ocean- atmosphere system. *J. Phys. Oceanogr.*, in press.

Trenberth, K. E., G. W. Branstator, D. Karoly, A. Kumar, N-C. Lau, and C. Ropelewski, 1998: Progress during TOGA in understanding and modeling global teleconnections associated with tropical sea surface temperatures. *J. Geophys. Res.*, 103, 14,291-14,324.

Trenberth, K.E. and A. Solomon, 1994: The global heat balance: Heat transports in the atmosphere and ocean. *Clim. Dyn.*, 10, 107-134.

Trenberth, K.E. and J.W. Hurrell, 1994: Decadal atmosphere-ocean variations in the Pacific. *Clim. Dyn.*, 9, 303-319.

Tsuchiya, M., R. Lukas, R.A. Fine, E. Firing and E. Lindstrom, 1989: Source Waters of the Pacific Equatorial Undercurrent. *Prog. Oceanogr.*, 23, 101-147.

Vialard, J., and P. Delecluse, 1998a: An OGCM study for the TOGA decade. Part I: Role of salinity in the physics of the western Pacific fresh pool. *J. Phys. Oceanogr.*, 28, 1071-1088.

Vialard, J., and P. Delecluse, 1998b: An OGCM study for the TOGA decade. Part II: Barrier-Layer formation and variability. *J. Phys. Oceanogr.*, 28, 1089-1106.

Wallace, J.M. and D.S. Gutzler, 1981: Teleconnections in the geopotential height field during the Northern Hemisphere winter. *Mon. Wea. Rev.*, 109, 784-812.

Watanabe, T. and K. Mizuno, 1994: Decadal changes in the thermal structure of the North Pacific. Int. WOCE Newsletter, 15, 10-14.

Webster, P. J. and R. Lukas, 1992: TOGA COARE: The Coupled Ocean-Atmosphere Response Experiment. *Bull. Amer. Met. Soc.*, 73, 1377-1416.

White, W. B., J. Lean, D.R. Cayan, and M.D. Dettinger, 1997. Response of global upper ocean temperature to changing solar irradiance. *J. Geophys. Res.*, 102, 3255-3266.

White, W.B., and D.R. Cayan, 1998. Quasi-periodicity and global symmetries in interdecadal upper-ocean temperature variability. *J. Geophys. Res.*, in press.

Williams, R.G., M. Spall, and J. Marshall, 1995: Does Stommel's mixed-layer "demon" work? *J. Phys. Oceanogr.*, 25, 3089-3102.

Wyrtki, K., 1975: El Nino-the dynamic response of the equatorial pacific ocean to atmospheric forcing. *J. Phys. Oceanogr.*, 5, 572-584.

Wyrtki, K., and B. Kilonsky, 1984: Mean water mass and current structure during the Hawaii-to-Tahiti Shuttle Experiment. *J. Phys. Oceanogr.*, 14, 242-254.

Xie, P, and P.A. Arkin, 1997: Global precipitation: A 17-year monthly analysis based on gauge observations, satellite estimate, and numerical model outputs. *Bull. Am. Met. Soc.*, 78, 2539-2558.

Yamagata, T., Y. Shibao and S.-I. Umatani, 1985: Interannual variability of the Kuroshio extension and its relation to the Southern Oscillation/El Niño. *J. Oceanogr. Soc. Japan*, 41, 274-281.

Yasuda, T. and K. Hanawa, 1997: Decadal changes in the mode waters in the midlatitude North Pacific. *J. Phys. Oceanogr.*, 27, 858-870.

Yu, Z., J.P. McCreary Jr., and J.A. Proehl. 1995: Meridonal asymmetry and energetics of tropical instability waves. *J. Phys. Oceanogr.*, 25, 2997-3007.

Zebiak, S.E., and M.A. Cane, 1987: A model El Nino-Southern Oscillation. *Mon. Wea. Rev.*, 115, 2262-2278.

Zhang, R.-H., and Z. Liu, 1998: An isopycnal analysis of decadal ocean thermocline variability in the North Pacific: Subduction and wave pathways. *J. Climate*, submitted.

Zhang, Y., J.M. Wallace, and D.S. Battisti, 1997. ENSO-like interdecadal variability: 1900-93. *J. Climate*, 10, 1004-1020.