US CLIVAR Pacific Implementation Plan

Summary version, 04 Aug 2000

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Coupled atmosphere/ocean processes across the Pacific Ocean region exhibit perhaps the most pronounced interannual to decadal variability anywhere on earth, and their influences on climate encompass much of the globe and impact much of its human population

Our basic understanding of ENSO is now fairly mature, and has led to routine ENSO forecasts with skill in predicting ENSO out to a year. However, many aspects of ENSO are still not well understood, including decadal variability in its character and its possible sensitivity to future anthropogenic climate change.

Our understanding of coupled decadal variability in the Pacific sector and its predictability are much more rudimentary. A characteristic patterns of decadal variability with 1-2 K swings in sea-surface temperature coupled to changes in atmospheric circulation has been documented to correlate with such diverse measures as salmon populations in the North Pacific, rainfall in the South Pacific Convergence Zone and snowpack and drought over the Pacific Northwest. There is controversy about whether ocean dynamics are at all important to climate variations on these time scales, or whether the large heat capacity of the ocean can by itself explain much of what is seen. Several plausible competing theories (see below) suggest interesting dynamical mechanisms by which the ocean may help support variability on this time scale; they cannot easily be tested with the sparse record of historical subsurface ocean data. Our understanding of both atmospheric processes (notably deep convection) and mixing processes in the ocean must also be improved to trust predictions of coupled models on this time scale.

The centerpiece of Pacific CLIVAR is the PBECS (Pacific Basin Extended Climate Study). PBECS aims to produce a comprehensive three-dimensional set of observations of the entire upper Pacific ocean, its boundary currents, and air-sea fluxes over a period of 15 years. These observations will be used to test our ability to model ocean mixing and dynamics and atmosphere-ocean feedbacks. In addition, a series of focussed studies will further our observational understanding of important physical processes such as subduction, upwelling, cloud feedbacks, and deep convection.

In this document, we will summarize the overall thrusts of Pacific CLIVAR. Much more detail about PBECS and the science of decadal coupled variability can be found in the PBECS Implementation Plan. The EPIC science and implementation plans also provide much more information about that CLIVAR-endorsed process study, which is in an advanced stage of planning for a field phase in Aug-Sep 2001.

Nature of Pacific decadal variability

Several hypotheses have been advanced to explain Pacific decadal variability. The most widely discussed hypothesized can be categorized as follows:

a. Intrinsically tropically driven (e. g. chaotic variability in Cane-Zebiak type simple ENSO models) with midlatitude teleconnections.

b. Midlatitude to tropical feedbacks thru advection of anomalies in subtropical overturning cells (e. g. Gu and Philander 1996)

c. Wind stress curl - ocean Rossby wave/gyre dynamics - SST feedbacks in midlatitudes (e. g. Latif and Barnett 1994)

d. Atmospherically driven stochastic variability reddened by atmosphere-ocean and possibly low cloud feedbacks.

They are described and referenced at length in the PBECS implementation plan. An important aspect of coupled variability on decadal timescales is forcing by the intrinsic variability of both the atmosphere and the ocean. In the tropics, the mean atmospheric circulation responds fairly consistently to typical ENSO-type SST anomalies, but averaged over a month or even an entire winter season, the midlatitude atmospheric circulation shows large variability due to random perturbations by storms. This is especially true over the North Pacific, which is a center of action of a preferred spatial mode of atmospheric variability called the Pacific North America (PNA) pattern. The main response to both typical tropical and midlatitude Pacific SST anomalies is to force a slight (though important) change in the winter-mean PNA pattern. The lack of consistency in this signal and the similar midlatitude response to both tropical and midlatitude ocean forcing makes the long record of atmospheric observations less decisive in discriminating between the above mechanisms. In the ocean, there are also intrinsic modes of variability, e. g. associated with western boundary current dynamics which may provide a forcing for coupled climate variability.

It is entirely possible that even full understanding of Pacific decadal variability coupled to extensive observation of the full coupled system will not yield substantial increases in the predictability of interannual to decadal climate variations. However, the scientific payoff of studying this variability will nevertheless be large. This is because decadal variability currently challenges coupled models - different state-of-the-art produce different interannual to decadal climate variability, and the reasons are not well understood. A comprehensive basin-wide decadal length data set documenting the entire Pacific region, and an ambitious program to use this dataset to improve our understanding of physical processes in both ocean and atmosphere can critically test coupled models at the long time scales on which we most want them to be useful for prediction of climate change and variability.

General goals of Pacific CLIVAR

We start by summarizing the long-term goals of Pacific CLIVAR:

1. Better understand Pacific basin-scale atmosphere-ocean variability, its predictability on seasonal and longer timescales, and anthropogenic impacts. Particular foci include ENSO and its decadal variability, and the Pacific Decadal Oscillation. This goal requires further comprehensive analysis, testing and improvement of coupled models.

2a. Document time varying T, S, currents in the upper ocean at 300 km, 10 day resolution over the entire basin N of 40 S for a 15 year period, with higher resolution in boundary currents and near the equator. Use an ocean data assimilation model to provide a three-dimensional time-dependent gridded analysis based on this data.

2b. Document time-varying vertical and lateral fluxes and air-sea exchange of heat, fresh water, and momentum over the corresponding period.

3. Improve the physical parameterizations in OGCMs, AGCMs and NWP models via process studies and via the use of ocean data assimilation, which as a by-product identifies apparent systematic errors in the atmospheric forcing of the ocean or the assimilating ocean model.

Our corresponding 5-year goals are as follows:

1. Preliminary testing of decadal variability mechanisms based on all available observations. The initial choice of PBECS process studies and of regions for sustained observations will be motivated by their utility for testing and discriminating hypothesized mechanisms of decadal variability. Understand the range of decadal variabiity mechanisms and their associated predictability characteristics in several credible coupled models.

2a. Routinely produce ocean data assimilation fields (freely available, less than six month processing delay) based on a fully deployed climate observing system. Assess feasibility/accuracy of meaningful pre-PBECS upper-ocean reanalyses.

2b. Provide basin-wide surface flux components of heat, freshwater, and momentum, with the goals of accuracies of better than 10 W/m^2 in the net heat flux, 20% in precipitation, and 10% in wind stress sought for monthly mean fields.

3. Improve the representation of subtropical boundary layer clouds and the placement and temporal variability of deep convection in AGCMs suitable for atmospheric reanalysis and coupled modeling, so as to at least halve systematic AGCM monthly-mean errors in surface flux components.

Strategy

The scientific and coupled modeling issues that are at the heart of Pacific CLIVAR are already being studied in work funded by a variety of agencies, but in a rather piecemeal way. Our observational goal of three-dimensional full-basin ocean sampling is also part of a much broader effort. The particular role of CLIVAR will be to rap on and integrate these chunks, add reinforcement, concrete and windows, and design and build the building for maximum scientific impact. This requires a management and outreach strategy, as well as an attractive scientific plan that can attract other modelers, analysts and data gatherers to work with CLIVAR. These are all aspects of PBECS, the centerpiece of Pacific CLIVAR. CLIVAR will also include short-term process studies, an annual meeting aimed at attracting interaction with the broad community of scientists working on Pacific decadal variability and showcasing the PBECS datasets, and a modeling interface aimed at promoting analysis of decadal variability in coupled models and improving targeted physical parameterizations in AGCMs and OGCMs.

Pacific CLIVAR components

1. PBECS (2000-2015)

PBECS is an ambitious and comprehensive program for measuring and understanding monthly to decadal variability from 2000-2015 over the entire Pacific Ocean above 2000 m depth and north of 40 S. It will involve considerable international and multi-agency involvement in the ocean observing system deployment, data assimilation, and potential process studies. A complete description can be found in the PBECS Implementation Plan. The five components of PBECS are

a. Basin-wide observations of the upper ocean
b. b. Observing strategies for surface fluxes, western boundary currents,
c. near-equatorial circulations and upwelling, and mesoscale eddy fluxes.
d. 4D ocean data assimilation to produce a gridded ocean analysis from the above data
e. Data analysis and hypothesis testing focussed on seasonal to decadal variability mechanisms, and incorporating retrospective observations where possible.
f. Improvement of those physical parameterizations in ocean and atmosphere
g. models important to coupled variability, as diagnosed from the PBECS data and other results.

In addition, PBECS will evaluate the need for process studies to further document and understand particular physical processes or their interactions, e. g. subduction, ocean mixing, boundary layer clouds and turbulence, or deep convection.

Components of the PBECS basin-wide observational array

A summary of the proposed elements of PBECS and their estimated cost to CLIVAR is given in Table 1 (below).

Required

Element	**Cost to CLIVAR**
1200 Argo profiling floats	External (NOPP?, intl.)
ENSO observing system	External (NOAA)
Satellite altimetry	External (NASA)

Satellite scatterometer, SST, cloud, and precipitation...	External (NASA)
Operational atmospheric observing/analysis system	External (NOAA, intl.)
Computing resources for Ocean Data Assim. External	(JPL-Scripps)

Highly recommended

5 current VOS XBT/XCTD sections	$700K/yr (partly external?)
3 additional VOS XBT/XCTD sections	$300K/yr
TAO near surface ADCP, 2 longitude lines	$500K over 3 yrs + 15%
TAO salinity, 20 moorings x 5 sensors	$500K over 3 yrs + 15%
2-4 moored buoys, incl. air-sea fluxes, met.	$500K/yr each
8 VOS IMET systems	$150K each + Maintenance
2-3 underwater glider systems for near-equatorial western bdry currents	$100K/yr each
Island sonde sites (5, 2 launches/day)	$200K startup + $400K/yr
(A 915 MHz profiler site is...	($150K startup + $50K/yr)
Central data archive	$200K/yr
Surface flux working group	$50K/yr?
tech support,travel Periodic model-data-diagnostics conference	$50K/yr? logistics

Under discussion

100 surface drifters for subpolar N Pacific	$400K/yr
4 IMET systems for TAO buoys	$160K over 3 yrs + 15%
1 Glider system for E bdry current off S America	$100K/yr
Sondes from TAO cruises, VOS XBT lines	$200K/yr
Acoustic rainfall measurement	$100K/yr per station

The following externally-planned elements are essential components of the ocean observing system, and must be continued for at least 10-15 years. It is expected that these will be primarily funded outside of CLIVAR, and they are critical to its success

a. 1200 Argo profiling floats, including contributions from the U.S. and international partners, covering the entire Pacific N of 40 S at approximately 300 km horizontal resolution, and profiling temperature and salinity down to 2000 m depth every ten days. These will map the broad scale ocean state and allow inference of lateral transport by broad currents.

b. The ENSO observing system (temperature and wind measurements of the TAO/TRITON array, drifters, tide gauges) is central to observing equatorial processes. Some CLIVAR-sponsored augmentation of the TAO buoy instrumentation is proposed (see below).

c. Satellite altimetry with coverage and accuracy comparable to TOPEX/POSEIDON. The NPOESS scatterometry system as currently proposed by NASA for use starting by 2010 is insufficiently accurate for PBECS data assimilation requirements .

d. Satellite scatterometer, SST, cloud and precipitation retrievals for accurate basin-wide air-sea flux analyses.

e. The current operational atmospheric observing system, including routine synoptic surface, radiosonde and satellite observations, assimilated into a gridded atmospheric analysis at daily or higher frequency.

f. Extensive computing resources are required for the ocean data assimilation. Some computing resources are being obtained from ? by the Scripps-JPL consortium currently doing this work, but they may not be sufficient to provide high-quality gridded ocean state products within a few months of real time, which is the PBECS goal.

The following PBECS elements are highly recommended. Again, measurements must be taken for 10-15 years:

g. Five existing high-resolution XBT/XCTD sections from VOS, taken quarterly, are the primary measurements of basin-scale lateral oceanic mass, heat and salinity fluxes including the effect of mesoscale eddies.

h. TAO enhancements (near surface ADCP for current measurements on two longitude lines, salinity on 20 moorings). The augmentation of salinity measurements depends on clear demonstration of the importance of high-frequency salinity sampling that ARGO floats will not supply.

i. Additional cross-basin high resolution VOS XBT lines, especially meridional lines in the far eastern and western Pacific (3 proposed in addition to 5 current externally funded lines)

j. Moored buoys collecting time series of S, T, surface fluxes and meteorology inregions of special interest, including the Kuroshio Extension Ocean Station PAPA (50 N, 145 W), the central N Pacific (35 N, 165 W), off the west coast of North America (perhaps in coordination with other coastal weather or marine ecology studies), the HOTS site, and the west coast of South America (where a NOAA-funded buoy is currently stationed at 18 S, 85 W). As a contribution to the international network of surface reference sites and ocean time series stations, 2-4 CLIVAR-supported extratropical moorings will be needed.

k. Volunteer observing ship IMET surface flux and meteorology systems on the 5 existing and 3 proposed high-resolution XBT lines for basin-wide surface forcing ground truth.

l. Western boundary current monitoring. Some international help is both required and anticipated to do this. Transport variations in the East Australia and Kuroshio currents play critical roles in some theories of decadal variability. Current high-resolution XBT sections traverse each of these currents at two latitudes, and it is hoped that scientists from Japan, Taiwan and China will continue measurements of the Kuroshio at low latitudes. The Indonesian Throughflow, to be monitored by Australian XBT sections, is the main conduit between the tropical Indian and Pacific Oceans. Tropical western boundary currents fluctuate on shorter timescales and are an important conduit between off-equatorial and equatorial currents. In particular, measurements of mass, and ideally heat and salinity, transports are required for the Mindanao current, and the New Guinea Coastal Current and Undercurrent. Underwater gliders have been proposed as cost-effective for this purpose. Although they have not been fullyproven, we will assume that 2-3 US CLIVAR-supported glider sections will be deployed to monitor these two current systems.

m. Enhanced atmospheric monitoring. CLIVAR will be heavily dependent on gridded atmospheric analyses produced by numerical weather prediction centers or the NASA GEOS for specifying the time-varying atmospheric state. These analyses combine all observations received in near-real time by the centers; later reanalyses may include other observations. A reasonable density of ship and land based surface observations are currently entering routine analyses, except in the southeast Pacific. However, routine upper air observations are very sparse except in the western tropical and southwestern Pacific. Currently, it appears that many radiosonde and profiler sites around the Pacific basin which nominally take soundings at least daily are not getting soundings into the operational data stream on a regular basis. One PBECS priority will be to: - facilitate the timely communication of all available upper-air data. In addition, PBECS proposes to: - reinstate radiosonde launches at Galapagos, Midway, Wake Is., and at least one radiosonde or, failing that, a 915 MHz profiler site in the

Line Islands (2-6 N, 157-162 W), which provide a unique natural cross-section across the central Pacific ITCZ.

n. A central data archive, or at least an effective virtual data archive (i. e. a decentralized archive with a central WWW-accessible directory) needs to be maintained to ensure that PBECS products are readily accessible to the analysis and coupled modeling community in a timely fashion. Without this, PBECS will be severely hindered from achieving its scientific goals of improving understanding of coupled interannual to decadal variability.

o. A PBECS surface flux working group is needed to decide the optimal available analyses to use for forcing the assimilating ocean model, and to work with atmospheric forecast/analysis centers to improve air-sea flux parameterizations using the PBECS and other observations.

p. A periodic annual or biennial CLIVAR-sponsored model-data-diagnostics conferenceis highly recommended to publicize the PBECS observations, encourage diagnostic analysis of Pacific low-frequency variability and the physical processes that contribute to it, encourage critical comparison of coupled models with PBECS and other observations, and discuss the plausibility of proposed variability mechanisms.

The following observational components have also been proposed by PBECS as adding value but have not been fully discussed by the CLIVAR Pacific Implementation Panel.

q. 100 surface drifters to track near-surface currents in the N Pacific subpolar gyre.

r. Maintain 3-5 TAO buoys across the Pacific to measure air-sea flux components. This would provide routine open-ocean equatorial monitoring of fluxes for comparison with large-scale analyses and inclusion in the preparation of basin-wide flux fields.

s. Glider monitoring of the eastern boundary current off South America.

t. Other atmospheric observations (dropsondes from high-altitude balloons, acoustic rainfall measurement from ocean subsurface).

u. Implement regular GPS-sonde sampling from the TAO deployment cruises and investigate the feasibility of deploying radiosondes from high-resolution VOS lines.

Finally, current agency support for coupled modeling studies of mechanisms of decadal variability, their predictability, and intercomparisons between coupled models comes largely from outside the CLIVAR program, and is likely to continue to do so. Given this environment, PBECS (and US Pacific CLIVAR) does not propose an explicit coupled modeling component. Instead, the role of PBECS is envisioned to be seeding and steering coupled modeling work, using analyses of the PBECS data and the proposed CLIVAR-sponsored conferences.

2. Process Studies

Pacific CLIVAR includes one currently endorsed process study (EPIC), and several suggested process studies. The suggested process studies will be developed in the next few years into formal proposals to US CLIVAR which include detailed implementation plans, and will be considered by the Pacific Implementation Panel and the SSC on their merits during this proposal development phase. Process studies will be evaluated based on their potential for cost-effective improvement of physical understanding or parameterization of processes that are central to modeling interannual to decadal variability.

a. EPIC (2000-2004)

The goal of the Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC) is to better document and understand physical processes controlling coupled interactions in the E Pacific. It consists of two phases, the first centered around the EPIC2001 field experiment surveying the dynamics of the stratus-cold tongue-ITCZ complex and the underlying ocean in the E Pacific, and a potential second phase to concentrate on possible interactions between the marine boundary layer and South America on a variety of timescales.

EPIC2001, the first field phase of EPIC in Aug-Sep 2001, will focus on cross-equatorial boundary layer flow, initiation and organization of deep convection in the ITCZ, SE Pacific stratus cloud along 95 W, and feedbacks of these processes on the ocean. An EPIC 2001 implementation plan is at . NSF has approved EPIC 2001, made funding decisions on individual PI proposals, and will provide the 60 hours of NCAR Electra flight time for tropical convection missions. There is also considerable NOAA investigator involvement (from ETL, AOML and PMEL) and facilities support, including the R/V Ron Brown and a P-3 aircraft. If ARGO float deployment in the EPIC region (between 20S-20N and E of 110 W.) can be done prior to Aug. 2001, this would considerably improve monitoring of broad scale subsurface structure. NSF PI support for EPIC 2001 is roughly $2.5 million for FY 01-03.

EPIC Phase II (2003?) has been suggested as a monthlong study (joint with the PACS group and VAMOS) to look at possible covariations and feedbacks between stratus cloud and boundary layer properties and deep convection over the S American continent. Deep convection might impact the stratus through modulation of compensating subsidence and/or free-tropospheric humidity/temperature. If this affected the radiative cooling within the PBL, it would affect the strength of the subtropical high, near-coastal winds, and coastal upwelling, which might on longer timescales feed back on the convection. Diurnal through synoptic timescales of variability could be addressed in such an experiment. S American Pacific Rim countries might provide considerable support; San Felix Island off Chile and ships could provide measurements of horizontal divergence and cloud/boundary layer structure. Coastal and mountain stations would help quantify orographic flows and feedbacks. More preliminary study is still needed to identify whether the stratus/convection link is clear enough to be of major climate importance.

b. Other potential PBECS process studies

The following process studies have been suggested as useful complements to PBECS, and are discussed in more detail in the PBECS Implementation Plan. It is anticipated that a subset of these will be formally proposed to CLIVAR in the upcoming years. The following are 'near-term' studies that do not depend on prior deployment of the full PBECS observing system:

i. Diapycnal fluxes and mixing, using microstructure measurements at selected tropical and subtropical sites.

ii. North Equatorial Current bifurcation and low-latitude western boundary current dynamics, using supplementary observations to the PBECS-proposed glider profiles.

iii. Studying the dynamics and detailed structure of equatorial upwelling, using a fine-scale array of moorings and current meters. One goal would be to understand the influence of local winds vs. remotely controlled thermocline structure; a second goal would be to examine the source of upwelled water.

iv. Kuroshio/Oyashio Extension Study, including deep recirculation and air-sea interactions (this would be joint with Japan)

The following proposed studies are better carried out once the PBECS observing system is fully deployed, after 2004:

v. Subtropical subduction study, examining the details of how anomalies in the properties of subducted water are created and advected in the subtropical cell.

vi. Evolution of subducted PV anomalies (looking at isopycnal mixing and spiciness in the SE Pacific, including on scales smaller than the ARGO array resolution).

3. Supporting studies

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

a. TRMM and future NASA projects

The TRMM satellite should provide high-resolution swath observations of rainfall over the tropics and subtropics through at least 2003, improving our understanding of tropical convection and precipitation distribution. Further space-based precipitation radars (and the CLOUDSAT/PICASSO-CENA mm-wave radar and lidar combination for active cloud remote sensing) are currently under planning.

b. THORPEX

PBECS may also benefit from both observations and observing system simulations from The Hemispheric Observing System Research and Prediction Experiment (THORPEX), coordinated by USWRP. THORPEX will start in 2001, with a major field phase in 2003-2005, and will include a variety of supplemental surface and upper-air observations over the North Pacific

Ocean. Depending on results from THORPEX, some of this operational enhancement of the atmospheric observational network over the North Pacific may become permanent.

c. GAINS

The Global Air-Ocean In-Situ System is being proposed to WMO and national funding agencies as a 50 year international program utilizing balloons drifting in the stratosphere as platforms for deploying dropsondes over remote oceanic locations. A pilot study is proposed for 2003.

d. CORC

The Consortium for Ocean Research and Climate (CORC) is a long-term climate program in the Pacific that places an emphasis on the Eastern Pacific that will help build toward PBECS. It is focusing on the cold tongue, upwelling and other branches of the shallow overturning circulation that are implicated by some theories in modulating the evolution of ENSO. Data assimilation modeling will be used as a way to to maximize the value of the observations. Surface drifter deployments will be carried out, with emphasis on surface meteorology measurements. A VOS program is underway. Upgraded IMET packages will be placed on high resolution XBT lines in the Eastern Pacific and cross- basin lines. maintenance of Scripps-operated hi-res XBT/XCTD lines is planned with the intent of adding new Eastern Pacific lines. An Underway CTD is being developed and could be used perhaps on TAO servicing cruises and then on frequently repeating VOS lines. Profiling float deployments will continue and the plan is to support EPIC 2001. Another goal of CORC is to measure the convergence to the equator directly. Work on the use of autonomous gliders to maintain repeated sections on a seasonal time scale is also in progress.

e. KESS

The scientific goal of the Kuroshio Extension System Study (KESS) is to clarify how SST anomalies in the

Kuroshio-Oyashio outflow regions in the midlatitude North Pacific Ocean are created, and what dictates their spatial and temporal evolution. The scientific objectives and justifications are expounded in Davis et al. (2000). At present, 14 PIs from 5 U.S. universities or research institutions are in the process of putting together a collaborative proposal to be submitted to NSF-OCE on August 15, 2000. KESS is a 5-yr project involving a variety of in-situ instruments, satellite measurements, numerical modeling, and data assimilation. It is a joint project with Japan, and Japan KESS is already funded by STA. JAMSTEC is at present deploying a test TRITON buoy and other moored instruments at the KESS site.

The following observational elements are now planned: KE and recirculation dynamics. High-spatial-resolution current, temperature, and salinity measurements would be collected to study variability of the inflow, eddy-mean interaction, recirculation dynamics, and cross-frontal exchange. An eddy-resolving array combining moorings, inverted echo sounders, acoustic tomography, and RAFOS floats is planned to achieve this ambitious goal. Concurrently, longer-term analyses of satellite SSH observations would be combined with in situ current observations and tomographic measurements on larger scales to observe the strength and heat content of the recirculation. Regional wind and buoyancy forcing estimates are needed, and NCEP (or other) fields must be calibrated by in situ meteorological buoys.

Upper ocean heat budget. Simultaneous in situ measurements of the thermocline depth, integrated heat content, and SST are clearly needed. Lateral/vertical entrainment processes should be measured at the base of the wintertime mixed layer. By assimilating in situ and satellite observations into an ocean circulation model, the mechanisms and the accuracy of the model's the heat budget would be evaluated. Time series of satellite and in situ measurements would also be used to estimate the heat budget. KESS aims to elucidate the processes going on in this complex region so that affordable monitoring systems can be designed. In the meantime, PBECS scientists should consider, in cooperation with Japanese scientists, if there are augmentations to the KESS array that would significantly increase its utility for climate studies, such as surface heat fluxes.

F. HOTS (HAWAII OCEAN TIME SERIES STATION)

HOTS (Hawaii Ocean Time Series Station) is a multi-disciplinary time series station off Hawaii. In addition to ocean thermodynamic profiles, it samples a variety of biological and chemical quantities.

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Preface

This summary has been prepared for consideration by the US CLIVAR Scientific Steering Committee (SSC). It is based on discussion to date by the U.S. CLIVAR Pacific Implementation Panel and on the efforts of the U. S. community to develop the Pacific Basin Extended Climate Study (PBECS), basin scale sampling, and process studies in the Pacific. International efforts to develop coordinated Pacific CLIVAR implementation plans have to date taken place through partnerships in planning and proposing process studies and through ongoing dialog about plans for the basin scale elements. The PBECS documentation, upon which this plan draws heavily, can be found at the U.S. CLIVAR website (http://www.usclivar.org). In January 2001 the first International CLIVAR Pacific Implementation Workshop will be held in Hawaii to develop an international implementation plan and initialize an International CLIVAR Pacific Panel.

1. Introduction

The objective of the CLIVAR Pacific program is to observe and model the Pacific Ocean and overlying atmosphere well enough that the evolution of climate phenomena can be quantitatively diagnosed within the framework of data-assimilating models. The Pacific Basin Extended Climate Study (PBECS) was formulated as the core activity of U. S. Pacific CLIVAR. For PBECS, the approach taken is to obtain, for 15 years over the Pacific Basin, observations to constrain data-assimilating models well enough that competing theories of climate variability can be tested and models of that variability improved. The observations will include global satellites, long-term in situ observations from other planned and ongoing programs including the El Niño-Southern Oscillation (ENSO) Observing System and Argo, and new measurements put in place by PBECS to observe specific components of the climate system. This document takes the PBECS Implementation Plan further by identifying tasks and discussing timing, costs, and prioritization. Section 13, where all tables and figures are located, provides a quick recapitulation and Section 14 a summary.

The Pacific observing system must be adequate to measure and constrain within assimilating models, and on the scales important to climate phenomena, key processes like advection, air-sea fluxes, and the effects of sub-grid-scale mixing. Considerations of PBECS science goals led to a plan for sustained ocean, surface, and atmosphere observations that would continue the length of Pacific CLIVAR. These are of two types: sustained basin-wide and sustained, focussed. The basin-wide sampling includes elements such as Argo and the World Weather Watch (WWW), which will cover the basin at moderate density. The sustained, focussed sampling will be of increased density, as needed to resolve variability within a region such as the Kuroshio Extension and sample its long-term variability. In addition to PBECS, a number of limited duration process studies are seen as key elements of Pacific CLIVAR. These will be shorter in duration, cover sub-regions of the basin, be highly focussed on key physical processes, and contribute essential information about processes and parameterizations.

The specific phenomena of interest to Pacific CLIVAR that motivated the implementation plan are:

Decadal modulation of El Niño-Southern Oscillation (ENSO). The historical record over the last 100 years shows that ENSO cycles have differed, with some decadal periods characterized by a prolonged tendency toward one phase of the cycle. Explanations for this vary from subtleties in atmospheric triggering, to nonlinear chaotic development of the ENSO cycle itself, to decadal changes in the "background " state of the equatorial ocean. Understanding the cause for decadal differences in ENSO evolution is key to improved climate forecasting. Examining various hypothesized mechanisms for decadal modulation of ENSO will be a primary goal, with particular attention placed on air-sea coupling and on oceanic advective pathways that bring anomalies into the equatorial zone where they can affect ENSO evolution.

Decadal variability. The instrumental record over the last 100 years also shows that large-scale, coupled decadal variations have occurred in both the North Pacific atmosphere and ocean. The dominant pattern of change, the Pacific Decadal Oscillation, has been connected to climate changes over North America and to fisheries cycles (Mantua et al., 1997) in the North Pacific. Theoretical and model studies have proposed mechanisms by which the ocean participates in the observed decadal variability either actively or passively. The intent is to develop a better understanding of what causes SST variability outside the equatorial zone and support diagnosis of future decadal variability and assessment of its predictability.

The dynamics of ENSO. Conceptually, relatively simple waveguide dynamics modulate thermocline depth, which affects equatorial sea-surface temperature (SST). SST changes the overlying atmospheric convection and wind stress patterns and this, in turn, is atmospherically teleconnected over a significant fraction of the globe. Different ENSO models depend on different mechanisms in their upper-ocean heat budgets and, consequently, evolve differently. The goal is to provide improved assimilated data sets for diagnosing future ENSOs, provide insight into ways dynamical models could better simulate ENSO evolution and, hopefully, improve ENSO forecasts through improved observations available to forecasters and improved understanding and modeling of the processes.

Processes that govern the storage, vertical and horizontal transport, and vertical and horizontal mixing in the upper 1500 m of the Pacific and the atmosphere above. Understanding the exchange of heat, freshwater, and momentum between the atmosphere and ocean and the redistribution of these properties within the ocean and the atmosphere is central to addressing the three phenomena identified above. Fieldwork with high spatial and temporal resolution, but of limited duration, can illuminate the physics of storage, transport, and redistribution and lead to better parameterizations of the high frequency processes involved.

2. Implementation Strategy - Overview

The idea of using data-assimilating models to link together basin-wide observations in order to diagnose and understand climate variability arose from a series of meetings aimed at developing ways for U.S. scientists to help achieve the goals of CLIVAR. Subsequently, the scientific basis for PBECS was formulated ("Prospectus for a Pacific Basinwide Climate Study ", Lukas et al. (1998), which can be downloaded from http://www.usclivar.org). Later, a comprehensive discussion of why and how to implement PBECS was developed ("Implementing the Pacific Basin Extended Climate Study (PBECS)", Davis et al. (2000), also available on that website). The purpose of this implementation plan summary is not to reiterate this science plan's motivation for studying climate variability in the Pacific sector nor to go into the detail provided in the PBECS implementation document, but rather to summarize the rationale for selecting elements with which to implement CLIVAR in the Pacific and to begin the discussion of prioritization, timing, cost, and coordination. Achieving success in this basin will involve the cooperation of scientists from the many nations around the Pacific. In January 2001 the first international CLIVAR Pacific Implementation

Workshop will be held. This meeting will draft an international Pacific Implementation Plan and form an international CLIVAR Pacific Panel. As this cooperation develops, the U.S. Pacific Implementation Plan will certainly evolve.

Observing climate processes throughout an entire ocean basin is motivated by the success of the ENSO observing system and made feasible by high-quality satellite altimetry, new technologies that reduce the cost of making long-term in situ ocean observations, and the capabilities of dynamical models to blend observations into analyzed data sets. A general strategy is to use the assimilating models and the high spatial and temporal resolution afforded by satellites to knit together cost-effective in situ observations. The new in situ technologies that make the PBECS and Pacific CLIVAR approach feasible include: (1) the TAO array that can observe the equatorial winds and the heat redistribution that accompanies ENSO evolution, (2) profiling autonomous floats for broad-scale sampling of temperature, salinity and velocity, (3) drifters that measure surface circulation and its variability, (4) repeated high-resolution temperature and salinity sections, collected with expendable probes using Volunteer Observing Ships (VOS), that measure the lateral heat fluxes of heat and freshwater, (5) a combination of VOS observations, satellite altimetry, moored profilers, and autonomous gliders to economically measure the mass and heat transports of concentrated boundary currents, and (6) accurate and reliable surface meteorological sensors that allow the air-sea fluxes of heat, freshwater, and momentum to be determined from moored buoys and VOS. Sustained satellite observations are a necessary element of this strategy, including: (1) altimeter mapping of the sea surface height; (2) vector wind maps from a high-resolution scatterometer of the quality of QuickSCAT; and (3) SST from AVHRR or microwave radiometers.

While PBECS specifically addresses climate variability on the basin scale over the long term, success in diagnosing and predicting this variability will depend on improved understanding of processes that can be gained only through process experiments of high intensity and limited duration. Thus the implementation strategy for Pacific CLIVAR includes process experiments that will be needed to improve the models. As an implementation strategy, the U.S. CLIVAR Pacific Implementation Panel will seek to work with groups of investigators who develop plans for Pacific process studies, particularly where there is substantial synergy between the process studies and the sustained, basin scale and sustained, focussed efforts and where international coordination is important. It is seen that there will be a succession of such efforts embedded in Pacific CLIVAR and that the phasing and interdependence of these studies on the sustained observing system will need consideration.

Because progress depends on rapid data exchange among observers, data analysts, and modelers, and because the data is meant to support operational activities, data will be made public and disseminated as quickly as is technically feasible. Because of the focus on long timescales, the intent is to conduct Pacific CLIVAR for 15 years. This will place a premium on organization to insure that needed observations and analyses are maintained. It will also require agencies to provide continuity of funding for decadal timescales. Support and coordination of the sustained, basin-wide observations will require coordination between Pacific CLIVAR and the international groups charged with implementation of elements of the global ocean observing system (GOOS), such as the Argo Science Team, the Ship of Opportunity Implementation Panel (SOOPIP), and the Data Buoy Cooperation Panel (DBCP). It is anticipated by Pacific CLIVAR that key pieces of the sustained, basin-wide observing system and of the associated data assimilation and modeling efforts will be in place. Under this assumption, the task at hand for Pacific CLIVAR is to work to field the additional sustained, basin-wide observations, the sustained, focussed observations, and the process experiments it needs to meet its science goals.

3. Science Foci and Goals

As described in greater detail in the PBECS documents the main climate phenomena of interest are decadal modulation of ENSO, decadal variability of the Pacific, and the dynamics of ENSO itself. Associated with these foci are goals that motivate the observing and modeling program developed for Pacific CLIVAR.

Decadal variability of ENSO

Over the last decade there has been vigorous investigation of possible causes for the variability; this search remains a goal with the need to consider:

Atmospheric and western-boundary processes: The tropics may be capable of developing decadal variability on their own, and this variability could modulate the background upon which ENSO evolves. Alternatively, it may be that decadal variability is generated at midlatitudes and then transmitted into the tropics via either the atmosphere or the ocean. Western boundary reflection may be important, and if anomalies may either originate at relatively low latitudes or be amplified by air-sea feedbacks as they proceed through the tropics.

The subtropical cell: Several hypotheses for decadal climate variability rely on changes in the heat transport of the North Pacific Subtropical Cell (STC), the shallow vertical overturning circulation that carries northern hemisphere thermocline water into the tropics. This overturning circulation consists of subduction in the subtropics, equatorward transport of thermocline water into the tropics, equatorial upwelling, and a return flow of near-surface water to the subtropics. A goal of Pacific CLIVAR is to test these hypotheses and to better understand the subtropical cell and its variability and how they effect the decadal variability of ENSO.

Equatorial response: No matter how thermal anomalies reach the equator, those associated with changes of the oceanic density alter the depth of the zonally averaged thermocline, rather than its east-west slope, since they do not require changes in the equatorial zonal wind for their existence. This zonally averaged change can alter SST by changing the efficiency with which upwelling cools the surface. Emerging spiciness anomalies at the equator, on the other hand, do not alter the oceanic pressure field or circulation in any way, and so directly affect SST at the existing equatorial outcrops. Because equatorial zonal winds respond rapidly and strongly to SST anomalies (Lindzen and Nigam, 1987), even small changes can set of a growing response. It is important to know if the equatorial response to the arrival from the higher latitudes of waves or dynamically neutral spiciness anomalies differ.

Decadal variability of the Pacific

The North Pacific also undergoes substantial variability at decadal periods. Possible causes for decadal variability need to be explored, including:

Stochastic forcing: Even in the absence of feedback from the ocean, stochastic atmospheric forcing of the ocean leads to enhanced oceanic variance at low frequencies, and in some instances to distinct spectral peaks. Low-frequency SST variations may result when the upper-ocean heat budget integrates surface heat flux forcing, converting a white spectrum of atmospheric forcing to a red spectrum of SST response or, possibly, to spectral peaks in the low-frequency SST response. Similar ideas apply to the excitation of planetary waves by stochastic Ekman pumping.

Western boundary currents: The dynamics of the ocean, itself, can lead to low-frequency variations in the western-boundary currents and their eastward extensions, just in the areas where large low-frequency SST signals are observed (e.g., Zhang et al., 1997).

Tropical basin-scale modes: In the studies of Knutson and Manabe (1998) and Yukimoto et al. (1996,1999), an internal decadal oscillation develops that involves tropical convection anomalies similar to those that occur during ENSO. Similarly, Tziperman et al. (1994) report a decadal signal in their coupled solution that is generated by tropical ocean-atmosphere interactions.

Decadal feedbacks in the extratropics: One of the primary candidate mechanisms involves North Pacific Ocean interactions with the Aleutian Low atmospheric pressure system. This process appears to be active in fully coupled ocean-atmosphere models.

ENSO

The potential interactions of ENSO with both faster intraseasonal processes and slower decadal and centennial phenomena are a focus. The processes of El Niño itself must be better understood, and models of it made more accurate, if the mechanisms of interaction are to be determined. At the same time, phenomena in other regions and having other timescales and other physics must be documented before their interaction with ENSO can be examined. A priority is placed on elucidating the critical processes in the upper ocean and at the air-sea interface, better understanding tropical/subtropical ocean interactions, and examining cycles of decadal variability.

Processes that govern the storage and vertical and horizontal transport and mixing in the upper 1500 m of the Pacific and the atmosphere above.

Understanding the exchange of heat, freshwater, and momentum between the atmosphere and ocean and the redistribution of these properties within the ocean and the atmosphere is central to addressing the three phenomena identified above. Field work with high spatial and temporal resolution, but of limited duration, will be directed at illuminating and parameterizing the physics of storage, transport, and redistribution. Diapycnal fluxes and mixing, the generation of subducted T/S anomalies, subtropical-tropical exchange, boundary current transport, equatorial upwelling, the generation of subtropical anomalies, and the wind-driven near-surface transports are among the processes to be considered in the Pacific.

Improving climate prediction

In addition to improving modeling by developing better paramerizations and understanding of physics through process studies, CLIVAR Pacific will help improve seasonal forecast systems by improving the quality and quantity of ocean data available to initialize the ocean, by improving the forcing fields that are also critical for initializing the ocean, by providing data for model validation and improvement, and by conducting process studies that lead to model improvements. Until we understand how complex a model must be for seasonal forecasting, sufficient data must be available to initialize and to evaluate all systems. Sustained observations with resolution on the model's resolved scales are needed to detect and describe the physical processes that bring about climate change before we can know how complex a model must be to simulate those processes. Data that we anticipate will improve climate prediction by improving model initialization include temperature, salinity, and the forcing fields.

Temperature: Subsurface temperature has traditionally been the primary data used to establish the initial conditions for operational seasonal forecasts. The present observing system has notable gaps, particularly in the Southern Hemisphere. Deployment of Argo in combination with adding select VOS lines will address those deficiencies. Accurate equatorial SSTs play a critical role in getting atmospheric convection right and therefore in making successful ENSO forecasts and are important both for establishing the ocean initial conditions and for evaluating the performance of the coupled model forecast. Increasing temporal and spatial resolution of SST will be considered in light of the potential for increased understanding of processes, as for example, the diurnal cycle

Salinity: Recent work shows that variations in subsurface salinity may account for 5 to 10 cm in sea-surface height variability in the western and central equatorial Pacific. The evidence also suggests that the effects of salinity on sea-surface height may, in part, compensate for the effects of temperature. Salinity data will be collected from Argo and TAO moorings will be collected to determine the importance of accurate salinity to the ENSO forecast problem.

Altimeter data: Altimeter data will provide global coverage and high spatial and temporal resolution, needed to minimize aliasing of smaller scale features from the more widely sampled temperature data and to be used in conjunction with in-situ temperature and salinity data to examine variability in sea surface height.

Forcing fields: In initializing a forecast model the forcing fields are as important as the data that are assimilated. To improve initialization, better forcing fields are required. Improved surface forcing can also improve prediction skill through the better testing of model performance and, by better partitioning buoyancy flux between heat and freshwater, improved flux fields will improve the utility of altimetric measurements of sea-level height in initialization and in model validation.

Data for validation: Velocity data are unlikely to be soon routinely assimilated for climate forecasting. Long time series of velocity data from moorings are rare and drifters and floats describe only one level. Velocity data from moorings, floats, and drifters are needed to validate model performance

<u>Improving coupled models</u>

Coupled models of the climate system are used to explore, simulate, and predict climatic variability on timescales from months and longer. The challenge for coupled modelers is to ascertain whether their models are operating in realistic parameter regimes, and how to improve them if they are not. For this, observations are essential.

El Niño and its variability: El Niño prediction depends on coupled ocean-atmosphere models that obtain the bulk of their skill from the accurate observations of the subsurface ocean used for initialization. A common failing of coupled general circulation models is the difficulty in maintaining a proper "cold tongue " in the eastern Pacific. Making additional observations in the eastern tropical Pacific is perhaps the best strategy for improving this situation. As more complex coupled models are being developed to simulate decadal variations in ENSO and its predictability; a key element of Pacific CLIVAR will be to maintain longer period ocean measurements to ascertain the ways the ocean actually changes and to assess the meaningfulness of coupled model results.

Decadal climate variations: To study long-term climate variations we may examine long coupled numerical model experiments or relatively short observational records. We cannot advance the observational record faster than real time, but the observations can be used to significantly improve the models upon which we must rely for long-term statistics. Two strategies will be followed; the first is to observe as much of the system as possible for as long as possible, and the second is to conduct process studies to address specific unknowns in the model systems.

Surface fluxes: Better fluxes of momentum, heat, and water (latent heat) will assist in improving the ocean and atmosphere components of coupled models, and by making coupled-model diagnosis and verification more complete. Further progress in model development is critically tied to improved surface stresses. Because of the ocean's sometimes non-linear sensitivity to both wind mixing and the stress curl, resolution is as important as accuracy of large-scale averages. Near surface mixing involves relatively high-frequency turbulent exchange processes (perhaps including the diurnal cycle), so it will be helpful to characterize the temporal character of these fluxes. Ocean models are also ready to take advantage of significant improvements in surface heat flux components in order to improve parameterizations of vertical and horizontal mixing and testing near surface advection. Mixed layer turbulence depends on buoyancy fluxes so knowledge of the surface freshwater flux is needed. For improving atmospheric models, radiative fluxes and the air-sea exchange of water are most important because they provide a quantitative test of parameterizations of clouds and precipitation, and hence of the internal heating of the atmosphere. In improving coupled models, measured surface fluxes play an important, if circuitous, role. By the nature of coupled models, surface fluxes are internal model variables that are highly sensitive to small changes in either of the component models. It is not clear how to assimilate flux information into the coupled models to improve model physics and parameterizations. Too often, discrepancies in surface fluxes can be falsely attributed to problems in one component model, leading to counterproductive "fixes." On the other hand, since coupled models are inescapably limited by the quality of the component models, the role of surface fluxes in improving these models is extremely important.

4. Data Assimilation Modeling

PBECS will in Pacific CLIVAR extend the process-study methodology to climate by using models to bring together diverse sets of data and reliable dynamical constraints to form the best possible picture of the evolving climate system. The PBECS documentation reviews the status of data assimilation modeling and the goals of such work in Pacific CLIVAR. Here we reiterate the tasks that need to be accomplished and the requirements placed on the observational strategies by the data assimilation modeling.

The enhanced observations, improved dynamical models, and data assimilation will be brought together to yield (1) a much improved estimate of the state of the Pacific Ocean and (2) a quantitative evaluation of what processes have been resolved and what needs further improvement in terms of dynamical models, assimilation methods, and observing systems. By filling in for missing observations and using dynamics to correct sampling errors, assimilation will produce complete fields of u, v, w, T, S, and p as well as mixing fluxes and parameters like eddy viscosities. A close interaction between the data assimilation, modeling, and the field studies will be essential.

Improving the assimilation product and the underlying dynamical model will require determining data and model errors and error statistics, preparing and quality controlling observations, pre-processing data for volume reduction, and comparing model output with data and simple models to detect biases that may signal model deficiencies and evaluate the quality of the assimilation product. Currently, limited computational resources, both computational speed and memory requirements, are hindering progress in applying data assimilation to basin-scale ocean problems. An element of implementing Pacific CLIVAR will be marshalling the needed computational resources.

Improvements in surface forcing fields and in the quality of observational ocean fields used for model validation will significantly assist in detecting model errors and assimilation biases. Errors in the initial conditions affect the model solutions for times longer than decadal. Pacific CLIVAR will improve the analyzed data for initializing models and assimilation studies. Even a “perfect” model will imperfectly reproduce the state of the ocean when its forcing is in error. In coastal and tropical regions, forcing data may be the dominant source of “model error.” Thus minimizing forcing error must be a priority for model-based studies of interannual to interdecadal phenomena. Extending the analyses to high latitudes coupled with the increased observations there of the surface mixed layer and thermocline will have a major impact on parameterization improvement for coupled prognostic models.

Modeling the coupled behavior of the equatorial waveguides poses special challenges. Observations show tremendous shear in the upper ocean. Very high resolution (10 m or less in a level-model sense) is the minimum to resolve the shear near the surface and near the equator. To the extent that surface-advective processes affect SST, models with less resolution will inappropriately diminish the importance of such processes. Special efforts to observe the vertical structure of near-surface currents will provide a critical evaluation of tropical ocean model skill. To the extent that simulating SST change requires accurately modeling the mixed layer within the waveguide, near-surface vertical velocity field also must be correctly modeled, and penetration of solar radiation and vertical mixing across the base of the equatorial mixed layer will have to be parameterized. In addition to process experiments, accurate forcing fields must be available to support this type of mixed-layer modeling. Modeling the equatorial thermocline is also a challenge.

Modeling near-equatorial, large-scale atmospheric dynamics in response to SLP, SST, and convection also poses special challenges. Very few data sets exist with good vertical resolution and the long duration to permit evaluation of model skill within the atmospheric waveguide (roughly within 10° of the equator). There are two regions where sustained atmospheric observations are needed. Special observations, perhaps including enhanced profile data from the near-Dateline islands of the equatorial Pacific, could provide critical information for improving atmospheric models of ENSO. An ITCZ atmospheric observing effort would also be very helpful.

5. Sustained, Basin-Wide Ocean Observations

The above discussions and the more detailed presentation in the PBECS documents, taken together with empirical and model information on scales, point toward the phenomena and processes that must be observed in the Pacific. Here the plans for sustained, basin-wide sampling in the ocean are presented. Some concerns about special regions are raised, which will be returned to later in the section on sustained, focussed observations. Table 1 of Section 13 provides a tabular summary.

The most promising feedback processes for explaining decadal modulation of ENSO and decadal variability like the PDO involve generation of oceanic anomalies in one location, movement of this anomaly by oceanic processes of advection, wave dynamics or eddy transport, and the subsequent impact of this anomaly on air-sea fluxes at a new location. Anomalies can be generated in the mixed layer by buoyancy fluxes (heat or fresh water) or wind stirring. They can also be generated anywhere in the upper ocean by Ekman pumping or anomalous advection. The variables that must be observed, and the scales to be resolved to avoid aliasing and capture the sought-after signal, to diagnose anomaly generation are:

- air-sea fluxes of heat, water and momentum - Δx ~300 km, Δt ~12 hour
- profiles of temperature and salinity - Δx ~300 km, Δt ~10 day, Δz ~5m
- near surface currents - Δx ~300 km, Δt ~10 day

The strategy for understanding the propagation of subsurface oceanic anomalies will involve observing lateral fluxes and changes in internal ocean structure. Resolution of S as well as T is essential to determining the extent to which anomalies are dynamically active or density compensated. Different sampling requirements are indicated for the interior ocean, the boundary currents, and the equatorial waveguide:

- profiles of temperature and salinity - Δx ~300 km, Δt ~10 day, Δz ~5m, z max ~2000 m
- boundary currents, profiles of T, S - Δx ~10 – 50 km, Δt ~ 1month, Δz ~ 5m, z max ~2000 m
- equatorial waveguide, profiles of T, S -Δ x ~1000 km, Δy ~100 km, Δt ~5day, Δz ~5m, z max ~ 500 m

Direct velocity observations should be expanded in the equatorial waveguide to better characterize advective transport, particularly above the thermocline. Along the equator, however, upwelling and the impact of very high near-surface gradients and shears additionally requires

- near-surface velocity observations - Δx ~1000 km, Δy ~100 km, Δt ~5day

Many of the ocean observations are already in place, and others are being developed by other programs and nations. Central to the ocean observing system is a suite of satellite sensors that provide regular and global coverage. In situ observations cannot approach satellite coverage, but in situ observations will improve the accuracy of satellite measurements, like SST, or extend observations to fields not measured from space, like ocean temperature and salinity profiles to describe the vertical structure associated with the sea-surface height (SSH) anomalies observed by altimeters. A backbone for the sustained in situ measurements will be the ENSO Observing System together with the array of profiling floats from Argo. An international consortium of agencies and scientists is implementing Argo to provide temperature and salinity profiles in the upper 2 km with a design resolution near 300 km and 10 days. The ENSO Observing System includes the TAO/TRITON array, which provides high-temporal-resolution observations of winds and oceanic thermal structure at about 70 locations, with ocean velocity, salinity, and additional surface meteorological measurements at a smaller number of sites. The ENSO observing system also includes an array of low-resolution XBT sections, surface drifters that observe SST and surface currents, and an array of tide gauges to supplement altimetry. Pacific CLIVAR cannot be successful without the maintenance of the satellite, Argo, and ENSO observing systems for 15 years. In addition to the satellite, Argo, and ENSO observing systems, PBECS will depend on other widespread ocean observations. Described below are the major observational elements of the desired sustained, basin-wide ocean climate observing.

Satellite Observations of the Ocean

The satellite-based ocean measurements that will be most useful are sea-surface height (SSH), surface wind stress, and sea-surface temperature (SST). The interannual and longer timescales of variability that are the focus of Pacific CLIVAR require continuous, uninterrupted observations of these variables over the full duration of the program. Altimeter measurements of SSH include important climate signals such as steric heating of the upper ocean and large-scale, low-frequency variability of upper-ocean geostrophic currents and also show the long, baroclinic Rossby waves. The combination of SSH observations with profiles of density and velocity imposes essential constraints on the data assimilation models. Because the ~700 km resolution of operational weather analyses is too coarse and because of concerns about the quality of those winds, satellite vector winds are required. Sea-surface temperature (SST) is a key observation for Pacific CLIVAR, and satellite observations offer more complete space-time coverage than ships and buoys. However, to achieve the accuracy in SST required for climate studies, remote data must be blended with in situ measurements.

Sea-surface height: The TOPEX/POSEIDON and ERS-2 altimeters are now in operation. The repeat periods are 10 days for TOPEX/POSEIDON and 35 days for ERS-2. The shorter repeat period of the TOPEX/POSEIDON orbit reduces temporal aliasing of mesoscale variability, but results in a coarse ground track pattern. The design lifetimes of altimeters are typically 3 years but altimeters can last much longer than 3 years. The joint NASA/CNES Jason-1 mission and European Space Agency Envisat mission have been formally approved for launch during 2000. Jason-1 will sample the TOPEX/POSEIDON ground track and Envisat will sample the ERS-1 and ERS-2 ground tracks. Follow-ons to these two altimeter missions have been proposed but have not yet been approved. The future of the desired very accurate satellite altimetry is thus uncertain beyond Jason-1 and is very uncertain beyond Jason-2.

Surface wind stress: At present, the only satellite measurements of surface wind stress are from a microwave radar scatterometer, and these wind fields have demonstrated great value with their improved spatial resolution. The QuikSCAT and ERS-2 scatterometers are now in operation. The spatial coverage of the wide-swath QuikSCAT scatterometer is more than three times that of the ERS-2 scatterometer which greatly improves the accuracies of wind fields constructed from QuikSCAT data. The design lifetimes of radar scatterometers are typically 3 years. The NASA SeaWinds scatterometer to be launched in 2001 on ADEOS-II and the European Space Agency ASCAT scatterometer to be launched in 2003 are both formally approved. The SeaWinds scatterometer is identical to QuikSCAT. The sampling coverage of the dual-swath ASCAT scatterometer is about half that of QuikSCAT and SeaWinds. The launch of SeaWinds will provide coverage simultaneous with QuikSCAT, dramatically improving the space-time resolution and accuracy of wind fields constructed from the tandem scatterometers. The AlphaSCAT follow-on to SeaWinds has been proposed to NASA, which is supportive but has not yet formally committed funding. NASA has indicated its intention to transition satellite measurements of surface vector winds to NPOESS operational satellites before 2010. Unfortunately, the presently planned NPOESS configuration cannot accommodate radar scatterometry. As a substitute for scatterometry, NPOESS is pursuing a low-cost, low-power passive polarimetric microwave radiometer technique for estimating vector winds. If development continues on schedule, the U.S.Navy will launch a polarimetric radiometer in 2003 on the Coriolis/WINDSAT satellite. Until the spaceborne capabilities of this technology have been demonstrated, the future of highly accurate and densely sampled satellite observations of surface vector winds is uncertain beyond SeaWinds on ADEOS-II and highly uncertain beyond AlphaSCAT.

Sea-surface temperature: Satellite measurements of SST have been available since 1973 from the infrared radiometers, with high-quality SST estimates from the Advanced Very High Resolution Radiometer (AVHRR) available since 1979. An AVHRR is included on each of the two NOAA Polar Orbiters that are generally operational at any given time. There are also infrared radiometers on the NOAA Geostationary Operational Environmental Satellites (GOES) and on several European and Japanese satellites. Infrared radiometers measure SST only in cloud-free conditions, which is a significant limitation since the sea surface is obscured by clouds about 60% of the time in the tropics and more than 75% of the time at middle and higher latitudes (Hahn et al., 1995). Undetected clouds are one of the largest sources of error in infrared estimates of SST. In addition, stratospheric aerosols from major volcanic events have a significant impact on the accuracy of SST retrievals (Robock, 1989; Reynolds, 1993) as do a number of other biases (Reynolds et al., 1989). Infrared measurements of SST will be available operationally throughout the Pacific CLIVAR observational program. Many of the problems inherent in infrared measurements of SST can be overcome with passive microwave remote sensing (6-11 GHz) for which, in rain-free conditions; the atmosphere is nearly transparent. The TRMM Microwave Imager (TMI) has been measuring SST since December 1997 with a spatial resolution of 46 km and an rms accuracy of 0.5°C (Wentz, 1998). The Advanced Microwave Scanning Radiometer (AMSR) that will be launched on the EOS-PM platform and the ADEOS-II satellite includes a new low-frequency channel that will provide SST retrievals with even greater accuracy than are being obtained from the TMI. Thereafter, microwave measurements of SST will be available operationally from the Conical Microwave Imager/Sounder (CMIS) that will be in the U.S. NPOESS operational satellite program. Depending on the exact launch dates of the various satellites and the duration of the AMSR data records from EOS-PM and ADEOS-II, there may be a gap in the microwave SST data record part way through the Pacific CLIVAR observational program.

Future U.S. operational satellites: The lead-time to incorporate a new satellite sensor into the U.S. operational satellite system is of the order of a decade or longer. A coordinated long-range plan must therefore be developed at the earliest possible opportunity to assure continuity of the oceanographic satellite sensors for climate observations. In response to this need and to budgetary constraints, a new program called the National Polar-orbiting Operational Environmental Satellite System (NPOESS) is under development. As noted above, the CMIS for microwave measurements of SST is included on NPOESS-1. SSH and surface vector winds have not yet been given high priority in the NPOESS planning. Unless instruments for measuring these variables with the accuracies and sampling needed are adopted by NPOESS, the satellite records of SSH and surface wind are in jeopardy of falling short of the full duration of Pacific CLIVAR. The outcome of the NPOESS development process will play a crucial role in the success or failure of satellite-data acquisition and analysis efforts during the second half of the PBECS 15-year observational period.

Argo

The Argo profiling float array will be the central element of the sustained in situ ocean observations and essential source of temperature and salinity profiles and interior velocity measurements spanning the basin. From the Aleutians to 40°S and across the full width of the Pacific, over 1200 floats will profile every 10 days from about 2000 m to the sea surface. They will provide information in near real time for data analysis, model initialization, and assimilation. The Argo data will tie together the Pacific observing system, providing the large-scale context for regional measurements.

Profiling floats and altimetry together provide a dynamically complete description of sea-surface height and its subsurface expression. On the large spatial scales common to the two measurements, the combined system accounts for both the density-related and reference-pressure contributions to sea-level variability. Models assimilating altimetric height alone cannot yet accurately describe this decomposition and the depth-distribution of the density signal. The ocean's dynamics and evolution depend critically on vertical structure, so the subsurface array is a necessary part of the total observing system. The high along-track spatial resolution of the altimeter can be used to interpolate between more widely spaced subsurface density profiles. Further, the salinity data from the floats is critical; temperature alone is not sufficient to adequately estimate dynamic height. Salinity variability is a significant contributor to sea-surface height (e.g., Gilson et al., 1998) in addition to providing primary diagnostic information for the freshwater budget.

As well as providing the data needed to complement altimetry, the profiling float array will also provide fundamental information on a stand-alone basis information about pathways, circulation, transport and heat and freshwater storage. Floats that drift at thermocline levels will provide direct observations of water parcel trajectories and associated water mass properties. The floats provide both direct observations of velocity at a reference level and geostrophic shear estimates. Closure of the oceanic heat and freshwater budgets will require measurements of advection, storage, and air-sea exchange. Storage of heat and fresh-water in the coupled climate system is dominated by the oceanic component. The float array is the only element of the PBECS observation strategy for measuring large-scale heat and freshwater storage. A primary design criterion for Argo is to obtain sufficient independent estimates of storage on climate-relevant large spatial scales to average over noise due to mesoscale eddies and small-scale features.

The design of the Argo sampling array balances requirements against the practical limitations imposed by technology and resources. A complicating factor is that the statistics of ocean variability are poorly known in many regions. The design of an interior ocean array has been considered from a variety of different angles (Argo Science Team, 1998, 1999). The findings, reviewed in the PBECS implementation document, pointed toward sampling at approximately 3° spacing in latitude and longitude, which Pacific CLIVAR endorses and seeks. All Argo data will be publicly available as quickly as is technically practical, using near-real-time data via the GTS, with automated quality control, for operational users and forecast centers. A data set with scientific quality control, including expert examination of individual profiles and sequences, comparison to ancillary data sets and climatologies, and best recalibration of salinity data, will be available 3 months from collection. Argo has strong international support and participation. Partners in implementation of the Pacific array include Japan, Canada, and Australia. Commitment of U.S. resources will provide powerful leverage for a Pacific-wide observing system.

High resolution temperature-salinity transects

The High Resolution XBT (HRX) program provides boundary-to-boundary profiling along selected lines, with closely spaced XBTs to resolve the spatial structure of mesoscale eddies, fronts, and boundary currents. Along the HRX lines. Probe spacing is typically 10 km in boundary regions and 50 km in the ocean interior. Most profiles go to

800 m and XCTDs measure salinity at approximately 5% of the stations. Time series of HRX lines are as long as 13 years in the case of PX6 (Auckland-Suva). The repetition frequency is about four times per year. In the implementation of Pacific CLIVAR, the intent is to use the HRX lines to provide an eddy-resolving subsurface complement to the profiling float array and altimetric data sets. Accurate determination of oceanic transport of heat, freshwater, and thermocline water masses requires that boundary current transport and interior eddy transport also be observed. The HRX transects provide the needed eddy-resolving measurements along a few lines, providing geostrophic and Ekman-transport variability on seasonal and longer timescales. With respect to altimetry, the HRX lines can reveal the subsurface structure of mesoscale and boundary-scale features not observed by the float array. In addition to routine XBT and XCTD profiling, the HRX ships are also used for ancillary measurement programs and to test new instrumentation. The intent is to install full suites of IMET meteorological sensors and to include sea surface salinity, atmospheric and sea surface CO_2 observations as well as the deployment of profiling floats and surface drifters. New instruments now under development or testing include an improved XCTD, recoverable 200-m CTD, and electronic XBTs (to 2000 m).

The Pacific HRX lines are listed in Table 3. The existing HRX transects, carried out on an international basis, include: (1) zonal crossings of the North Pacific (PX37/10/44) and South Pacific (PX50/34), with meridional transport objectives as discussed above, (2) meridional lines in the central and eastern Pacific (PX6/31, PX81/38) to observe the structure and fluctuations of the zonal tropical current systems, (3) choke point transects across all entrances and exits to the Pacific-including the Indonesian throughflow (IX1), the Southern Ocean south of Australia (IX28), and Drake Passage (AX22), (4) additional western boundary current crossings (PX30, PX40). Other transects identified as high priority include meridional lines in the far eastern Pacific (e.g., Peru-California) and western Pacific (e.g., Noumea-Japan), and a zonal line at lower latitude in the South Pacific. A recent review of the present XBT networks (Smith et al., 1999) concluded that, as the Argo float array is implemented, the XBT sampling should transition from area-based to line-based sampling. Such a transition will align the network with CLIVAR needs by providing the supplemental eddy- and boundary-scale information on the HRX lines. Pacific CLIVAR will participate in the redesign and redeployment of the XBT networks toward the end that they optimized for PBECS objectives and anticipates data from 5 Pacific HRX lines currently supported as well as adding support for 2 additional lines.

The TAO array

The TAO/TRITON array will be the central element in the PBECS observational network in the equatorial Pacific and key to monitoring, detecting, understanding, and forecasting year-to-year climate swings associated with the ENSO cycle. Some TAO moored time series are approaching 20 years in length and provide some information about decadal variability as well. Surface winds, air temperature, relative humidity, SST, and ocean temperatures in the upper 500 m are measured at all locations. Five sites along the equator are instrumented for upper-ocean velocity profiles. At several sites, surface salinity, rainfall, and shortwave radiation are also measured. Beginning in 2000, the western portion of the TAO array (137-156°E) will be instrumented with Japanese TRITON moorings. Data are transmitted to shore in real time and distributed via the GTS. The following enhancements to the TAO array should be implemented for PBECS:

Salinity: Additional and high temporal resolution that would complement Argo is sought by enhancing in situ measurements on TAO. The western and central equatorial Pacific are characterized by large interannual variations in surface and subsurface salinity (Delcroix et al., 1998; Kessler, 1999). Lack of salinity observations can sometimes lead to errors in dynamic height that are comparable in size to the ENSO signal in the western Pacific. High temporal resolution salinity data are sought to elucidate oceanic response to rain, to examine the role of salt stratified barrier layers, and as a tracer of the meridional overturning circulation in the tropical and subtropical oceans. An additional 20 TAO moorings should have salinity sensors at 5 depths each.

Velocity measurements: At present, the TAO array includes current measurements at only five sites along the equator, using ADCPs and mechanical current meters to provide profiles of velocity in the upper 250 m. The failure of geostrophy near the equator makes direct velocity measurements useful at all depths, particularly for model validation and development, and for diagnosing oceanic processes involved in generating ENSO timescale variations. Surface drifters diverge from the equator because of poleward Ekman flows, and shipboard ADCP data lack sufficient temporal and near-surface coverage. As part of PACS/EPIC, some near-surface real-time current meters are already planned along 95°W (at 10 and 40 m). The TRITON moorings along 156-137°E will be instrumented to measure velocity at a single 10 m depth. To fill the present gap, it is recommended that additional current measurements by made between 110°W and 165°E, inclusive, with a priority placed on instrumenting 2 longitude lines to span the zonal currents.

Surface fluxes: The Pacific CLIVAR (see later section) strategy for fluxes includes maintaining a number of moorings making high-quality surface observations. The PACS/EPIC program will contribute to this effort in the eastern Pacific by equipping several TAO buoys along 95°W to measure additional surface meteorology during 1999-2003. Similar upgraded surface meteorology measurements should be made as part of the sustained observations of Pacific CLIVAR from ~3-5 TAO buoys spaced across the basin.

Boundary currents

Monitoring boundary currents is challenging because they are swift, narrow, and highly time dependent. The WOCE strategy of using dense mooring arrays to monitor transport is well proven, but expensive. Alternatively, it is often possible to rely on geostrophy by measuring the horizontal pressure field through a combination of moorings, autonomous vehicles (such as gliders), satellite altimeters, and, where available, expendable profiles from Voluntary Observing Ships. Since pressure is the spatial integral of current, horizontal resolution can be coarser than for velocity measurements. In principle, pressure measurements straddling a boundary current are enough to measure mass transport (but not heat and freshwater transport). In practice, the absolute pressure field is difficult to diagnose and the horizontal extent of boundary currents is difficult to determine because of adjacent recirculation features. Gliders are capable of repeatably measuring temperature and salinity structure from the sea surface to 2 km depth either at one nominal location or along programmable routes. Hydrographic moorings are able to measure temperature and salinity profiles from near the surface to near the ocean bottom on sub-daily intervals. Satellite altimeters measure the sea-surface height relative to an unknown spatially varying mean. To meet PBECS objectives, boundary current measurements must determine mass, heat, and, in most cases, freshwater transports, and extend from the boundary into any recirculation regions. An early task in implementing Pacific CLIVAR will be to demonstrate the efficacy of a method or combination of methods for monitoring boundary currents. It is anticipated that the U.S. will contribute to 2-3 boundary current monitoring sections/arrays.

Surface drifters

On decadal timescales and longer, advection dominates storage in the temperature and freshwater budgets of the upper ocean. The advection process is complex because it can be three-dimensional, and both the time-mean and temporal changes of the temperature and salinity gradients, as well as of the velocity, can combine to produce the spatial and temporal evolution of the fields. Since 1988, drifters with drogues at 15 m have provided a basin-wide description of the tropical near-surface velocity and SST. In 1999, the drifter array within 20° of the equator provided over 32,000 daily-average velocity and SST observations. These tropical observations will be continued as part of the ENSO observing system and enhanced by the Consortium on the Ocean's Role in Climate. However, drifter deployments in the subtropics and subpolar basins will not be done in quantity unless Pacific CLIVAR mounts them. The circulation of subpolar North Pacific could be systematically observed with 206 drifters per year deployed from VOS; 110 deployed in the central gyre north of 40°N and 48 could be deployed in the Alaskan Stream and 48 in the Oyashio. These boundary-current deployments could occur quarterly from fishing and fisheries survey vessels along four transects with four drifters deployed on each. The U.S. might be responsible for the eastern basin half of the array while Japanese colleagues might take responsibility for the western-basin deployments. Some cooperation might be given by operational meteorological agencies of U.S., Canada, and Japan who can use the drifters to enhance surface observations of atmospheric pressure and winds for marine forecasts.

Repeat hydrography

While Argo will provide temperature and salinity profiles in unprecedented density, there are at least three reasons this will not completely replace traditional hydrographic observations for climate purposes: (1) Sampling on hydrographic sections can be multi-variate (e.g., time-tagged chemical tracers like CFCs, CO_2, nutrients, and oxygen) and include quantities that cannot be measured from long-lived autonomous instruments, (2) High quality hydrographic observations will for the foreseeable future offer the highest quality observations of salinity, temperature and other fields as hydrographers typically "calibrate" their CTD profiles with more accurate bottle data, and (3) Argo sampling is confined to the upper 2000 m, giving no observations of the deeper waters. At present, discussion of the CLIVAR strategy for deep ocean observations continues. The Ocean Observing Panel for Climate (OOPC) has called for a working group to develop such a strategy for climate studies in general, and it is timely for Pacific CLIVAR to participate and establish a dialog with those interested in the carbon cycle, tracers studies, and climate modeling that will lead these discussions to converge on a sampling plan. As a strawman, five to seven zonal and meridional lines throughout the basin, each occupied on a 5- to 10-year period, have been suggested. A fairly comprehensive suite of observations would be advised until we can understand how the various tracer fields can be related to each other.

Ocean time series

The reasons to augment the other elements of the sustained observing system with fixed-point ocean time series were spelled out in the recommendations in relation to climate modeling made at the OOSDP/GOOS/CLIVAR Workshop on Ocean Time series (Baltimore, MD, 1997). They include: (1) sustain long, consistent, in situ time series of ocean climate variables for direct comparison with ocean-model hindcasts; determination of statistics of signals and model errors; assessment of the climate state relative to the historical record, and to rates of change of different components of climate system; specification of initial conditions for climate predictions and for calculation of skill scores, (2) develop new in situ time series of ocean climate variables for the purposes above, and to help resolve the spatial structure of important signals, (3) maintain existing ocean weather buoys for their contribution to improving ocean surface forcing fields and their error characteristics, (4) deploy a limited number of state-of-the-art air-sea flux buoys to improve and calibrate numerical weather prediction (NWP) flux fields in distinct regions of the climate system and (5) deploy high-quality meteorological buoys in sufficient numbers and appropriate places to detect discontinuities of analyses. The recent Ocean Obs ’99 conference in St. Rapahel included discussions (Send et al., 2000; Taylor et al., 2000) of the strategies for implementing long time series stations for climate and reflected consensus on the rationale for and siting of the time series sites. The Pacific sites recommended there are shown in Table 1. OOPC has called for the formation of a Time Series Science Team to work in parallel with the Argo Science Team and push forward the implementation of these time series sites. PACS has funded an initial 3-year deployment of a surface mooring west of northern Chile (85°W, 20°S), and Pacific CLIVAR needs now to participate in the activities of the Time Series Science Team to implement select other sites in the Pacific. Pacific CLIVAR anticipates support of 2-4 extratropical surface mooring sites.

6. Surface Fluxes

Another element of the sustained, basin-wide sampling plan is observations of the surface fluxes. As discussed above, air-sea fluxes of momentum, heat, and water play a central role in testing and improving the component of coupled ocean-atmosphere models. They are also particularly useful for diagnosing the mechanisms of ocean-atmosphere coupling in models and nature. The importance of the fluxes in understanding ocean and atmosphere budgets and their variability has long been recognized, but flux estimates have been plagued with errors due to the lack of direct and indirect measurements, and uncertainties in how to parameterize them from routine observations.

Climatologically, air-sea fluxes provide vital sources and sinks of heat and moisture to the global atmosphere (Trenberth and Solomon, 1994) and the means by which mean ocean-surface conditions modulate the atmospheric phenomena. On the other hand, in the extratropics, it is clear that the atmospheric circulation, via anomalous winds and fluxes, is the dominant driver of upper ocean thermal anomalies (e.g., Davis, 1976), but a long-standing issue has been the extent to which anomalous sea surface temperature (SST) feeds back to affect the atmosphere and whether, and under what conditions, significant heat flux is associated with SST anomalies. Indeed, the sign of the relation between anomalous heat flux and SST is a direct indication of whether the SST modulates the flux or vice versa. There is some evidence that, as timescales lengthen, there is a shift in the balance between atmosphere-forcing-ocean and ocean-forcing-atmosphere. Determining this low-frequency relation is particularly challenging because several variables are involved, the SST "signal" is only a few tenths of a degree (White et al., 1997), and is small compared to observation and flux parameterization errors. To confirm and elucidate these results will require stable long-term observations of the fundamental weather variables over the Pacific basin.

At present, surface flux data are mainly obtained from three sources: in situ measurements from ships and buoys, remote sensing from satellites, and output from numerical weather prediction (NWP) models such as those at NCEP and ECMWF. Each source has advantages and limitations. In situ observations of moderate quality are available along ship routes from Volunteer Observing Ships (VOS). High quality surface meteorology and surface fluxes can be obtained from a limited number of moored buoys. All surface observations depend on bulk parameterizations to produce fluxes and these need improvement, particularly under high winds and stable conditions. Satellites now provide global measurements of SST, surface radiation, and vector wind, and studies are underway to examine the extent to which sensible and latent heat fluxes can be derived from remotely sensed data. However, satellite measurements need in situ calibration and validation, and satellite orbits limit the time resolution possible in the global fields. NWP models have the advantage that they can provide global surface meteorological and flux fields on global grids at time intervals (6 hours) that resolve diurnal and synoptic weather variability. These fields, though, may contain large uncertainties due to deficiencies in the models and their inability to assimilate satellite and in situ surface meteorological data.

The goal for the Pacific CLIVAR flux effort is to be obtain air-sea fluxes over the Pacific basin with net heat flux accurate to better than 10 W m^{-2}. A net heat flux of 10 W m^{-2} would heat the upper 500 m of the ocean 0.15°C in 1 year, a signal the size of decadal changes reported in the Atlantic (Parilla et al., 1994). To achieve this goal, the components of the net heat flux, which vary on a wide range of time and space scales over magnitudes approaching 1000 W m^{-2}, must each be measured to an accuracy of a few W m^{-2}. Deployments of well-instrumented buoys coincident with ship measurements of surface fluxes have shown that mean fluxes (3-week average) from such buoys meet the heat flux goals (Weller and Anderson, 1996). Buoys are now equipped to measure rainfall and vector winds to determine the freshwater and momentum fluxes. On a limited basis, such buoys are also equipped to measure the turbulent flux directly, providing both accurate measurements of the mean observables, and supporting studies of the transfer coefficients for bulk formulae. However, it is unlikely that any type of buoy could be deployed in numbers sufficient to map the fluxes over the Pacific.

Historically, fluxes have been mapped using surface meteorology from the VOS together with empirical formulae. Early VOS data had data-quality problems, but recent improvements in procedures and equipment make the VOS valuable platforms, both as now equipped and as upgraded, complete flux platforms. Traditional VOS instrumentation has been basic and limited, including barometer, anemometer, engine injection temperature sensor, and wet- and dry-bulb thermometers. Accurate and portable IMET hardware that has been developed to install on VOS that will collect all the observations made from the IMET buoys. The in situ Pacific flux array will be a combination of well-equipped surface moorings labeled, "surface flux reference sites" that measure all the variables needed to determine the air-sea fluxes of heat, freshwater, and momentum with high accuracy and high temporal resolution (e.g., 1-minute samples for 1 year with satellite telemetry of hourly values), other surface moorings including those of the National Data Buoy Center and the TAO array, improved VOS equipped with a complete set of IMET sensors, routine VOS, and drifting buoys. Equipping and operating the improved VOS should be coordinated with the present Ship Of Opportunity Program (SOOP). VOS data taken close to the surface flux reference sites would be compared to buoy data to quantify the quality of the VOS data, to guide choices of the regionally appropriate empirical flux formulae (especially for the regular VOS without radiation sensors), and to examine the spatial and temporal variability of the surface meteorological and air-sea flux fields.

The obvious limitations of such an observing system are spotty spatial coverage and limited space/time resolution. As a result, for some studies in PBECS, such as an examination of ocean influences on storm tracks and the role of synoptic atmospheric forcing in the evolution of the ocean in the northwestern Pacific, insufficient detail would be available and a second strategy could be employed. For a period of several years, an array of surface moorings would be deployed to explicitly resolve the space/time variability of the surface forcing fields, perhaps as a component of a regional process study. More generally, coverage would be improved by bringing in NWP and satellite data. The 6-hourly time resolution, global coverage, and dynamic framework for assimilation of in situ data provided by the NWP models are attractive attributes, as is the global coverage provided by satellites. Thus, the strategy for obtaining flux fields will bring together all available information and: (1) use in high quality situ data (2-4 surface reference sites plus the fully equipped TAO sites and the upgraded VOS on the HRX lines) to correct NWP fields, (2) improve NWP surface meteorology and fluxes by partnership with NCEP, ECMWF, and other modeling groups, working to improve NWP surface meteorology and fluxes. This will involve several tasks. First, there should be an ongoing comparison of model surface meteorology and fluxes with in situ data. Data from surface-flux reference sites would be compared with model data to define biases. The WCRP Working Group on Numerical Experimentation has agreed to work together on this comparison in parallel with their ongoing Atmospheric Model Intercomparison Project (AMIP). Second, ways to routinely assimilate more of the accurate in situ surface data should be investigated. Third, the flux parameterizations used in models must be examined, (3) improve the use of remote sensing data. Of particular interest are precipitation and surface radiation, as the NWP model fields of these quantities have large errors. A partnership between those working remotely sensed data, with their excellent coverage, and with in situ data for calibration and validation should be explored. sensed and in situ data sets, and (4) assimilate remotely sensed and in situ data into NWP models, noting that eventually ocean heat and water budgets might be added as further constraints in producing flux fields or used to validate the surface flux fields.

7. Integrated atmospheric observations

The success of coupled ocean-atmospheric models, as well as the utility of assimilated data sets for research purposes from PBECS, will depend crucially on detailed atmospheric observations with sufficient coverage in both time and space. The existing atmospheric observing system, especially over the extratropical Pacific, has large gaps in coverage. PBECS, in conjunction with other observational efforts, could substantially improve this situation through the optimization of emerging sustained observing and data assimilation systems. Pacific CLIVAR process studies would field additional, limited duration, atmospheric observing efforts. The expansion of Pacific atmospheric observations for CLIVAR is a substantial undertaking that will necessarily involve the cooperation of multiple international agencies. Fortunately, several initiatives and organizational efforts that have already been put forth can bear directly on the problems of data gathering and assimilation over the Pacific. Some of these efforts are being organized under the auspices of the World Meteorological Organization (WMO) World Weather Research

Programme (WWRP), and the WMO Working Group on Numerical Experimentation (WGNE). By aiding implementation of these initiatives, PBECS could in turn benefit such programs by providing additional impetus for extended observations in the context of a CLIVAR ocean/atmosphere research effort.

Since one primary focus of PBECS is ENSO variability, atmospheric observations within the equatorial wave guide are of prime importance. These observations must, to the best degree possible, be able to resolve not only the several thousand kilometer scale of MJO variability, but also the somewhat smaller scale and higher frequency phenomena such as convectively-coupled Kelvin waves and cyclone pairs related to equatorial Rossby modes (Kiladis and Wheeler, 1995; Numaguti, 1995), which are linked to the occurrence of "westerly wind bursts" and subsequent oceanic Kelvin modes (Harrison and Larkin, 1998). Thus a strategy that takes maximum advantage of Pacific geography, the TAO array, and volunteer observing ships (VOS), to improve coverage of both surface and upper level observations is needed.

In addition to equatorial Pacific observations, extratropical Pacific atmospheric observations should also be given high priority. In particular there are critical questions concerning the role of ocean-atmosphere feedbacks in decadal atmospheric variability over the North Pacific. The extent of the role of North Pacific SST in determining the subsequent evolution of the atmosphere on a variety of time scales from intraseasonal to decadal is still an open question (Robinson, 2000). Conversely, the combined effect of radiative fluxes and wind stress forcing of the North Pacific on ocean circulation is an important question in modeling interannual and decadal fluctuations (e.g. Deser et al., 1999). Unfortunately the lack of land based observational platforms over the extratropical North and South Pacific requires a heavy reliance on mobile platforms, such as VOS and aircraft, and on remote sensing from satellites. Remarkably, instrumentation available at key island stations, such as Midway and Wake, is not currently making routine observations. Getting routine reports from these stations is considered to take highest priority, since they would provide direct observations of fluctuations in the Pacific jet and storm track systems deemed ultimately critical to modeling variability of the North Pacific oceanic circulation.

In order to optimally initialize coupled ocean-atmosphere models, an efficient methodology of data collection and assimilation is necessary to assure the utilization of all available data with adequate quality control. This is a primary consideration of PBECS.

Status of the Existing Atmospheric Observing Network

At present, there are large gaps in both the surface and upper-atmospheric observing networks over the Pacific. The existing surface observing system consists of direct observations from island stations, VOS, telemetered observations from both drifting and moored buoys such as the TAO array, and satellite measurements of surface wind from the ERS-2 and QuickScat scatterometers. Existing upper-level observations are obtained from radiosonde profiles from island stations and occasional ship launches, pilot balloon launches from islands, data collected from wind profilers, and aircraft observations. These upper-air observations are supplemented by remote measurements from satellites, which provide cloud vector winds and temperature and humidity sounding data. In fact, much of the upper-air data available over vast reaches of open ocean comes from satellite estimates. While extremely valuable, these data sources do not measure atmospheric state variables directly, nor do they provide high vertical resolution. Consequently, they suffer from inaccuracies in both the algorithms used to retrieve the desired parameters and uncertainties in the assignment of a given observation to an altitude above the earth's surface.

The GCOS Global Surface Network (GSN) sites are primarily land-based surface observation stations reporting temperature and precipitation. Many also provide humidity and radiation measurements. In the Pacific, the region of best coverage lies over the warm pool and just south of the equator to about where island stations are plentiful. However, island surface stations suffer from local effects and may not best represent conditions over the open ocean. Thus for the purposes of initialization of forecast and coupled models, supplemental surface observations from buoys, ships of opportunity, and satellite are crucial. As can be seen at the NCEP and ECMWF sites, the real time surface data coverage provided by these supplemental observations is quite extensive, especially over the open ocean.

Profilers within the Trans-Pacific Profiler Network (TPPN), maintained by the NOAA Aeronomy Laboratory, are located at Biak, Christmas Island, and Piura are sites where 50 MHz profilers, which measure wind and vertical motion from roughly 2 to 15 km, are located. 915 MHz profilers are located at the other sites, including Christmas Island. These platforms measure wind and vertical motion from near the surface up to about 5 km. The array is meant to provide accurate (to within 1 m s^{-1}) measurements of wind at high vertical (<500 m) and temporal (30 minute or better) resolution along the equatorial wave guide. The 915 MHz profilers also provide information on droplet size distribution, cloud base elevation, and freezing level (Gage et al., 1994) and are currently being used as ground-truth validation for the Tropical Rainfall Measuring Mission (TRMM) project. From a comparison of the locations of observations getting into the NCEP and ECMWF data assimilation systems with the locations of TPPN sites, it appears that the operational centers do not now utilize all of the profiler data on a regular basis. The Aeronomy Lab is working with the centers to correct this.

Additional observing components that will contribute atmospheric observations have been presented earlier. They include surface moorings, Volunteer Observing Ships (VOS), and surface drifters. Atmospheric observations from the TAO buoys include surface wind, air temperature, and relative humidity at all of the sites, and rainfall and shortwave radiation are also measured at some sites. At present surface wind, air temperature, SST and humidity are telemetered to the GTS, and these data appear to be used regularly for operational assimilation at both NCEP and ECMWF. Extratropical surface buoys are also part of Pacific CLIVAR, by other Pacific nations as well as the U.S. These would include the well-instrumented surface reference sites discussed in the section on surface fluxes, some of the long time series sites, and national weather buoys. Both standard VOS and the upgraded VOS planned for the high-resolution XBT lines in the Pacific would contribute surface meteorological observations. The surface moorings, subsurface moorings, surface drifters, and perhaps the profiling floats should be equipped to measure precipitation, with an in the water measurement available using ambient noise observed with a hydrophone.

Recommendations

For the atmospheric observing component of PBECS, an optimization of the existing land-based observing platforms, as well as the addition of some radiosonde sites at key locations, would be most useful. On the ocean, enhancement of surface meteorological observations should be considered by upgrading the instrumentation on selected VOS lines (the HRX lines), by upgrading 3-5 TAO moorings to measure all parameters needed to infer fluxes, and deploying and maintaining 2-3 surface reference sites outside the equatorial zone. If feasible, radiosonde ascents from VOS should also be considered, as should the continuation of balloon launches from the TAO servicing ships. The continued maintenance and possible expansion of the TPPN into the northern Line Islands is a cost effective way of increasing automated boundary layer observations of wind and vertical motion in a key region of tightly coupled air-sea interaction and strong interannual variability.

The possibility of aerosonde observations from land- or ship-based locations should be seriously considered. These light weight, robotic aircraft appear to have the potential for quality, high-resolution, targeted observations over remote regions of the Pacific at relatively little cost. Aerosondes have been used successfully in several recent field programs, and recently developed models have a nominal range of 5000 km and 50 hours endurance per flight. Models under development are expected to extend that range considerably. More detail on aerosondes can be obtained at http://www.aerosonde.com/company _structure.htm

A concerted effort to efficiently collect and disseminate data from all platforms in near real time, from one location, would provide a cost effective means of increasing the spatial and temporal coverage of atmospheric observations needed for operational data assimilation into models and for reanalysis products suitable for case study and statistical research applications.

Island-Based Observations: An effort to re-establish radiosonde sites at stations with pre-existing historical records (Table 7) is encouraged. For the statistical study of variability from the diurnal and synoptic time scales out to interannual and decadal time scales, it is imperative to have observations that are taken regularly and in a consistent manner at the same site for extended periods. This is also desirable for model data assimilation purposes, where coding and quality control of the data can be optimized for maximum impact on the analysis. While the distribution of islands in the Pacific is unfavorable for land-based observation platforms over vast reaches of the mid-latitude oceans, certain geographical accidents actually are quite favorable for monitoring the equatorial wave guide and the transition from the equatorial dry zone into the core of the ITCZ. Specifically, the fortuitous alignment of islands along the equator provides for reasonably spaced coverage for surface and radiosonde observations except for the longitudinal range from 157°W to 90°W. In addition, the alignment of the Line Islands from Christmas Island (2°N, 157°W), north to Fanning Island (4°N, 159°W), Washington Island (5°N, 160°W) and Palmyra (6°N, 162°W) offers a natural and convenient transect for observations from the dry zone at Christmas, which receives less than 500 mm of precipitation per year, to Palmyra, which averages more than 5000 mm of precipitation per year, over a distance of only 650 km (Morrissey et al., 1993). This configuration of islands was effectively exploited to study the circulation of the ITCZ to equatorial transition in 1968 during the Line Islands Experiment (e.g. Madden and Zipser, 1970). This region is strongly influenced by ENSO, and would provide a cost effective means for observing changes in the structure of the ITCZ associated with SST fluctuations over the tropical Pacific. In addition; the Line Islands lie close to the location of greatest discrepancy between different methods of satellite based precipitation estimates within the ITCZ (Janowiak, 1995).

While the ITCZ is relatively well sampled over the western warm pool at very reliable reporting stations such as Truk (7°N, 152°E) and Yap (9°N, 138°E), the character of the eastern Pacific ITCZ is different and much more influenced by ENSO (Kiladis and van Loon, 1988) and by Rossby wave activity originating in the extratropics (Kiladis, 1998). At least one instrumented site should be considered at either Palmyra or Washington Island to sample the active convective region of the ITCZ. It is not clear what the logistics of a radiosonde operation at one of these islands would be. Barring a radiosonde, an automated 915 MHz profiler should at least be considered to sample boundary layer winds and the structure of precipitating convective and stratus clouds at this location. Surface observations would also be extremely valuable.

In order to take maximum advantage of Pacific geography, efforts should be taken to assure that radiosonde and/or profiler observations are also obtained at the following locations:

San Cristobal, Galapagos (1°S, 90°W): This location is listed as a GCOS, GSN and GUAN site, although the observations appear to be quite intermittent and do not regularly appear on the GTS data stream at NCEP or ECMWF. The Aeronomy Laboratory's 915 MHz profiler has been in operation reliably since October 1994, and is being utilized for boundary layer research (Hartten and Gage, 2000). Given the location of the Galapagos within the equatorial cold tongue, and the strategic importance that regular profiles of wind, temperature, and humidity observations would be to programs such as PBECS, EPIC, and PACS, every effort should be made to return the Galapagos radiosonde and surface station to regular operation. The supporting infrastructure is already in place at this site, which has an airport with the necessary trained personnel on hand for observations. The main problem at present appears to be the communications equipment used to send data to the GTS, and a lack of funding to provide for the necessary expendables for radiosonde launches.

Midway Island (28°N, 177°W): Given the paucity of atmospheric data over the North Pacific, this location as the northernmost island south of the Aleutians should be a high priority for instrumentation. Although Midway has a lengthy historical record of surface and radiosonde observations, and is still a U.S. protectorate, upper level observations ceased in 1997 when the U.S. Navy vacated the island, and it was taken over by the U.S. Fish and Wildlife Service. Now a National Wildlife Refuge, Midway has an airport that sees frequent ecotourism flights from Hawaii, with several personnel certified as NOAA weather observers. Regular surface and tide observations are still being taken and are reported to the National Weather Service and the FAA, although the surface observations do not appear regularly as GTS observations at the operational centers. The management of the airport is very willing to cooperate to reestablish upper air observations at this site. Funding appears to be the main issue. The possibility of Midway acting as a monitoring site for other PBECS activities, such as a base for aerosonde or ship operations, should be explored.

Wake Island (19°N, 168°E): Observations from this site would fill an important gap in subtropical observations between Guam (13°N, 145°E) and Hawaii. As with Midway, Wake has a long historical radiosonde record, although the more recent record in the NCAR sounding archives is quite discontinuous, but still has some data from as recently as 1998. If the site is still operating the soundings do not appear to be getting onto the GTS data stream at present. A relatively modest effort could be made to assure that such observations are transmitted correctly to be used for data assimilation and archived for research purposes.

There appear to be many island stations taking observations over the Pacific in conjunction with the GCOS, GSN and GUAN for climate monitoring purposes, but currently not reporting in real time on the GTS (this can be seen through a comparison of network diagrams with the surface and upper level observations shown being assimilated at the ECMWF and NCEP sites). The possibility that these stations could report those observations in real time should be investigated. If cost effective, these data could fill in important gaps in the network, particularly over the subtropics of both hemispheres but especially over the subtropical South Pacific, where islands abound.

Ship Based Observations: Ship-based ocean state observations have been discussed earlier. Enhancements of atmospheric observations from the existing VOS lines should be given high priority. An effort to upgrade shipboard surface observations from VOS could, at relatively little cost, increase the coverage and accuracy of surface temperature, wind, pressure, humidity, flux, and radiation measurements. These parameters are crucially important to driving ocean models, and to the initialization of atmospheric and coupled models, yet are at presently poorly represented, at best, in reanalyses and operational analyses over data sparse regions.

The possibility and feasibility of radiosonde ascents from high-density XBT lines should be considered. One potential drawback of this approach would be the necessity of training on shipboard personnel in the launching of these devices. As an alternative, automated shipboard balloon launching is also a possibility. However, given the potential expense of these systems, VOS lines which would utilize them should be carefully assessed to avoid redundancy with other enhancements by the proposed atmospheric observing programs to be discussed below. Nevertheless, the implementation of regular GPS sonde ascents from the NOAA R/V Ron Brown and Ka'imimoana has the highest priority. Efforts to continuously maintain C-band radar, S-band wind profiling, cloud radar and air-sea flux instrumentation aboard these two vessels are also critical.

Satellite Observations: Existing and proposed satellites designed to improve monitoring of the ocean and atmosphere are described in the section on the sustained, basin-wide observing system. As seen at the NCEP and ECMWF data assimilation sites, large data sets of remotely sensed wind, humidity, and temperature as well as radiation parameters are continuously being updated for use in operational forecasting. It is important to continue research by groups at NASA and universities developing algorithms to improve the quality of these data. These observations are readily available from the GTS in real time and after the fact at several data centers such as NESDIS, providing a valuable resource for data assimilation and research for PBECS. In addition, the TRMM project, administered jointly by NASA and NASDA (Japan), promises to greatly improve the quality of remotely sensed rainfall, cloud height and droplet size distribution data that will become available operationally within the time frame of PBECS. More information on TRMM can be found at trmm.gafc.nasa.gov/

Focussed Observational Efforts

In addition to the above platforms, several field programs involving significantly enhanced upper atmospheric observations over the Pacific and the rest of the globe are being considered for the next few years. These programs would greatly improve the amount of data on the state of the stratosphere and troposphere particularly over the currently data sparse regions of the extratropics outlined above. Entrainment of the products produced by these programs into any PBECS data assimilation system should be encouraged. A formal collaboration between these observing programs and CLIVAR would almost certainly be beneficial for a broad variety of applications, among them data assimilation for synoptic-to-medium range forecasting, initialization of global coupled models, and ultimately for research purposes on weather and climate variability on all time scales. Among those programs, the following appear to be particularly relevant:

The Hemispheric Observing System Research and Predictability Experiment (THORPEX). THORPEX is a program of observing system research and development aimed at improving skill of weather forecasts for Northern Hemisphere nations on time scales ranging from nowcasts to 10 days. The program will draw upon current and future data impact studies, observing system simulation experiments, and data assimilation development. The program would deploy in situ observing systems such as aerosondes, driftsondes, and buoys under operational conditions, in an effort to determine the best feasible mix of platforms to improve the initialization of numerical weather prediction models for forecasts over the Northern Hemisphere. THORPEX would also evaluate the impact of satellite observing systems on model initialization, as well as the use of "targeted" observations.

The initial experimental design involves oversampling the North Pacific atmosphere with as many observational resources as possible for several months. The effect of such observations can then be objectively determined by numerical model hindcasting where observations are withheld to determine their net impact on the forecasts. A key aspect of THORPEX of particular relevance to PBECS is the use of driftsonde balloon systems currently being developed by the Atmospheric Technology Division at NCAR. These would provide atmospheric sounding data over the North Pacific (and the Atlantic) by launching large but expendable balloons into the stratosphere from eastern Asia and North America which carry payloads of several dozen dropsondes. The dropsondes would be deployed at pre-determined intervals to gather detailed data on temperature, wind, humidity, and perhaps ocean state data as the balloons are advected across data-poor regions. These data would be transmitted to operational centers via the GTS and would be available for data assimilation to operational centers, PBECS model initialization, and researchers in real time.

Other observations and platforms being proposed for THORPEX include: (1) equatorial winds and the heat redistribution that accompanies ENSO, (2) aerosondes to be launched from Hawaii and western North America, (3) targeted observations by aircraft provided by the U.S. Air Force to be deployed from Hawaii to Japan to measure the atmospheric state, especially at jet stream level, (4) moored surface buoys provided by PMEL to measure surface pressure and sea surface temperature at hourly intervals, transmitted to the GTS, (5) radiosonde ascents from ships in conjunction with the ACE-ASIA atmospheric chemistry program, and (6) atmospheric soundings over remote oceanic locations delivered by shear directed super pressure balloons (see GAINS below).

An observing system test and evaluation phase of THORPEX is being planned for early 2001. The THORPEX major field campaign is currently slated for several seasons within the 2003-2005 time frame. The WWRP will facilitate the field and research activities, and the USWRP will act as a coordinating agency for U.S. participants in THORPEX. More detailed information on THORPEX can be found at www.nrlmry.navy.mil/ langland/TH0RPEX_document/Thorpex_plan.htm

Global Air-Ocean in-situ System (GAINS). GAINS would provide several hundred long-lived balloons cruising along constant latitude circles in the stratosphere near 60 hPa. These would deploy dropsondes for meteorological, atmospheric chemistry, and ocean state measurements at either predetermined or operationally determined intervals. The balloons would be recoverable after several months of service, and are intended to provide data for observation sparse regions of the ocean for synoptic to climate time scales. As with THORPEX, GAINS data would be relayed to the GTS in real time for operational and other data assimilation purposes. Since GAINS data will be global and available to worldwide meteorological services, it is anticipated that the costs will be shared multinationally, and the data will be distributed under WMO auspices. GAINS is being proposed as a 50-year operational program which would eventually utilize up to 400 balloons. A prototype proof-of-concept balloon is being planned for 2001, and a pilot study using up to 3 balloons is slated for 2003.

Focused Research on Intraseasonal Tropical-Midlatitude Interactions to Improve NOAA's Weekly to Seasonal Forecast Capabilities. This initiative by NOAA's CDC and ETL would focus on improving weather and climate forecasts on weekly to seasonal time scales through improvements in observations, analyses, understanding and modeling of intraseasonal tropical-midlatitude interactions and their regional impacts on the U.S. The efforts would begin in 2002 with focused studies over the Pacific, with an initial emphasis on identifying key mechanisms of tropical-extratropical interactions that can lead to improvements in forecasts in the 8-14 day range. The program would result in dense targeted observations over regions of strong tropical convection such as the Madden-Julian Oscillation and adjacent subtropical jet regions known to be affected by such forcing. The project would also likely involve efforts to improve data assimilation into the operational forecast system, and produce an archive of detailed atmospheric observations over the tropics and subtropics of the Pacific for research purposes.

<u>Data Assimilation and Archiving</u>

CLIVAR and the other programs mentioned above can best benefit from an expanded data base only if such observations are made available in a timely fashion for data assimilation, and properly archived in consistent formats for future use in research applications. While the expansion of the various types of observations is a priority, close attention must be paid to the ways the data are collected and disseminated. Ideally, a central location for the dissemination of all oceanic and atmospheric data related to CLIVAR and related programs would be ideal for this purpose. As an absolute minimum, there should be a "virtual data center" with pointers to all available data resources resulting from CLIVAR programs. For real-time access of both point measurements and gridded output, data distribution by user-initiated "pulls" from a web or ftp site has proven to be very practical. Consequently, data sets and software can be effectively distributed worldwide with standard formats. If a large volume of accesses is anticipated, the Unidata concept of scheduled "pushes" through a local data manager may be more appropriate. The importance of these relatively inexpensive measures has been demonstrated in many past field programs such as GARP, TOGA COARE, and TEPPS, among others. Management of the potentially enormous volume of oceanic and atmospheric data generated by future programs will necessarily require implementation of emerging technologies for data archival and processing. Serious consideration should be given to a centrally located effort of data management to avoid the loss or unavailability of such data to the community.

8. Sustained, focussed elements of Pacific CLIVAR

In addition to the basic principle of bringing basin-wide observations, data assimilation, modeling together the Pacific CLIVAR plan is driven by specific science foci. Here, sampling enhanced beyond the density of the sustained, basin-wide program is discussed, motivated specifically by those foci:

Subtropical Overturning Circulation

A number of theories for decadal modulation of ENSO and for other processes of decadal variability involve oceanic connections between the subtropics and the tropics. These connections are usefully discussed in the context of the subtropical overturning circulation in which water upwells at the equator where it modulates sea surface temperature, is carried poleward by Ekman transport and subtropical western boundary currents, subducts in the subtropics, and finds its way back to the equator through a combination of interior "Sverdrup" advection and concentrated currents. A main focus of the PBECS observing and assimilation system is understanding this Subtropical Cell (STC) and its role in the feedback processes that affect decadal variability and the ENSO cycle.

Interior processes

The link between the atmosphere and subsurface ocean in the subtropical Pacific is dependent on processes that ventilate the thermocline. When the wintertime mixed layer restratifies under springtime heating the newly formed thermocline has properties (i.e., temperature, salinity, potential vorticity, chemical tracers) set by interaction with the atmosphere. Once subducted, this water is insulated from further interaction with the atmosphere, thus setting water properties and circulation patterns in the permanent thermocline. Subducted anomalies from the eastern Pacific may be advected along mean-current pathways to the tropics and then be upwelled to influence the tropical ocean-atmosphere system. Alternatively thermocline anomalies may also be generated by anomalous advection of mean properties by Rossby and Kelvin waves or anomalous advection along gradients or across fronts. A combination of the two mechanisms is likely, and PBECS observations and analyses must be able to quantify their contributions while addressing the roles of air-sea fluxes, wind mixing, local wind forcing, anomalous advection, or other internal ocean processes. The observations must also determine where subducted anomalies are primarily generated, the relative importance of anomalies arriving at the equator via mid-ocean vs. the western boundary, and the relative roles of planetary wave dynamics, advection, and eddy transport on anomaly advection in the thermocline. In addition the observations should clarify whether anomalies are dissipated by fluctuating thermal and velocity fields driven by Ekman pumping, or by mesoscale variability. Higher sampling density, particularly for salinity, is needed. Observing anomaly generation will depend mainly on the improved surface-forcing fields and Argo. For gyre-scale variability, including detection of anomalies as they are generated, we will rely on the Argo array to measure temperature, salinity, and velocity over the entire tropical and subtropical Pacific. It is not practical to deploy an eddy-resolving array over the complete domain, so the strategy is different for large-scale and mesoscale variability.

Large-scale variability: The sampling must provide sufficient data to map, on seasonal timescales and with good signal-to-noise, variability in large-scale equatorward geostrophic circulation, to initialize models, and to constrain assimilation analyses. Sampling studies based on altimetric data in the southeastern Pacific, subsampled at Argo resolution (3°, 10 day), show that the float array will provide good estimates of the large-scale geostrophic transport variability. An additional objective of the float array is to directly determine the Lagrangian pathways of equatorward flow in the thermocline. Some floats will be parked at thermocline depths in order to satisfy this objective. The tradeoffs inherent in different parking levels are not yet well understood; in the initial Argo deployments in the southeastern Pacific, approximately half of the floats will park in the thermocline and half at a deep level. This ratio will evolve over time to optimize the array, as more is learned about the behavior of floats at each level and of the signals observed by the array.

Mesoscale variability: Two components of the broad-scale observing system have some eddy resolving capability, altimeters and the High Resolution XBT transects. The plan is to use the combination of these to observe the space-time characteristics (altimeter) and subsurface expression (HRX) of mesoscale variability.

Low-latitude western boundary currents

One hypothesis for decadal modulation of ENSO, and for decadal variability itself, is that subtropical oceanic anomalies are advected to the equator where they influence the tropical atmosphere. While it is possible for water subducted in the subtropics to reach the equator through the interior circulation, or possibly through strong horizontal mixing, it can also reach the equator through the western boundary currents. In the North Pacific this is the main path, and special focus must be placed on the low-latitude boundary currents.

The Northern Hemisphere: Though large-scale geostrophic inflow to the equator might be anticipated, a mean upwelling favorable wind stress curl in the ITCZ produces a thermocline ridge near 8-10°N that forces most of the equatorward flow originating in mid-latitudes to the western boundary in the North Equatorial Current (NEC). The NEC is the southern limb of the northern subtropical gyre and the northern limb of a cyclonic tropical gyre. The NEC bifurcates at the Philippine coast near 14°N, flowing north as the Kuroshio into the northern gyre and flowing south as the Mindanao current into the complex circulation near the equator. There is recirculation associated with the cyclonic Mindanao Eddy a few hundred kilometers offshore and some flows into the Suluwesi Sea and then into the Indonesian Throughflow (Godfrey, 1996). As the current passes south of the island of Mindanao (at about 5°N) drifter trajectories suggest a complex and probably highly temporally variable flow field (Lukas et al., 1991). Model solutions (Gu and Philander, 1997, among others) show that Mindanao Current thermocline-level water that flows eastward into the NECC moves into the EUC within a few thousand km.

Measuring the Mindanao Current and the flows into the equatorial circulation from the western boundary is sure to be challenging. Moorings are the best proven, if expensive, approach. The steep and rugged bottom topography off the Philippines coast (the Mindanao Trench is more than 9000 m deep less than 80 km offshore), and the deep, rapid currents mean that a moored array may not be feasible. Surface drifters have proven useful in resolving many of the complex features of the surface currents (Lukas et al., 1991), and regular reseeding of drifters should be relatively easy. However, sampling of water properties and transport through the thermocline is sought; and this will not be done well by Argo floats, which lack the spatial resolution needed (order 10 km) and there are no known frequent VOS crossings. Autonomous gliders or moored profilers might collect repeated T and S profiles on either side of the current, thereby giving good measures of geostrophic transport, and gliders might observe sections through the currents. Coastal sea-level gauges have promise for monitoring the geostrophic flow of the Mindanao Current between Palau Island and Mindanao (Lukas, 1988), possibly in conjunction with inverted echo sounders to better sample the recirculation. Lukas (1996) suggested that acoustic tomography would be appropriate for monitoring fluctuations of NEC transport in the far west and its bifurcation. A careful study of the options is needed.

The Southern Hemisphere: The main sources of the South Equatorial Current (SEC) and the Equatorial Undercurrent (EUC), and a significant source of the North Equatorial Countercurrent (NECC), are in the southern hemisphere. The southern counterpart to the NEC-NECC tropical gyre extends across the equator and includes as its westward limb the northern portion of the SEC and as its eastward limb the southern portion of the NECC (and the EUC at thermocline level). Just as the Mindanao Current closes the northern tropical gyre by connecting the NEC to the NECC and EUC, in the southern hemisphere a western boundary path carries water from about 15°S, where the SEC bifurcates at the Great Barrier Reef, along Australia and the south coast of New Guinea, and then northwestward along the northern coast of New Guinea to the equator (cf. Lukas et al., 1996). Along the northern New Guinea coast this equatorward transport is carried partly by a surface flow (New Guinea Coastal Current, NGCC), which seasonally reverses in the tradewind/monsoon wind cycle, and beneath this, focused near 200 m, by the New Guinea Coastal Undercurrent (NGCUC), which consistently flows toward the equator (Lindstrom et al., 1990). Lindstrom et al. (1987) inferred from water properties that the NGCUC was the main source of the EUC. Thus, the NGCUC transports subtropical water to the equator where it is carried to the east and eventually upwells and modulates SST where the atmosphere is most sensitive to SST. In order to determine if the southern hemisphere can modulate ENSO through changing the mass, heat, and/or freshwater transports of the NGCUC, these transports must be measured for more than a decade.

On the basis of information gathered in the WEPOCS experiment (Lukas et al., 1996; Lindstrom et al., 1987, 1990; Tsuchiya et al., 1989), two complementary strategies present themselves. Off the east coast of New Guinea, the currents are forced though two narrow passages. The main path, through Vitiaz Strait, is confined to a 40-km passage, while there is a smaller flow through St. George's Channel, a 30-km-wide gap. These confined flows may be suitable sites for surface moorings (blow down of subsurface moorings makes them unsuitable for capturing the shallow flows). These passages might also be suited for measurement by pairs of moored profilers, pairs of pressure gauges or, if suitable ferries or inter-island packets could be found, repeated observation by XBT and/or ADCP. The 100 cm s^{-1} speeds found in Vitiaz Strait probably preclude using autonomous gliders, and the current strength may also be a problem for moored profilers. An alternate strategy employed in WEPOCS is repeated sections north from New Guinea somewhere between 143 and 148°E. Autonomous gliders sampling temperature and salinity could monitor the New Guinea Coastal Current and Undercurrent on a monthly basis using geostrophic calculations referenced by glider drift. It would be desirable to add an ADCP to the glider and extend such sections north to capture both the Equatorial Undercurrent and its NGCUC source in a single section.

Indonesian Throughflow

Transport of water from the Pacific to the Indian Ocean significantly impacts both global climate and diagnosis of climate processes occurring in the Pacific. The convergence of the Mindanao and New Guinea western boundary currents feeds eastward equatorial flow in the Pacific Equatorial Undercurrent and surface and subsurface countercurrents. This convergence also feeds a complex flow westward and southward through the Indonesian Seas, which enters the Indian Ocean between Australia and the Indonesian Archipelago (the Indonesian Throughflow (ITF)). The mean mass, heat, and freshwater transports of the ITF are poorly known (Bryden and Imawaki, 1999; Wijffels, 1999), and the variability is high. From the CLIVAR perspective there are three main reasons to sample at least its mass, heat and freshwater transport on a seasonal timescale: (1) the ITF may affect Australasian climate. Although apparently by different mechanisms, the warm Indian SST and cold Pacific SST parts of the SST pattern resulting from ITF variability have reinforcing effects on the Australasian monsoon (Soman and Slingo, 1997), (2) the ITF may be involved in ENSO and its predictability. Coupled modeling work by Schneider (1998) reveals that the ITF heat transport has a substantial impact on global climate. When the ITF moves heat from the equatorial Pacific to the Indian Ocean, deep atmospheric convection is moved westward with it, and (3) the ITF affects analysis of Pacific climate dynamics. Because of its topographic complexity, it is unlikely that climate models will soon be accurately predicting flow through the ITF. Thus ITF transports will enter PBECS assimilation analyses mainly through observations. Without measurements of the ITF transports it will be very difficult to diagnose variability of the heat budget of the western tropical Pacific on climate timescales.

Measuring the transport of the ITF is considered in depth by Imawaki et al. (1999). It is complicated by complex bathymetry, nearness to the equator where direct current observations are required, and strong variability on 40- to 60-day periods. While current meters and moored profilers may be required to apportion transport between the various inter-island passages, and to understand water-mass transformation during this odyssey, measurements of the net inflow between the Philippines and New Guinea and of outflow between Indonesia and Australia appear to be the most effective ways to measure inter-ocean transports. Hiroshima University has implemented a repeated XBT and ADCP section between Japan and Australia. The XBT/XCTD line IX1, which coincides with hydrographic lines during JADE and WOCE, has produced a geostrophic estimate of the upper ITF transport and heat flux since 1984, and is logistically attractive in providing VOS crossings roughly fortnightly. Australian scientists now oversee low resolution XBT sampling on the IX1 line roughly every two weeks. The main limitations at present are: (1) lack of synoptic salinity coverage, (2) limited depth of sampling, as present XBT data cuts off at 750 m, too shallow to capture the entire ITF, (3) no direct velocity observations so that Ekman transport and any other ageostrophic flows are not captured by the present sampling. An effective way to address the Indonesian Throughflow would be for the U.S. to cooperate with Australia in upgrading the IX1 VOS line by providing the following: deep XBTs to extend depth coverage; XCTDs, underway CTDs, and/or thermosalinographs to observe the salinity needed to make accurate geostrophic transports and to measure freshwater transport; and an ADCP on at least one ship to calibrate the geostrophic calculations and measure the Ekman transports of fresh water and heat.

The equator

Equatorial upwelling is the path by which the water in the subtropical overturning circulation returns to the surface along the equator, where it can be Ekman-advected back to the subtropical gyres. Upwelling is a central ingredient in the ENSO cycle, and it is believed that changes in the properties of water upwelled at the equator can lead to significant changes in the ENSO cycle. Complicating the picture of basin-scale thermocline-level convergence and Ekman divergence, Lu et al. (1998) found two meridional-vertical cells in their layer-model solution: the subtropical cells that transport water over many degrees of latitude, and a smaller, shallower cell that recirculates warm near-equatorial upper water within about ±5° latitude. GCM solutions reported by Blanke and Raynaud (1997) suggest that geostrophic convergence in the interior ventilates the upper EUC (Lu et al.'s shallow equatorial cell), while lower EUC water enters near the western boundary and exits into the east Pacific cold tongue.

From a climate perspective, it is upwelling's role in determining SST that is important. Upwelling is both a local response to surface winds and a component of the gyre-scale circulation. Each aspect affects SST. The local wind probably determines how much water upwells while equatorially trapped waves and the general circulation advection determine what water is upwelled. The source of the upwelled water determines, in part, the SST. Indeed, the relationship between SST and thermocline depth used in simple ENSO models (Cane and Zebiak, 1987) is shorthand for a complex heat budget in which the upwelling temperature-transport (wT) is the main cooling effect. Since there is variation in how different ENSO cycles develop, and in how well specific models predict them, it appears essential to understand what varies in this full heat budget between different ENSOs. With better satellite wind fields, TAO and Argo large-scale T and S fields, and a few moored current observations, it may be possible to describe the upwelling transport on latitude scales of a few degrees and longitude scales of 10 to 20°. The current meters would be most useful on and near the equator, at a few longitudes where they could define the large-scale zonal currents. Other current meters close to the surface, off the equator, could measure transport and vertical shear in the Ekman layer.

To evaluate the effects on SST of changes in the equatorial thermocline water properties, it will be necessary to understand how thermocline water that has been carried into the equatorial undercurrent from the subtropics reaches the surface, how it is modified in the strong shears of the equatorial zone, and how the processes that bring it to the surface are affected by equatorial winds. For this purpose, simultaneous observation of the surface wind, and of vertical profiles of the horizontal velocities, temperature, and salinity at locations close enough to estimate meaningful gradients, would be most useful. Again, a combination of improved winds, moored velocity profiles, and higher resolution T and S sampling are likely to be the main observing elements. Other techniques that might be used include surface drifters to give high horizontal resolution velocity measurements and ADCP and CTD profiles taken during regular servicing of the TAO array could provide high meridional resolution, if infrequent, pictures of velocity and water properties. The greatest progress in unraveling the equatorial processes affecting ENSO may come from models that blend data of different types, fill in the unmeasured, and allow vertical velocity to be inferred indirectly. At present it is clear that much information is needed before an efficient system for sustained observation of the processes that govern SST in the equatorial zone can be implemented. The first step should be a well-designed process experiment with a broad range of techniques employed both to understand the component processes and to determine where and what type of observations would be most useful, and whether and how upwelling or its variability might be inferred from other types of sustained observations.

Extratropical Climate Feedbacks

An oceanic link between the tropics and subtropics may be responsible for Pacific decadal variability, but it has also been hypothesized that processes confined to the extratropical North Pacific can drive decadal variability. While it is uncertain that the atmosphere is responsive to the extratropical ocean surface on seasonal timescales, it is much more likely that this coupling is active on decadal timescales. There are concrete hypotheses, confirmed by model runs, for decadal feedback loops in the extratropical North Pacific. PBECS must observe and describe these feedback processes in order to test the hypotheses. While there are no analogous hypotheses for climate feedbacks in the southern hemisphere, the physics of the two hemispheres are not so different that we can afford to let the South Pacific continue to be as sparsely observed as it is today.

The North Pacific feedback loop

There are three key coupled processes that figure in models of a North Pacific climate feedback loop: oceanic thermocline adjustment to changing wind-stress curl, SST response to the changing thermocline, and atmospheric response to changing SST. While elements of this loop are observed in the North Pacific, detection of the full feedback process will be difficult. Here we discuss approaches to the problem.

Basin-scale thermocline and current fields: Argo will provide excellent coverage of basin-scale thermocline variations in the subpolar and subtropical gyres. Surface drifters can provide information on the surface currents and SST in the subpolar and subtropical gyres. The Oyashio and Kuroshio boundary currents are important elements in the general circulation but will not be well observed with floats or drifters. Thus, it would be very helpful if past and future measurements of hydrography on the many lines off the East Asian coast were made available for scientific use. Japanese scientists have aggressively expanded climate-relevant observations of Kuroshio transport. Imawaki et al. (1999) reviews methods for sustained observations of the Kuroshio transport; the work there found that SLH slope determines transport to within 5.6 Sv over a variability range of 60 Sv. The Oyashio has not yet been "calibrated" in this fashion, but this will be accomplished by international partners, thereby converting the long altimeter record into a record of Oyashio transport.

Causes of SST variation: The region of maximum anomalous extratropical low-frequency large-scale SST variability extends roughly from 150°E to 160°W and 35°N to 45°N. The western part of this region includes the Kuroshio-Oyashio extension (KOE) that figures prominently in theories of decadal variability. PBECS must learn the processes that control SST evolution in this key region of the Pacific Decadal Oscillation (PDO), which will be difficult. The Kuroshio Extension System Study (KESS) is a process experiment focused in the KOE that can provide a foundation for understanding the complicated oceanic processes that change SST in the KOE. Farther east, the processes are evidently simpler and the scales larger, so design of a measurement array should be simpler. Yet to be learned is where SST is determined mainly by air-sea fluxes forcing one-dimensional mixed-layer processes, where large-scale currents contribute to SST anomalies, and how thermocline depth affects these. By combining various observational methods (TOPEX, moorings, tomography, in situ temperature and salinity profiles, etc.) it will be possible to devise an array from which we can learn, for example, if SST anomalies are formed in the KOE near the coast and then extend eastward under the force of ocean advection or by a coupled air-sea process.

It is recommended that the KESS array were supplemented with an eastward extension of buoys since it is localized in the eddying region of the KOE. These would focus on air-sea fluxes, elements of one-dimensional processes in the mixed layer, thermocline structure, and horizontal advection. The OWS P site (50°N, 140°W) is one of the few places in the open ocean with a multi-decadal record of upper ocean and air-sea flux observations, but the frequency of modern sampling is barely seasonal. Sustaining an observing effort at this site will provide the ability to understand how conditions in the first decade of the new millennium compare with those during the 1970s. A site NNW of Hawaii (35°N, 165°W) is recommended, near the maximum of PDO SST variability, where it could serve as a surface reference site. Maintenance of these sites and addition of new ones connecting them to the KOE will be very helpful to PBECS modeling and data assimilation studies while we await KESS results to design a full monitoring array.

Atmospheric sensitivity to KOE SST anomalies: Long-term surface heat-flux measurements are crucial for establishing ocean- atmosphere feedback processes on decadal timescales. KESS can help, but additional heat flux buoys would make important improvements. Although it is unclear how mid-troposphere atmospheric observations can be made for these timescales over the KOE region, they should be attempted to determine the heating rates and vorticity balances. A 1-year or one-winter process study of atmospheric response in this region would be an excellent way to validate the NCEP/ECMWF analyses; this type of experiment will have added benefits of improving weather and climate forecasting for Japan and the U.S. Downstream feedbacks under the Aleutian Low may also be important in the decadal feedback loops.

The Kuroshio-Oyashio system

As discussed above, describing the large variations of SST in the Kuroshio-Oyashio Extension (KOE) and the causes of these variations is central to understanding climate feedbacks in the North Pacific. In addition to interannual changes in the energy level of the mesoscale eddy field, both the Kuroshio and the Oyashio undergo large-scale variations in their path and transport on the interannual-to-decadal timescales which can be regionally and/or remotely driven by wind and buoyancy forcings. They may also be a result of self-sustained, internal ocean dynamics associated with the recirculation gyres of the WBCs. The KOE region can be separated into three sub regions: the recirculation region south of the Kuroshio Extension, the Mixed Water Region (including the Oyashio) to the north, and the Kuroshio Extension itself. Although these three regions are contiguous, they have distinctly different processes governing the regional SST changes.

Kuroshio Extension variations: North-south excursion of the Kuroshio Extension (KE) causes SST anomalies. Both the eastward surface transport of the KE and its zonal-mean position change coherently on the annual and interannual timescales and appear to be related to the strength of the southern recirculating flows of the current system, which may be determined by the following processes: (1) modulation of meanders and mesoscale instabilities, (2) changes in regional buoyancy and wind-forcing (Huang, 1990), and (3) changes in Pacific basin-scale (remote) forcing, exerted through the inflow of the upstream and Kuroshio, and/or through Rossby waves downstream (Qiu and Miao, 1999).

Recirculation gyre and subtropical mode water: SST in the WBC outflow region can also be influenced by changes in the mixed layer structures and by the entrainment from below the mixed layer. Changes in the WBCs can impact subduction through mode water formation, and the mode water can serve as a sequestered reservoir for SST changes in subsequent winters. We need to quantify the relative importance of the following terms: advected temperature anomalies in Kuroshio as basin-scale gyre strength varies; anomalous advection of heat by recirculation south of the KE; variations in net surface heat fluxes (atmosphere driving ocean); and changes in mixed layer temperature by vertical entrainment from the slowly varying Subtropical Mode Water reservoir.

Mixed water region (or KOE region): Decadal/interdecadal climate signals are strongly manifested in the Mixed Water Region to the north of the Kuroshio Extension (Nakamura and Yamagata, 1999) and have corresponding subsurface temperature signals associated with the thermocline variations (Watanabe and Mizuno, 1994; Deser et al., 1996; Miller et al., 1998). However, it is not clear how the SST and subsurface temperature couple with each other. The following processes can drive SST variations in the Mixed Water region: thermocline shoaling/deepening associated with wind-driven spin-up; anomalous Oyashio intrusions due to wind-driven spinup and/or anomalous density-driven current component; SST advection by time-varying Ekman transport; anomalously large cross-front exchange from ring-formation and meanders that brings near-surface warm waters to the mixed water region.

Kuroshio-Oyashio Observations: Enhanced monitoring and process-oriented studies in the WBC outflow region are crucial to understanding the Pacific decadal variability: how the ocean and the atmosphere are coupled and what determines the SST anomalies on interannual-to-decadal timescales. Diagnosis of the heat budget for the long-term SST changes in the KOE will depend on measurements of the oceanic state and of surface heat fluxes. These should be made for multiple years, covering several of the winter seasons when the air-sea coupling is most active. They should encompass the WBCs, their neighboring recirculation gyres, and the region to the east of the KOE where decadal variability is strong. All of the large-scale sustained measurements in PBECS (e.g., satellites, VOS, floats and gliders, drifters, and moorings) could be used for this. But how to proceed, and how elaborate a system will be needed, is not yet clear.

For the foreseeable future, in-situ process-oriented observations in the WBC outflow region are recommended that would provide: (1) true mesoscale resolution as needed to understand the physics of strongly coupled barotropic-baroclinic eddies and associated cross-frontal structures and to help improve parameterizations in climate models, (2) measurements of the vertical structure of the recirculation gyres as needed to distinguish barotropic and baroclinic circulation changes and changes in the heat content, and (3) results from intensive observation systems that can be used to design long-term affordable observing systems for the highly nonlinear, complicated regions. An international process experiment planned between the U.S. and Japan, called the Kuroshio Extension System Study (KESS), may provide some of the high-resolution observations needed to design a sustainable observing system and is described later (Section 9).

<u>The southern subtropics</u>

The South Pacific subtropical gyre has strong interest for PBECS for several reasons. First, patterns of flow from the south are responsible for establishing characteristics of equatorial current systems (e.g., Johnson and McPhaden, 1999), and, therefore, may modulate the background upon which ENSO evolves, and they are the source of the cross-equatorial transport needed to balance the Indo-Pacific throughflow. Second, there are substantial hemispheric symmetries and asymmetries in the circulations of the North and South Pacific that are important elements of describing and understanding climate variability in the Pacific basin as a whole. Finally, the South Pacific has substantial internal variability on long timescales that are suggested (Sprintall et al., 1995; Peterson and White, 1998) to affect climate on regional or global scales.

Equatorward interior flow in the southern subtropical thermocline is split into two parts. Waters east of 95°W at 20°S directly feed the Equatorial Undercurrent in the central Pacific (Johnson and McPhaden, 1999, Fig. 1) while west of 95°W the equatorward flow feeds the western boundary current system. Approximately equal volumes of thermocline water follow the two pathways, but variability in the system is poorly known and further study is warranted.

The southwestern Pacific is an integral part of the climate puzzle of the Pacific Ocean as a whole but little is known about variability of the strong currents. There is presently high-resolution VOS sampling that crosses the East Australia Current near Sydney and Brisbane and crosses the East Auckland Current north of New Zealand on an approximate quarterly basis. Continuing these lines, and extending their depth and salinity coverage with occasional XCTDs and 2000 m XBTs, would be a significant step toward documenting the role of these boundary currents in climate variability. Reducing the aliasing of climate signals by short-term variability would substantially increase the value of these data. This could be done with glider sampling along the three XBT transects, extending from the shelf break out 500 km and sampling roughly once every 3 weeks. If possible, this sampling should include occasional transects upstream and downstream of the primary lines.

The Eastern Pacific

The eastern tropical and subtropical Pacific is the site of persistent stratiform clouds in the atmospheric boundary layer that are not well modeled and have an important influence on seasonal and interannual climate. The largest SST variability during ENSO is found in the eastern Pacific and yet we do not understand the heat budget of the cold tongue during either seasonal or ENSO cycles. Perturbations from El Niño events are seen to propagate along the eastern boundary toward higher latitudes, but the classical model of Kelvin waves serves to explain only a small part of this variability. Neither is the impact of interannual variability along the subtropical coasts to the adjacent landmasses understood. For these reasons and others, the eastern part of the Pacific must be included as a special region within PBECS.

Air-Sea coupling in the eastern Pacific

The climate of the eastern Pacific boundary current regime off the tropical west coasts of Central and South America consists of several related regimes: the subtropical southeast Pacific regime characterized by southeasterly trade winds, cool water, and extensive decks of boundary layer stratiform clouds, the eastern Pacific warm pool regime off the west coast of Mexico and Central America, and the cold-tongue/ITCZ complex (CTIC) in the equatorial region from 10°S to 10°N. Each phenomenological regime is an important component of the Pan-American monsoon system with significant effects on the climate and weather in Mexico, Central America, and along the west coast of South America. Climate variability in the region is a mixture of strong seasonality created by the Pan-American monsoon and the basin-wide variability of ENSO (Wallace et al., 1989; Deser and Wallace, 1990).

Because the atmosphere's intrinsic predictability time is so short, much of prospective climate predictability around the eastern tropical Pacific, as elsewhere, depends on forcing at boundaries that has the system's memory. The prediction of rainfall over the Americas, the response to ENSO anomalies, and the varying evolution of different ENSO cycles are all climate phenomena that are believed to be influenced by SST distributions in the eastern tropical Pacific. Coupled ocean-atmosphere simulations of the annual cycle of SST and other key climate processes are deficient in the eastern boundary current regime (Mechoso et al., 1995) and questions remain to be answered, including: (1) in the shallow mixed layers of the eastern Pacific warm pool, what is the relative importance of air-sea interaction and upper-ocean processes in setting the eastern Pacific warm-pool SST, (2) what is the reason the annual appearance of cool water in the CTIC, extending westward from the coast of South America along the equator, especially when the sun-earth orbital geometry , and (3) what are the possible feedbacks between the boundary layer stratocumulus clouds and the ocean?

Observing the Eastern Pacific

The eastern Pacific is one of the most data sparse areas over the global ocean. PBECS observations will make substantial contributions to understanding air-sea coupling in the eastern boundary current regimes in the following ways:

Upper-ocean temperature and salinity. PBECS increases in sampling the large-scale temperature and salinity structure of the eastern Pacific are critical to understanding the phenomena of interest. By better defining currents and heat storage, these data will make it possible to validate coupled ocean-atmosphere models and to sort out the mechanisms responsible for the warm pool, subtropical Southeast Pacific, and CTIC phenomena.

SST and surface currents. Stratocumulus clouds cover much of the eastern boundary current regime. In situ observations are sparse, and infrared satellite measurements cannot "see" the sea surface. Surface drifters will provide essential regional "calibration" data for both infrared and microwave satellite SST retrievals. The same drifters will provide direct observations of the surface currents associated with advection of upper ocean heat and SST. Augmentation of current measurements on TAO moorings will add valuable time-series data on upper-ocean currents and the effect of advection on SST.

Wind stress and fluxes. Presently, the primary sources of data for estimating wind stress and air-sea heat flux in the eastern tropical Pacific are TAO moorings, VOS, and satellites. The in situ observations have inadequate spatial resolution to define wind-stress and surface flux features that are important to the structure and variability of the region, while NWP analyses of heat flux have large biases and inadequate resolution. Continuation of satellite scatterometers and microwave wind measurements is therefore essential, as are the PBECS efforts to improve analyses of stress and surface fluxes.

Assimilation studies. PBECS can support understanding in the eastern tropical Pacific by increasing observations and understanding of the ocean-atmosphere processes responsible for the structure and evolution of the large-scale atmospheric heating gradients in the equatorial and northeastern Pacific portions of the cold-tongue/ITCZ complex. Hopefully, the PBECS approach of long-term observations integrated within a model framework will contribute toward this both directly and by providing a framework inside which process experiments can be particularly effective.

Planetary boundary layers. Progress in understanding air-sea coupling in the eastern tropical Pacific depends on observations and understanding of the dynamical, radiative, and microphysical properties of the extensive boundary-layer cloud decks in the southeasterly trade wind and cross-equatorial flow regime, their interactions with the ocean below, and the evolution of the upper ocean under the stratocumulus decks. These are currently being explored inside the EPIC process studies, which will study the atmospheric boundary layer, upper ocean, and convection along 95°W in 2001.

Plans. Three additional TAO moorings will be deployed along 95°W in 1999-2000 and the surface meteorology on these and other 95°W TAO moorings will be upgraded. Beginning in Fall 2000, a surface mooring to measure surface fluxes of heat, freshwater and momentum, and high vertical resolution upper ocean currents, temperature and salinity will be deployed under the stratocumulus cloud deck. The first year of data from these deployments will be used to examine the extent to which local air-sea interaction explains the evolution of SST and upper-ocean structure, cloud-SST feedbacks, and the extent to which existing coupled models can replicate this evolution. Based on what is learned from the comparison of models and new observations in 2000-2001, more detailed field studies may follow in 2003 or later. More surface moorings will be deployed along the South American west coast by Peru (funded) and Chile (planned). This emerging effort should be coordinated with PBECS and the long-term components included into PBECS growth.

The California Current System

Meridional current systems are observed along all of the west coast of all of the Americas. Within these circulation features are strong upwelling and downwelling centers that exchange ocean properties vertically. These currents and their poleward undercurrents are also the conduits of information and exchange of ocean properties over great distances between the tropics and the subpolar gyres. They are not steady circulation patterns, with mesoscale eddies and seasonal, interannual, and decadal time scale variations.

Observing the subsurface climate signal in the California Current system requires sampling that does not alias the large mesoscale eddies. The CalCOFI program carries out quarterly surveys of the southern California Bight with 100-300 km longshore resolution. Quarterly monitoring lines, with higher offshore resolution, have been established westward off the coasts of Monterey Bay, Oregon, Vancouver Island, and southward from Anchorage. High-density XBT lines cross segments of the eastern boundary current system on great circle routes between Hawaii, Los Angeles, San Francisco, Anchorage, and Peru. PBECS could, in cooperation with other programs concerned with the California Current System, further enhance observations in two specific ways to understand climate variability: First, it is proposed that an array of 5 moored, air-sea interaction buoys carrying a standard set of ocean and atmosphere observations be established between Vancouver Island and Baja California, Mexico to examine local forcing, local subsurface response, and also to ascertain whether, and how much of, the subsurface signal propagates northward by ocean dynamics, and how much by direct air-sea interaction. Secondly, autonomous gliders would occupy hydrographic sections at the same latitudes as the buoys and at additional lines placed between the buoys, for a total of up to sixteen sections. These sections would provide a more complete view of the temporally and spatially evolving subsurface field. Eventually, bio-optical observations could be added. The details of the field program are under development.

Southeast Pacific Ocean boundary currents

Over a large region off the west coast of South America, very low SSTs are associated with prominent decks of stratus and stratocumulus clouds. This association suggests a positive feedback mechanism for ocean-atmosphere coupling. If the positive feedback is essential to the maintenance of the stratus decks, then the system may be sensitive to external perturbations. Understanding the factors that contribute to the cold SSTs (including surface fluxes and offshore advection of cold upwelled water), as well as the factors that allow the formation of stratus decks (the strong subsidence inversion that caps the layer, and the vertical distribution of water vapor) is important to investigating this coupling feedback and its role in climate.

Coastal upwelling is prominent off the coasts of Peru and Chile because the coast is aligned with the low-level Hadley circulation winds (the height of the Andes close to the coast probably contributes to this alignment). Some of this upwelling may contribute to evolution of the equatorial cold tongue through advection of cold upwelled water from the coast towards the equator in the South Equatorial Current (Reverdin et al., 1994). A strong seasonal cycle has maximum equator- ward wind and minimum sea surface temperature (SST) in Austral winter. The upwelling raises shallow thermocline waters at the coast, which are then advected offshore by the Ekman flow. Of course, there is also strong interannual variability in SST, with significant warming during El Niño, even while the equatorward winds that drive the coastal upwelling off South America persist. This SST modulation could be accomplished in the face of upwelling-favorable winds through a deepening of the thermocline during El Niño, so that warm water is upwelled instead of cold, and/or by a strengthening of the offshore meridional surface pressure gradient so that geostrophic flow toward the coast opposes Ekman flow away from the coast (Huyer et al., 1987). The current system offshore of the continental shelf probably provides cold water for the upwelling and may also provide a significant route for oceanic equatorial to subtropical teleconnections. The Peru Undercurrent (PUC) flows rapidly (18 cm s^{-1}) poleward, and water mass analysis suggests that the PUC is fed by the equatorial undercurrent (Lukas, 1986).

The Peru-Chile Countercurrent (PCCC) is a larger poleward surface flow, located between 100 and 300 km offshore that (Strub et al., 1995, 1998) appears to be supplied with cold water from the southern subsurface countercurrent, an eastward jet on the south flank of the deep equatorial thermostad (Tsuchiya, 1985; Johnson and McPhaden, 1999). Its transport is twice that of the southern equatorial subsurface countercurrent (Rowe et al., 1999) and sufficient to supply all coastal upwelling poleward of 15°S (Strub et al., 1998). This magnitude is also significant from a general circulation standpoint, being half that of the interior ocean equatorward flow in the South Equatorial Current (Johnson and McPhaden, 1999). The PCCC could be a significant route for mass, heat, and freshwater exchange from the equatorial regime to the subtropics, the only other being poleward Ekman transport. The upwelling, PUC, and PCCC vary with season and phase of ENSO and have sufficient scale and magnitude to play a significant role in the basin-wide climate system. Because of its origin near the coast and its narrow offshore scales, assessment of the upwelling, its source waters, and its role in air-sea coupling will require a targeted array of in situ measurements, as will any attempt to quantify the potential equatorial to subtropical ocean route for mass, heat, and freshwater fluxes in the PUC and PCCC. The broad interior-ocean coverage provided by satellites and Argo profiling floats will not resolve these features. A minimum observational array for PBECS should allow determination of the sources of the upwelling, and the poleward fluxes of mass, heat, and freshwater in the PUC and PCCC. It would resolve variability of the system on seasonal timescales.

An array to observe the ocean components of this climate system should augment the surface moorings and improved VOS for air-sea interaction studies and coastal mooring array planned by Peru and Chile. Additional ocean observations would be an appropriate combination of high resolution XBT/XCTD sections, autonomous CTD gliders sections, and current and temperature measurements on available moorings. Up to three glider sections perpendicular to the coast between 5°S and 25°S would allow study of upwelling along the coast, and assessment of the current magnitudes and variability from the equator into the subtropics. Steep continental slopes here allow gliders to approach close to the shelf break while profiling to about 1000 m. A horizontal glider speed of 20 cm s^{-1} would allow a 300 km section with 5-10 km horizontal resolution to be made in 17 days. Sections would be subject to noise from internal tides and waves; this might be reduced by temporal filtering of records from the slowly moving vehicles or perhaps by using glider pairs to allow geostrophic shears to be calculated between simultaneous profiles. Sections might also be subject to aliasing by coastally trapped waves that are energetic in the 8-11 day band

(Cornejo-Rodriguez and Enfield, 1987), but this could be reduced using filtering that exploits the nonuniform sampling intervals associated with alternating sampling directions, and coherent filtering using altimetric records and data from a few moored current meters to define space-time patterns of variability.

9. Process Experiments

The interannual and decadal variability that is the focus of PBECS cannot be understood and predicted (Lorenz, 1969) without an understanding of higher frequency processes. It is, therefore, necessary to perform focused experiments to examine these processes and build parameterizations for inclusion in models, including assimilating models. A sequence of process experiments is an important adjunct to PBECS and an essential component of Pacific CLIVAR.

The focus of the process experiments is the shallow (less than 1000 m) meridional overturning circulation that links the subtropical and equatorial Pacific. The meridional circulation can be considered very broadly to have four components: (1) the movement of surface water downward out of the mixed layer in mid-latitudes, (2) equatorward geostrophic flow to the tropics, (3) upward transport to the surface near the equator, and (4) near-surface poleward flow in boundary and wind-driven currents. PBECS monitoring is designed mainly to quantify the equatorward (2) and poleward (4) branches of the meridional cell. Process experiments are suggested for all four of the branches to complement PBECS.

Consider the first branch of the meridional cell, the subduction of surface water in the sub-tropics. Atmospheric conditions are imprinted on the ocean as temperature-salinity anomalies at mid-latitudes. A key issue to be addressed by process studies is the generation of these anomalies. The T-S anomalies are then subducted into the ocean's interior, acting as a record of past atmospheric conditions. The process of subduction is itself dependent on air-sea fluxes. Annual and interannual variations of mixed-layer depth are crucial (Stommel, 1979), as are wind-driven flows. Process studies are needed to clarify the vertical structure of turbulent fluxes of heat, salt, and momentum in the upper ocean as anomalies are formed. After being subducted, anomalies of both PV and T-S properties are propagated by some combination of advection, wave dynamics, and eddy fluxes. Issues to be addressed in process studies are the rates of dispersion and dissipation along equatorward pathways. One critical element of this question is how anomalies are propagated and/or generated along western boundaries, particularly where low latitude interior currents bifurcate at the western boundary. A process study in the bifurcation of the North Equatorial Current would help to both understand the role this process plays in climate variability and to improve models of western boundary currents.

The third branch of the meridional cell involving upward fluxes near the equator has been poorly observed. Upon reaching the equator, the water that originated at the surface in mid-latitudes is finally upwelled. Quantification of this upwelling is an important goal of a process experiment. The upwelled anomalies affect sea-surface temperatures and thus are important in the equatorial ocean-atmosphere system. Such T-S anomalies have been observed to influence the atmosphere in coupled general circulation models, but the observational basis for understanding the process is weak and deserves attention. Particularly in equatorial latitudes where vertical gradients and shears are strong, diapycnal mixing clearly supports important vertical fluxes. Process studies with the goal of improving mixing parameterizations need to quantify the internal wave spectrum at low latitudes, evaluate the role of salt fingers, and resolve daily cycles.

The overturning cell's fourth, poleward, branch involves wind-driven currents in and just below the mixed layer. Better understanding these flows will help to improve the design of the monitoring observations for PBECS. For example, a better quantification of the vertical structure of wind- driven currents will aid in designing the program to measure near-surface velocity and the Ekman heat transport, which is greatly affected by the depth to which the currents penetrate.

Process experiments will benefit from the monitoring and assimilation activities in PBECS. The processes occurring along the meridional circulation have all, to some extent or another, been observed. In all of the cases summarized below, we have a clear idea of the problem to be solved. The technology to solve the problem is also in hand. What has often been lacking in past attacks on climatically relevant local processes is the simultaneous observation of the large-scale ocean. For example, the Subduction Experiment in the North Atlantic in 1991-1993 focused on the equatorward branch of the meridional cell. Detailed observations of the process of subduction were made, but it was difficult to relate them to basin-scale conditions. A great advantage of embedding process experiments in PBECS is the very existence of the broad-scale observing system, which will allow scientists to make the connection between local processes and climate.

The process experiments, discussed in more detail below, have as their overarching goals to improve parameterizations for use in models and to aid the design of the observational system. We anticipate that small groups of scientists will form to develop and carry out these experiments during the 15-year PBECS time frame. In the following, we simply highlight scientific objectives of importance to climate.

Diapycnal fluxes in the daily cycle below the equatorial mixed layer

Accurate estimation of sea-surface temperature (SST) is essential for realistic climate predictions, and nowhere is it needed more than on the equator. For example, Wang and McPhaden (1999) studied the seasonal heat balance in the equatorial western Pacific and found that the surface-layer balance results from a "complex interplay between surface fluxes, advection, and mixing." Their residual heat flux, representing the sum of turbulent entrainment at the layer base and downward heat diffusion, had the same magnitude as the net surface heat flux less the penetrative flux passing through the layer. When predicting climate, the mixing component cannot be calculated as a residual. Instead, it must be calculated from other variables in numerical models.

Owing to its recognized importance, near-surface mixing has been studied intensively on the equator during several process-oriented programs: TROPIC HEAT, TOGA/COARE, and TIWE. All of these have found surprisingly different average mixing levels resulting from changes in the intensity of a daily cycle of mixing in the stratified water below the surface layer (Gregg et al., 1985; Moum and Caldwell, 1985). A daily cycle of finescale shear variance and small-scale internal variability accompanies the mixing cycle, and this is not fully understood. It is clear, though, that: (1) diapycnal fluxes produced by stratified turbulence below the equatorial surface layer must be parameterized for use in climate models; (2) no satisfactory parameterization exists; even the mechanisms responsible are not agreed upon and it may not be possible to parameterize the mixing adequately with variables now in climate models. (3) further piecemeal work by individual investigators, whether cruises or models, is unlikely to converge on accepted answers soon enough for climate modeling; instead it is recommended that developing satisfactory methods for including deep-cycle fluxes into climate models requires oversight from a CLIVAR working group on models and process experiments. Such a working group could be charged with developing coordinated numerical studies, process experiments, and monitoring upon which to base flux representations. This would put necessary focus into the exploration of ocean mixing studies.

Understanding and parameterizing diapycnal mixing at low latitude

Three processes are known to produce diapycnal fluxes in the upper kilometer of the open ocean: breaking internal waves, salt fingers, and thermohaline intrusions. Of these processes, breaking internal waves are the most common and the best understood. However, how diapycnal diffusivity from breaking internal waves behaves at low latitudes is not well understood. Owing to the importance of low latitudes in modulating climate, process experiments to parameterize mixing rates there are recommended. Comparison of microstructure levels with K from a tracer release should be included in at least one program measuring low-latitude microstructure and internal waves. Significantly faster thickening of the tracer would indicate that salt fingers are important and their fluxes should be included in models. Thermohaline intrusions, particularly salt-stabilized temperature inversions, are common near fronts and are found to some degree nearly everywhere. They are often observed sloping across isopycnals and often contain signatures of double diffusion, but neither their generation nor their evolution is understood. Owing to the large magnitudes of thermohaline intrusions in equatorial fronts and apparently low levels of background mixing, intrusions may dominate diapycnal fluxes at low latitudes, even though they do not always contain strong microstructure. We cannot be confident of flux parameterizations until the contribution of intrusions are evaluated, and such an experiment should be one of the Pacific CLIVAR process studies.

Kuroshio Extension System Study (KESS)

The scientific goal of KESS is to clarify how SST anomalies in the Kuroshio-Oyashio outflow regions in the midlatitude North Pacific Ocean are created and what dictates their spatial and temporal evolution. The scientific objectives and justifications are expounded in Davis et al. (2000). At present, 14 PIs from 5 U.S. universities or research institutions are in the process of putting together a collaborative proposal to be submitted to NSF-OCE on August 15, 2000. The KESS project is for a 5-yr period and involves a variety of in-situ instruments, satellite measurements, numerical modeling, and data assimilation. It is a joint project with Japan, and Japan KESS is already funded by STA. JAMSTEC is at present deploying a test TRITON buoy and other moored instruments at the KESS site.

The following observational elements are now planned:

KE and recirculation dynamics. High-spatial-resolution current, temperature, and salinity measurements would be collected to study variability of the inflow, eddy-mean interaction, recirculation dynamics, and cross-frontal exchange. An eddy-resolving array combining moorings, inverted echo sounders, acoustic tomography, and RAFOS floats is planned to achieve this ambitious goal. Concurrently, longer-term analyses of satellite SSH observations would be combined with in situ current observations and tomographic measurements on larger scales to observe the strength and heat content of the recirculation. Regional wind and buoyancy forcing estimates are needed, and NCEP (or other) fields must be calibrated by in situ meteorological buoys.

Upper ocean heat budget. Simultaneous in situ measurements of the thermocline depth, integrated heat content, and SST are clearly needed. Lateral/vertical entrainment processes should be measured at the base of the wintertime mixed layer. By assimilating in situ and satellite observations into an ocean circulation model, the mechanisms and the accuracy of the model's heat budget would be evaluated. Time series of satellite and in situ measurements would also be used to estimate the heat budget. KESS aims to elucidate the processes going on in this complex region so that affordable monitoring systems can be designed. In the meantime, PBECS scientists should consider, in cooperation with Japanese scientists, if there are augmentations to the KESS array that would significantly increase its utility for climate studies, such as surface heat fluxes.

EPIC (2000-2004)

The goal of the Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System (EPIC) is to better document and understand physical processes controlling coupled interactions in the Eastern Pacific. It relies on and includes some parts of the sustained, focussed sampling in the region discussed earlier. It also consists of two process study phases, the first centered around the EPIC2001 field experiment surveying the dynamics of the stratus-cold tongue-ITCZ complex and the underlying ocean in the E Pacific, and a second phase to concentrate on possible interactions between the marine boundary layer and South America on a variety of timescales.

EPIC2001, the first field phase of EPIC in Aug-Sep 2001, will focus on cross-equatorial boundary layer flow, initiation and organization of deep convection in the ITCZ, Southeastern Pacific stratus cloud along 95°W, and feedbacks of these processes on the ocean. The Science Plan was submitted to NSF, and bundled proposals submitted to NSF February 15, 2000. Considerable NOAA investigator involvement and facilities support is involved, and NOAA is supporting sustained monitoring activities (including additional TAO buoys at 95°W and a surface flux reference site with oceanographic instrumentation for 3 years at 85°W, 20°S). It is recommended that after the initial pilot deployment of ARGO floats in the southern tropical Pacific for PBECS, the next priority for float deployment should be the EPIC region (between 20°S-20°N and east of 110°W) if this can be done prior to August 2001. This would considerably improve monitoring of broad scale subsurface structure.

EPIC Phase II (2003?) is being planned as a month-long study (joint with the Pan American group and VAMOS and international partners) to look at possible covariations and feedbacks between stratus cloud and boundary layer properties and deep convection over the South American continent. Deep convection might impact the stratus through modulation of compensating subsidence and/or free-tropospheric humidity/temperature. If this affected the radiative cooling within the PBL, it would affect the strength of the subtropical high, near-coastal winds, and coastal upwelling, which might on longer timescales feed back on the convection. Diurnal through synoptic timescales of variability could be addressed in such an experiment. South American Pacific Rim countries might provide considerable support; San Felix Island off Chile and ships could provide measurements of horizontal divergence and cloud/boundary layer structure. Coastal and mountain stations would help quantify orographic flows and feedbacks. More preliminary study is still needed to identify whether the stratus/convection link is clear enough to be of major climate importance. This will be done using data from EPIC 2001.

Generation of subducted temperature-salinity anomalies

The downward branch of the meridional circulation involves the subduction of mixed-layer water in the subtropics. Subduction is an important element in global ocean-atmosphere interaction. The surface layer of the ocean exchanges heat, fresh water, and gases with the atmosphere. This exchange stops once the surface water is subducted into the interior of the ocean, and the properties set by the atmosphere are carried away with the water. In this way heat and greenhouse gases, for example, are sequestered in the ocean. The properties thus set in the mixed layer and subducted into the geostrophic interior act as an effective tracer of ocean circulation and a record of past atmospheric conditions. A clear understanding of this downward branch of the meridional cell is crucial to our ability to predict climate.

The main focus of a process experiment on the downward branch of the meridional cell is to determine how temperature-salinity anomalies are created and injected into the geostrophic circulation. While it is clear that these anomalies are due to atmospheric forcing, the mixed layer is an energetic region in which the anomalies are stirred and mixed before they pass into the deeper geostrophic ocean. A process experiment is recommended with the objectives of observing and quantifying: (a) initiation of anomalies due to atmospheric forcing; (b) evolution of anomalies through stirring and mixing in the mixed layer; (c) propagation of anomalies from the mixed layer to thermocline; and (d) decay of anomalies in the thermocline. The observational capabilities already exist to address these objectives. It is possible to measure air-sea fluxes, horizontal and vertical structure of the mixed layer and thermocline, and turbulent mixing. The challenge of this experiment is that it is truly three-dimensional: both vertical and horizontal processes are crucial. The experiment is based on well-established theory, and theory is required in the context of this experiment to develop parameterizations for use in numerical models. The experiment will benefit greatly from the existence of PBECS monitoring; after anomalies have been tracked down into the geostrophic circulation, they can be handed off to Argo floats to follow their long-term propagation.

Processes of subtropical-tropical exchange

After they are subducted, it is unclear how anomalies are transported from the subtropics to the tropics. Variable subtropical-to-tropical exchange has been conjectured to induce decadal variation in low-latitude stratification and, in turn, the character of El Niño events, as discussed above. The modification of meridional exchange can be manifested as meridional mass transport anomalies, meridional heat transport anomalies, and/or meridional transport of potential vorticity (PV) anomalies. These are all related in one way or another to variations in air-sea heat, buoyancy, and momentum fluxes. A process experiment is envisioned within the large-scale PBECS observing system to explore the physics of the time-varying subtropical meridional overturning cell. The experiment would observe the evolution of a PV anomaly as it moves south in the low latitude central North Pacific to, and through, the thermocline ridge marking the boundary between the NEC and NECC at about 10°N. The specific objective would be to tag a PV anomaly and measure the rates at which the anomaly is dispersed and dissipated as it translates equatorward. The long-range goal of the study is improved understanding of how off-equator PV anomalies influence low-latitude sea-surface temperature. Of particular interest is how mixing influences the water passing through the PV barrier driven by upwelling at the ITCZ. Quantification of mixing within the upper Pacific Ocean's subtropical-tropical meridional overturning cell is needed to link dynamically the large-scale circulation observations of PBECS to the dynamics of low-latitude stratification change, SST variations, and decadal ENSO variability.

North Equatorial Current bifurcation study

Important pathways from subtropics to tropics involve low-latitude western boundary currents. The physics of western boundary currents are extremely complex, and present climate model resolutions are too coarse, and parameterizations too crude, to give confidence in the results of numerical experiments involving advection and mixing in this regime. Sparse enhanced monitoring of this regime will not provide a sufficient basis to improve models, nor will they overcome deficient model physics during data assimilation analyses. For PBECS, it is crucial to obtain accurate analyses of the cross-gyre exchanges that occur primarily in the western tropical Pacific when the North Equatorial Current (NEC) encounters the Philippine coast and splits into the Kuroshio and Mindanao Currents. The bifurcation of the NEC is affected by remote forcing from the interior of the Pacific and from the north along the western boundary, by local wind and buoyancy forcing, and by mesoscale eddies. The correct modeling of the interaction of these processes is essential to the correct modeling of the western boundary currents of the North Pacific. An intensive process study is required to provide the observational basis for assessing existing models, for improving deficiencies, and for determining the minimum long-term observing elements needed to support accurate analyses.

Equatorial upwelling and the emergence of subtropical anomalies

Equatorial upwelling is the choke point of the meridional overturning circulation, where much of the water subducted into the geostrophic flows of both subtropical gyres emerges to the surface. Once upwelled, this water interacts with the atmosphere, and coupled feedbacks can occur because of the sensitivity of equatorial winds to SST gradients. The poleward Ekman divergence of upwelled waters can also be a vehicle for interhemispheric exchange. Since it is not feasible to directly measure vertical velocities for sustained periods, monitoring this feature of the overturning circulation must ultimately be conducted through models constrained by assimilated data of diverse types, probably including horizontal velocities and water properties. A principal goal of a process study should be to learn what proxy observations will be most useful for inferring upwelling and its role in the overturning circulation within such data-assimilating models. The second purpose is to use an intensive observing period to investigate the processes by which upwelling influences equatorial SST, either through changes in vertical velocity itself, or of the thermocline stratification that affects the properties of the upwelled water. The third goal is to observe the sensitivity of the coupled feedbacks to the path and emergence region of advected anomalies, and the signal sizes of these emerging anomalies compared to internal tropical variability.

The process study will require simultaneous observation of winds and surface radiation fields along with vertical profiles of u, v, T, and S at a spatial resolution fine enough to distinguish the effects of horizontal versus vertical advection, mixed layer deepening and entrainment, and heating due to penetrative solar radiation. Ideally estimates of rainfall (probably from satellites referenced to moored rain gauges) would add the ability to confirm the processes deduced from the temperature balance with a salinity budget. Since we have only rather general ideas about the zonal or meridional scales on which upwelling takes place, an array of velocity moorings to measure divergence of the horizontal velocity components (which could also be sampling temperature, salinity, and winds) would likely require on the order of ten sites, in order to be able to take derivatives over a variety of separations and to span the region over which upwelling takes place (±3° latitude). Because much of the Ekman flow occurs in the upper 25 m that is poorly sampled by acoustic current profilers, deployment of point current meters at 10-15 m depth on several TAO picket lines would greatly contribute to our ability to understand the wind-driven divergence that drives upwelling. If, in the course of the PBECS program, a particular low-frequency subducted thermal anomaly is identified and is predicted to emerge in the equatorial upwelling regions, a study that goes beyond the standard PBECS observations should be mounted to examine how it emerges. This would provide an observational basis to test the ideas and hypothesis about the coupled response to emergent anomalies.

Vertical structure of horizontal currents

Determination of ocean circulation within PBECS will depend largely on an essentially geostrophic methodology using temperature and salinity observations under the constraints of hydrodynamic models. The upper ocean, as demonstrated by shipborne ADCP observations (Chereskin and Roemmich, 1991; Wijffels et al., 1994), however, is not in geostrophic balance. The ageostrophic circulation extends well below the temperature mixed layer. Models used to describe this upper ocean circulation parameterize mixing processes that have been well observed in the planetary boundary layer, or mixed layer (Large et al., 1994). Existing models of upper-ocean mixing do not adequately parameterize the transition of vertical diffusivity from the geostrophic thermocline circulation to the ageostrophic surface layer. This is because observations of the forcing of the three-dimensional structure of the upper ocean currents, together with the baroclinic density structure, have not been made in any mixed-layer experiment.

A complete horizontal momentum, heat, and salt budget experiment of the upper ocean would provide the data set needed to unravel the mixing process below the mixed layer. In such an experiment the pressure gradients and Coriolis forces could be separated and the vertical convergence of turbulent momentum fluxes would be isolated. This experiment is now possible because of autonomous techniques for measuring temperature and salinity, and ways of profiling ocean currents with individual moored instruments or moored acoustic profilers. The uncertainties of in situ air- sea flux estimates have been reduced five fold in the past 10 years so that heat and salt budgets below the mixed layer are now feasible. No longer do we need to measure heat content change to check the surface flux in tropical conditions. Accurate estimates of motion and fluxes in the upper ocean are required to achieve the PBECS objectives and this will require improvements of models of upper ocean mixing between the mixed layer and the main thermocline. Connecting satellite altimeter data to Argo subsurface observations also requires understanding the transition of dynamics in this region. The tropical current system south and east of Hawaii has a significant difference between geostrophic currents, which flow to the southeast, and the observed mixed layer circulation, which is to the north and west. This tradewind driven system is a prime candidate for study and would be a test bed for the methodology of the PBECS data and models.

10. Context

It is important to acknowledge that CLIVAR Pacific will only succeed if there is international collaboration on both the elements that CLIVAR assumes will be provided and those elements that CLIVAR plans to provide the support for. In the first category are the satellite observations, much of the basin-wide sustained oceanic, flux, and atmospheric observing systems, the numerical weather prediction activities, and much of the data assimilation modeling work. It is essential that CLIVAR Pacific interact with, influence, and help make the case for the support of these activities. In the second category, it is equally as essential that the multinational collection of scientists looking to participate in Pacific CLIVAR work together to maximize the benefit of the resources each nation can bring to the program. Toward that end, this plan should be considered by all who read it as a draft, open and desiring of comment from international as well as U.S. scientists and program managers. Comments should be sent to the U.S. CLIVAR Office (legler@earth.usgcrp.gov) for forwarding the U.S. Pacific Implementation Panel.

11. Cost

Cost estimates of essential PBECS elements:

Sustained observations

Satellite observations.	
Sea surface height	External support
Surface wind stress	External support
SST	External support
ARGO	External support
International array	External support
Additional floats	?
High-resolution transects	
Present lines	$700K/year
Proposed augmentations	$300K/yr
TAO	
Existing T(z)+met	External
Proposed augmentations:	
Near surface ADCP array (2 /mooring x 5°S-5°N x 2 TAO lines)	$500K/3yrs
Salinity sensor enhancement	
20 moorings x 5 sensors	$500K/3yrs
Flux enhancements (Precip, SW, LW, AtmosP)	
4 moorings	$160K/3yrs
(All these include calibration, spares, QC, data processing, tech support. Add 10-15% for web support/dissemination)	
Glider surveys	
1 glider continuously on station	$100K/yr
Includes spares, turnaround, travel, calibration, telemetry, QC, tech support (plus overhead). May need up to 10-15 surveys in operation	
Surface drifters	
Tropical	External
Alaska gyre drifters (100 drifters on station)	$400K/yr
Includes hardware, telemetry, shipping, QC, data processing	
Repeat hydrography	To be determined

Sustained observations (continued)	
Ocean time series	$500K/yr each
2-4 extratropical sites	
Surface fluxes	
Surface reference sites	
Moorings (hardware only)	$280K/ea
2-4 sites	
VOS deployment (hardware only)	$150K/ea
5 existing lines plus 3 additional	
Special focus regions	
Kuroshio extension mooring	$280K/ea
LLWBC moorings/sections (up to 3)	
Transport moorings only / per current (Mindanao+NGCC)	$1.5M/3yrs
(Based on experience w N Brazil Current)	
Work to determine how to sample varying T/S transport	$1M/yr
(Guess for NEC bifurcation study)	
gliders possible	
Augmentation of coastal sea level for altimeter	$500K/yr
(IES and coastal pressure gauges)	
California Current moorings	$1M/yr
5 moorings. Full met suite+T(z),U(z)+calib, data delivery	
Eastern Pacific	
stratus mooring	$280K/ea
additional TAO moorings	$250K/ea
glider sections of eastern bndy current	$100K/yr
Tropical atmospheric soundings	
Reestablishing island stations	$200K capital
2 soundings/day at 5 stations	$300K/yr
communications enhancements	$100K/yr
915MHz profiler site	$150K capital
operation	$50K/year
Extratropical atmospheric observations	
radiosondes from VOS, research vessels	$200K/yr
acoustic rainfall	$100K/yr
Central or virtual data archive	$200K/yr

12. Priorities and Readiness

Establishing the sustained observing system has the highest priority, together with spinning up the data assimilation and modeling.

It is clear that in some of the sustained, focussed sampling discussed above that they are not yet ready, as they depend on process studies to define how best to sample the region. In some cases, as with gliders, technology is still under development. Phasing of the process studies is recommended based on their dependence on the sustained basin-wide observing system. The following process studies have been recommended and are judged as 'near-term' studies since they do not depend on prior deployment of the full PBECS observing system: (1) diapycnal fluxes and mixing, using microstructure measurements at selected tropical and subtropical sites, (2) North Equatorial Current bifurcation and low-latitude western boundary current dynamics, using supplementary observations to the PBECS-proposed glider profiles, (3) studying the dynamics and detailed structure of equatorial upwelling, using a fine-scale array of moorings and current meters, and (4) Kuroshio/Oyashio Extension Study, including deep recirculation and air-sea interactions (this would be joint with Japan). The following proposed studies are better carried out once the sustained, basin-wide observing system is fully deployed, after about 2004: (5) subtropical subduction study, examining the details of how anomalies in the properties of subducted water are created and advected in the subtropical cell, (6) evolution of subducted PV anomalies (looking at isopycnal mixing and spiciness in the SE Pacific, including on scales smaller than the ARGO array resolution).

Priorities may also develop from the desire to coordinate elements of U.S. Pacific CLIVAR with international partners. In recognition of this, the Pacific Implementation Panel intends to revisit and refine the issues of priorities and timing after the international workshop in January 2001.

13. Tables

Table 1a.	Desired Sustained Basin-wide Observations
Table1b:	Enhancements to Sustained Basin-wide Observations
Table 2:	Elements of the Sustained Observing System
Table 3:	The high resolution XBT lines for the Pacific (HRX)
Table 4:	Recommended additions to sustained observing systems
Table 5:	Ocean time series sites for the Pacific.
Table 6:	Observational elements of the surface flux program.
Table 7:	Island sites.
Table 8:	Enhancements for the sustained, focussed ocean observations
Table 9:	Atmospheric Sustained, Focussed and Process Studies
Table 10:	Presently Planned CLIVAR Pacific Process Studies

Table 1a: Desired Sustained Basin-wide Observations

	Dx	Dt	Dz	z max
Ocean				
T(z), S(z)	300 km	10 day	5 m	2000 m
U(near surface)	300 km	30 day		
Surface				
meteorology, fluxes	300 km	6 hour		
vector wind	100 km	daily		
wind, air temp, SLP, RH	300 km	6 hour		
longwave, rain	300 km	6 hour		
shortwave				
currents	300 km	12 hour		
SST	100 km	6 hours		
SLH	300 km	6 hour		
Atmosphere				
T(z), humidity(z)		12 hour	?	?
U(z), w(z)		12 hour	?	?

Table 1b: Enhancements to Sustained Basin-wide Observations

	Dx	Dt	Dz	z max
Ocean boundary currents				
T(z), S(z)	10-50 km	30 day	5 m	2000 m
U(z)	10 km	30 day	5 m	2000 m
SLH gradient	cross current	10 day		
Ocean equatorial zone				
T(z), S(z)	1000 km	5 day	5 m	500 m
	Dy = 100 km			
U(z)	1000 km	5 day	5 m	500 m
	Dy = 100 km			

Table 2: Elements of the Sustained Observing System

Element	Observation	Dx, Dy, Dz, Dt,Depth	Notes:	CLIVAR action:	Requirements/Cost
Satellite					
altimetry	sea level		external support; works with tide gauge network	work to avoid loss of accuracy after JASON-1 and 2	
scatterometer active radar	vector wind		external support; proven accuracy	work toward future deployments	
scatterometer passive radar	vector wind		external support; concern over use as replacement for active scatterometer on new operational satellites	unproven	
radiometer AVHRR	SST		problems with clouds and aerosols; requires in situ SST	field sufficient in situ obs	
radiometer passive microwave	SST	50 km, 50 km, ? day, -	able to see through clouds		
Argo profiling floats	T, S profiles, parking depth velocity	300 km, 300 km, 10 day, down to 2000 m; park at 2000 m	external support	work with Argo science team to support acquisition and coordinate deployment	
Surface drifters	SST, SSS, 15 m velocity		external support for tropical drifters	requires CLIVAR support for extratropics	?? drifters/year at $?? per drifters
H-Res transects (HRX)	(select VOS lines)			help stabilize base support; add 3 lines	annual cost exclusive of expendables and hardware: $??/line
XBT	T(z)	10 km spacing in bndy current 50 km spacing in interior 1m,,~2-12 weeks, 800-1500m	broad scale XBT resources shifitng to these lines; cost increases a problem	work with international groups to select and equip desired HRX lines in Pacific; solidify U.S. support for probes	1999 probe usage: ?? XBT 2000 cost: XBT - $??,
Surface met	upgraded meteorology and fluxes	sampled 1 per minute along track	equipping HRX lines just beginning	needs CLIVAR support	~$40K/ship
XCTD, SSS, SST	S(z), surface salinity		5% of probes are XCTDs; SSS by thermosalinograph (TSG)	TSG deployment needs CLIVAR support	1999- ?? XCTD probes 2000 cost of XCTD-$? TSG installation cost - $?
Volunteer Observing Ships (VOS)	wind, SST, air temp, RH, sea state, cloud cover – standard manual obs		Part of World Weather Watch	interact with SOOPIP and JCOMM on VOS-CLIM project; upgrade sensors on HRX lines	
Tide Gauges	SLH		ground truth for altimeter		
Surface drifters	SST, near surface U SLP on subset		Tropical drifters are part of ENSO observing system	CLIVAR support for extratropical drifters needed	
TAO	wind,		external support for operational baseline array	Upgrades at select sites: salinity, velocity, surface fluxes	
Time Series	T, S, velocity, non-physical sampling, surface met and fluxes	select locations, select depths or profiling instruments in the ocean, able to sample rapidly (~ once per minute)	For ocean time series and as surface reference sites for fluxes	work with Time Series science team, participate in site selection, support some sites in advance of or instead of GOOS; evaluate HOTS	
Boundary current	T, S, veloc; transports		Monitoring heat and freshwater transport desired as addition	Conduct process studies, international partnerships to develop plans and startegies	
Repeat hydrography	T, S, tracers and other non-physical sampling			Develop plans with international parners; identify U.S. contribution	
Radiosondes	T(z), humidity(z), U(z)			Improve data return, add stations on islands and ships	
Atmospheric Profilers	U(z), w(z)			Sustain Pacific island proflier network	

Table 3: The High-Resolution XBT lines for the Pacific

Line	Location	Frequency	Nation/institution	Notes:	Cost
PX6	Auckland-Suva	4 sections/yr Dx=10 km in bndy currents, 50 km in interior for XBTs	?	13 year record	
PX37/10/44	zonal N. Pacific		?		
PX50/34	zonal S. Pacific		?		
PX 61/31	merdional central Pacific		?		
PX81/38	meridional eastern Pacific		?		
IX1	Indonesian throughflow		?	Choke point	
IX28	Southern Ocean, south of Australia		?	entrance to Pacific	
AX22	Drake Passage		?	entrance to Pacific	
PX30	Western boundary current		?		
PX40	Western boundary current		?		
			?		
			?		
			?		
			?		

Table 4: Recommended Additions to Sustained Observing System

Element	Observations	Dx	Dt	Dz	Z max	Note:	Cost
Boundary current arrays	T(z), S(z) U(z)	~50 km ~10 km	<1 day <1 day	10 m 10 m	2000 m 2000 m	Monitor heat and freshwater transport; technical and strategic challenges	
Surface flux observations	3-5 TAO sites; surface reference sites outside tropics; VOS					U.S. commitment is for maintaining 3-5 TAO sites and 3 extratropical sites	
Pacific HRX lines	T(z), SST S(z), SSS surface met/flux CO_2					Fully equip all Pacific HRX lines: Supply XBTs, XCTDs, thermosalinographs, met sensor upgrades. Reusable XBT/CTDs under development	
Extratropical surface drifters	SST, near-surface U, SLP						
Repeat hydrography	S(z), T(z), tracers		every 5-10 years		full depth	5 to 7 meridional/zonal lines; plan under development	
Ocean time series stations	U(z), T(z), S(z), biogeochemical				full depth	See Table 5	
Additional radiosondes	Atmospheric profiles T(z), humidity, U(z)					Use TAO ship, RV Ron Brown, consider VOS, sustain/add island sites (Table 7)	
Aerosondes	Atmospheric T, humidity and other met obs					Atmospheric AUV	

Table 5: Ocean Time Series Sites for the Pacific

Lat	Lon	Locale	Other justification:	Nation/institution	Cost
50	-150	Station Papa	Air-sea flux. Observe upper-ocean water mass property changes with partner stations, monitor strength of baroclinic gyre circulation. Long historic record,		
35	-165	Mama	Air-sea flux		
32	152	Kuroshio Extension	Monitor strength and properties of subtropical mode water. Air-sea flux. JAMSTEC.		
36.5	152	Kuroshio Extension	Monitor strength and properties of subtropical mode water. Air-sea flux. JAMSTEC.		
25.7	135.5	JMA OWS	Operational met buoy (Japan Meteorological Agency)		
28.2	126.3	JMA OWS	Operational met buoy		
29	135	JMA OWS	Operational met buoy		
37.5	134.4	JMA OWS	Operational met buoy		
-42	-130	Subtropical S. Pacific	Gather eddy statistics		
3	145	W. Pac. Warm Pool	Air-sea flux.		
-3	118	Indonesian Throughflow	Transport monitoring site		
-20	-85	Stratocumulus cloud deck	Air-Sea flux		
33	-158	HOTS	Multivariate sampling, continuing record		

Table 6: Observational elements of the surface flux progran

Element	Observations	Sampling	Nation/institution	Notes:	Cost
HRX VOS	surface met air and sea temp short and longwave rad wind, BP, RH, rain	1 minute		pCO_2 possible radiosondes under consideration	\$150K each capital \$20K/yr maintain
Standard VOS					
Surface Reference Sites	wind, bar. press, air and sea temp, incoming short and longwave, rel. humidity, rain	1 minute	2-4 U.S. extratropical 4 TAO	new sites add to existing TAO buoys	\$280K/yr each \$160K/3yr to enhance
Other surface moorings	wind, air and sea temp, RH, BP	varies	TAO, NDBC, JMA, Jamstec		
NWP models	surface met and fluxes	1° grid, 6 hour			
Satellite	SST, surface wind, shortwave, rain				

Table 7: Island Sites

Island	Location	Sampling	Nation/institution	Notes:	Cost
Line Islands					
Christmas	2°N, 157°W				
Fanning	4°N, 159°W				
Washington	5°N, 160°W				
Palmyra	6°N, 162°W			add radiosonde/profiler to Palmyra or Washington to sample ITCZ	
ITCZ					
Truk	7°N, 152°E			reliable reporting	
Yap	9°N, 138°E			reliable reporting	
San Cristobal (Galapagaos)	1°S, 90°W			radiosondes data intermittent; 915 MHz profiler since 10/1994	
Wake	19°N, 168°E			historical radiosonde site, but now intermittent;	
Midway	28°N, 177°W			radiosondes end in 1997, surface obs intermittent, possible aerosonde base	

Table 8: Enhancements for the Sustained, Focussed Ocean Observations

Element	Focus	Region	Sampling method	Nation/institution	Notes:	Cost
Subtropical overturning circulation	Interior large-scale variability		Argo		Some floats to be parked at thermocline depth	
	Interior mesoscale variability		HRX, altimeter		Needs to resolve eddies	
	Low-latitude WBC					
		Mindanao Current				
		New Guinea current system				
	Indonesian Throughflow					
	Equator					
Extratropical Climate Feedbacks						
	North Pacific feedback loop					
	Kuroshio-Oyashio System					
	Southern subtropics					
Eastern Pacific						
	Air-sea coupling in E. Pacific					
	California Current system					
	South Pacific bndy currents					

Table 9: Atmospheric Sustained, Focussed and Process Studies

Element	Focus	Region	Sampling method	Nation/institution	Notes:	Cost
THORPEX	Weather forecast improvement over Northern Hemisphere	North Pacific	Balloons with payload of dropsondes from Asia; Equatorial winds; Aerosondes from Hawaii and N. America; surface moorings for SLP, SST; radiosondes from ships	U.S. W. R. P. W. W. R. P.		
Global Air-Ocean in-situ System (GAINS)	Long-term (50 year) monitoring	Global, occupy constant latitude circles with high altitude balloons	Re-usable high altitude balloons with dropsondes	Multinational		
Intraseasonal Tropical-Midlatitude Interactions	Improve weekly to seasonal forecasts, identify key mechanisms for tropical-midlatitude interactions	Pacific	Dense, targeted observations over strong convection and adjacent subtropical jet regions	NOAA CDC and ETL		

Table 10: Presently Planned CLIVAR Pacific Process Studies

Experiment	Focus	Region	Sampling method	Nation/institution	Notes:	Cost
Diapycnal fluxes	diurnal cycle in mixing	equator			working group recommend for now	
low laititude diapycnal mixing	low latitude mixing process, internal waves	near equator				
KESS	SST anomalies and their evolution	Kuroshio-Oyashio outflow	moored array	Japan/U.S.	Japanese part funded U.S. part proposed	
EPIC	coupled air-sea interaction in eastern Pacific	eastern equatorial Pacific and startus cloud deck west of South America	ships, aircraft, mooring, profiling floats, drifters, gliders	U.S. Central and South America	EPIC 2001, phase 1 going ahead	
T/S anomalies	generation of subducted T/S anomalies	mid-latitude				
subtropical-tropical exchange	how anomalies move from subtropics to tropics					
NEC bifurcation	low latitude western bndy					
Equatorial upwelling	3 dimensional low latitude circulation					
Vertical structure	vertical structure of horizontal currents	mid-latitude				

14. Summary

The CLIVAR Pacific program has as its core the Pacific Basin Extended Climate Study (PBECS). PBECS is a basin-wide study of interannual-to-decadal climate variability in and over the Pacific Ocean. It also includes process experiments planned to explore high frequency processes where knowledge must be improved in order to make progress in PBECS. This implementation plan lays out the main elements of PBECS as defined in a series of community planning meetings. It also points to areas where additional planning is needed to complete PBECS. Here we summarize the plan and enumerate recommendations to begin implementing PBECS.

The PBECS strategy to understanding these phenomena will be comprehensive, integrating a diverse suite of in situ and remote-sensing observations inside data-assimilating models to describe the evolution of much of the Pacific Basin. The observational objective is to describe the Pacific Basin well enough that the evolution of climate-scale patterns can be diagnosed dynamically so that the various hypotheses for climate variability can be tested.

Consideration of the data assimilation effort leads to recommendations for:

1. Additional computer resources to support assimilation
2. Fostering interaction between observers and assimilators
3. Development and execution as part of Pacific CLIVAR of process experiments, numerical experiments, and model development activities to improve dynamical models.

The backbone of the observing array for PBECS will be the basin-wide, sustained in-situ and satellite observations. Three of these elements are essential and must be continued for 15 years for PBECS to succeed:

4. Satellite altimetry with coverage and accuracy comparable to TOPEX/POSEIDON
5. An array of 1200 Argo profiling floats should be maintained across the basin north of 40°S, profiling T and S to 2000 m on 10-day intervals
6. The ENSO Observing System, includingTAO

Recommendations for other elements of the basin-wide observing systems that are:

7. The high-resolution XBT/XCTD sections from VOS, augmenting existing lines with meridional lines in the far eastern and western Pacific
8. Satellite measurements of surface vector winds with coverage and accuracy comparable to QuickSCAT
9. High-quality infrared and/or microwave sensing of sea-surface temperature with in situ reference time series
10. Approximately 200 surface drifters in the subpolar North Pacific north of the ENSO Observing System

Air-sea fluxes of momentum, heat, and water play a central role in the coupled phenomena of PBECS concern. A complete strategy for improving the availability of high-quality surface flux. The following steps are recommended to implement the strategy to obtain air-sea fluxes:

11. Add surface reference sites (high-quality time series of surface observations from moored buoys) and specially instrumented VOS; with U.S. support for five high-quality VOS lines, equipping three to five TAO moorings, and maintaining three additional sites.
12. Compare these data with NWP fluxes and remote-sensing fields to define biases and error characteristics. and develop basin-scale flux fields
13. Help develop AGCMs that can successfully assimilate all kinds of in situ and remotely sensed data to produce better routine surface meteorology and surface flux fields.

The basin-wide, sustained array discussed above will resolve climate processes in the interior ocean. These broad-scale observations, however, are not well suited for measuring the transport and processes occurring in boundary currents or the highly zonated eastern tropical Pacific. Some of these regions are centrally involved in the climate processes of concern to PBECS and, therefore, special, sustained, focussed observations are recommended in special regions. Western boundary current regions and their extensions have been identified for study:

14. The Mindanao Current is the main conduit between the North Equatorial Current (NEC) and the North Equatorial Counter Current (NECC) and hence the equator; long-term measurements of mass, and if possible heat and fresh water, transport east of Mindanao should be maintained; these might be combined with measurements off Luzon to more fully monitor the NEC bifurcation.
15. The New Guinea Coastal Current and New Guinea Coastal Undercurrent are the main sources of southern hemisphere water to the western Equatorial Undercurrent and NECC; suitable long-term transport measurements should be maintained in Vitiaz Strait or north of New Guinea's north coast
16. The Indonesian Throughflow ; the U.S. should work with Australia to upgrade the repeated VOS section I1.
17. It is recommended that the existing VOS lines crossing western boundary currents be maintained and upgraded with increased use of 2000 m XBTs, XCTDs, and underway CTDs and augmented with autonomous gliders to increase sampling frequency. Two or three U.S. glider sections are suggested.
18. One or two moorings with high-quality air-sea flux sensors and upper-ocean instrumentation should be maintained eastward from the KOE. The present NOPP mooring at 35°N, 165°W is a candidate for the eastern end of this array. One of these could serve as a flux reference site (see item 11 above).

The eastern tropical Pacific is the site of strong air-sea coupling and affects affect the local climate of the Americas. The EPIC experiment is examining the coupling processes in the atmospheric and oceanic boundary layers and this may lead to design of long-term measurements that might be added to PBECS. For the time being, PBECS and the Consortium on the Ocean's Role in Climate will support process experiments in this region. The ocean along the west coast of North America is the site of substantial ocean and atmosphere variability, particularly resulting from the ENSO cycle. Study of the area is recommended:

19. In cooperation with coastal modeling, weather, and ecology studies, it is recommended that an array of air-sea flux and upper-ocean moorings and offshore VOS or autonomous glider sections be established and maintained along the U.S. west coast. Two moorings and three lines would be appropriate.

The eastern boundary region along South America is the site of coastal upwelling and prominent decks of stratus and stratocumulus clouds that have substantial effects on radiation. In that region:

20. It is suggested that repeated offshore autonomous glider sections be maintained between 5°S and 25°S to develop a data set for studying the upwelling source of cold water, its alongshore transport, and their interaction with the ENSO cycle. One to three sections would be appropriate.

Atmospheric observations are critical. While it is anticipated that many will be available as part of the operational meteorological system (World Weather Watch, GTS) and other through process and focussed studies originating in the atmospheric research community, it is anticipated that Pacific CLIVAR will support key additional observations in the Pacific including:

21. Reestablishing the tropical and subtropical atmospheric sounding island stations, establishing 915 MHz profilers in key locations, and adding radiosonde launches from Research Vessels and VOS.

Action items

Here, steps that need to be taken toward the implementation of CLIVAR in the Pacificare reiterated, but not with any priority intended bytheir order. These priorities and the timing of elements of Pacific CLIVAR will be developed further in concert with the international community before and at the Pacific International Implementation Workshop to be held in Hawaii in January 2001.

(1) The Argo array and VOS sections will not obviate the need for repeat hydrography in tracking slow climate-related variability. Development of a deep ocean observing strategy is needed, and Pacific CLIVAR should interact with the new OOPC activity to do this, with attention to the carbon cycle and tracers as well as physical variability. If the nations of the Pacific were to collaborate on this, it is likely that a basin-scale survey of five to seven lines might be repeated on a roughly decadal period with reasonable resources.

(2) A surface flux working group is needed to decide the optimal available analyses to use for forcing the assimilating ocean model, and to work with atmospheric forecast/analysis centers to improve air-sea flux parameterizations using the PBECS and other observations. This group should liase with the WCRP WGNE SURFA project to include in situ time series from surface flux reference sites in the ongoing AMIP. They should also develop partnerships with the NWP and remote sensing communities.

(3) Time-series stations provide a unique perspective on ocean climate change. Pacific CLIVAR should work in concert with the OOPC initiation of anOcean Time Series Science Team to move toward final selection of sites and obtaining multinational commitments for their long term support. As part of this HOT data, from a site north of Hawaii with the longest time series now being maintained, could be used to develop the rational and plans for the observations to be made at these sites.

(4) A periodic annual or biennial CLIVAR-sponsored model-data-diagnostics conference is highly recommended to publicize the PBECS observations, encourage diagnostic analysis of Pacific low-frequency variability and the physical processes that contribute to it, encourage critical comparison of coupled models with PBECS and other observations, and discuss the plausibility of proposed variability mechanisms.

(5) A working group on models and process experiments to oversee developing satisfactory methods for including deep-cycle fluxes into climate models. Such a working group should be charged with developing coordinated numerical studies, process experiments, and monitoring upon which to base flux representations. This would put necessary focus into the exploration of ocean mixing studies.

(6) Support for additional computing and data archiving and serving resources needs to be maintained and stated. The data assimilation effort requires computing resources. CLIVAR Pacific data (observations, model results, assimilation results) should be readily available from a central or a distributed data server.

(7) Enabling instrumentation development should be encouraged. In this category we note the potential of: 2000 m XBTs, reusable XBTs and CTDs, gliders, commerical production of IMET sensor sets, chemical and biological sensors, long-lived salinity sensors for floats and moorings.

(8) Support for continuing high quality altimetry, satellite wind, and satellite SST should be made clear. Support for and partnerships to obtain precipitation and surface radiation fields should also be developed.

(9) The density of Argo floats provided by international efforts should be monitored, with Pacific CLIVAR explicit in its support for the 3°, 10 day sampling and ready to consider ways to supplement the density in the Pacific basin if need be.

(10) Support for the exisitng High-Density XBT lines (HRX) needs to be stabilized and then support for 3 additional lines is needed. This includes XBTs, XCTDs, thermosalinographs, and IMETs for the ships.

(11) A dialog with KESS should be maintained, both to work toward long term sampling strategies and to examine high value augmentations to sampling in the region.

(12) Liason with those planning atmospheric observations in the Pacific has been started; this needs to be prusued and strengthened.

(13) A boundary current working group should be considered to provide a focal point for developing strategies for sampling those regions, including transitioning results from recommended process studies to plans for sustained observations. This group would focus on western, eastern, and equatorial boundary currents.

The dynamics of the equatorial processes like diapycnal mixing, upwelling, frontogenesis, and the shallow equatorial overturning circulation are central to the evolution of the ENSO cycle but are poorly represented in climate models. A strategy for describing these processes during the ENSO cycle should be developed and implemented.

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