US CLIVAR Pacific Implementation Plan

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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.