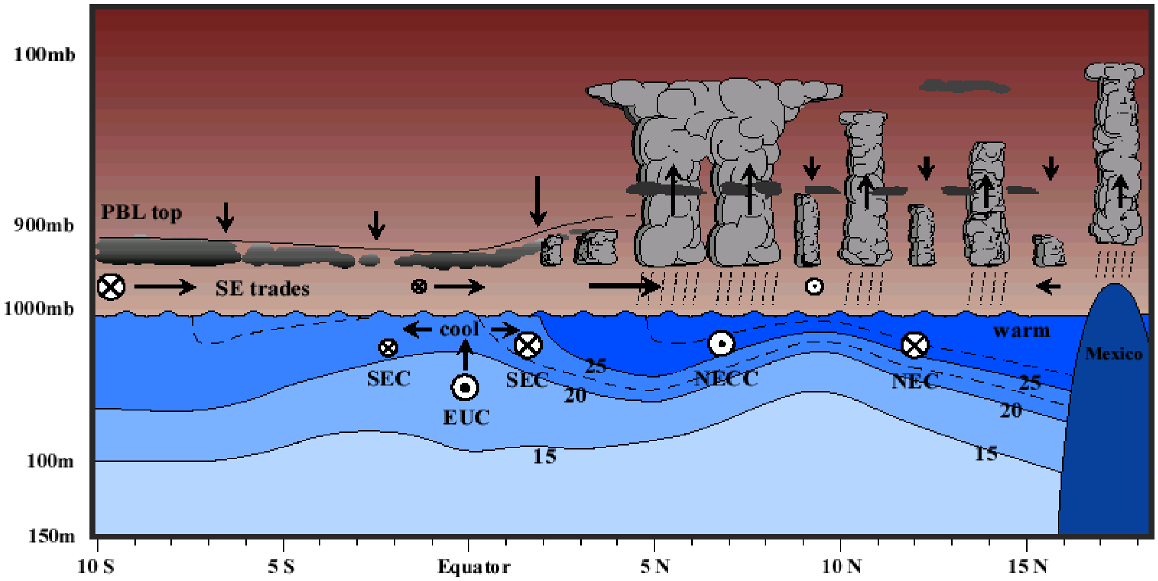
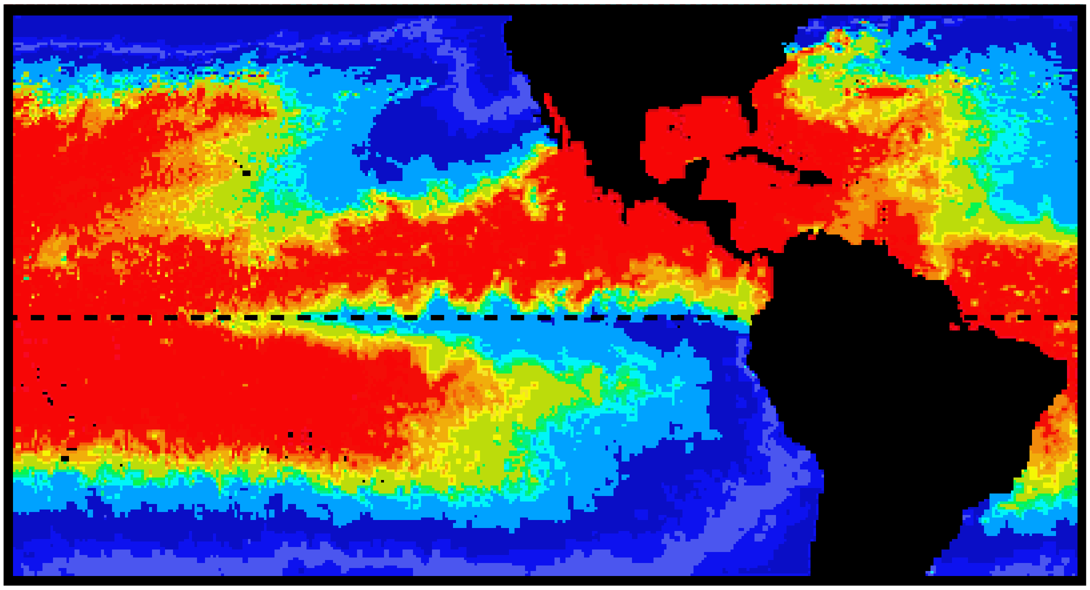
A Science and Implementation Plan for EPIC: An Eastern Pacific Investigation of Climate Processes in the Coupled Ocean-Atmosphere System





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Upper panel: Idealized cross section through the cold-tongue/ITCZ complex in the southerly monsoonal regime during the cool season (~July–September). Drawn by Steve Esbensen and Billy Kessler.

Lower panel: Schematic of the sea surface temperature field for July 1984 (based on a 2 week average of satellite data), adapted from Pan American Climate Studies: A Scientific Prospectus, available from http://tao.atmos.washington.edu/pacs/. Cool water is blue. The cold tongue extending west from South America at and below the equator is clearly visible.

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Preface

Anomalous sea surface temperatures in the eastern tropical Pacific have, as evidenced by the 1997 El Niño, the ability to perturb the atmosphere and alter weather and climate in remote locations, including North and South America. One of the strongest, regular features of the sea surface temperature field in this region is the annual appearance of cool water (as shown on the cover image of satellite sea surface temperatures from July 1984) extending out from the west coast of South America westward along, and south of, the equator. The difficulties we have, at present, in simulating the annual evolution of this cold tongue in state-of-the-art coupled ocean-atmosphere models suggest that we have not yet achieved a good understanding of atmosphere-ocean coupling in the eastern tropical Pacific. Further, the coupled models exhibit considerable sensitivity to changes in the parameterization of the stratus deck region. Thus, we have concern that we do not yet have the basic understanding of the coupled ocean-atmosphere system in the eastern tropical Pacific required for development of the capability to make reliable seasonal to interannual predictions of both this region and of the remote regions influenced by its variability.

In this document we develop these concerns more fully, outlining the science issues associated with atmosphere-ocean coupling in the eastern tropical Pacific and pointing to gaps in our knowledge about that system. Plans for field work that would target those gaps, and result in the improved understanding needed to advance predictive capability, are then presented. Specifically, we put forward here programs to address air-sea interactions in the cold tongue/ intertropical convergence zone (ITCZ) and in the stratus deck region. Finally, we note that these efforts will enjoy synergy with monitoring and other observing programs whose observations will place these process studies in a broader space and time scale context.

This plan has developed from contributions by Bruce Albrecht, Steve Anderson, Wesley Berg, Nick Bond, Dudley Chelton, Shuyi Chen, Meghan Cronin, Russ Davis, Charlie Eriksen, Steve Esbensen, Chris Fairall, Carl Friehe, Greg Johnson, Billy Kessler, Arun Kumar, Jose Meitin, Clayton Paulson, Dave Raymond, Dan Rudnick, Dave Rogers, Mike Wallace, Bob Weisberg, Bob Weller, Steve Williams, Chidong Zhang, and others. This plan also stems from from previous and ongoing discussions about the science foci and plans for a Pacific Basin Extended Climate Study (PBECS) and for the Pan American Climate Studies (PACS), including a pair of meetings in Miami in September 1997 and an EPIC Implementation workshop in Tucson in October 1998. Addditional discussions held at meetings and workshops on the Variability of the American Monsoons System

(VAMOS) element of CLIVAR and with the U.S. CLIVAR Scientific Steering Committee have helped shape EPIC. The text and graphics build upon and include the work of Mike Wallace, Todd Mitchell, Candace Gunderson, and others at the University of Washington. For background, readers are referred to the PACS Scientific Prospectus and Implementation Plan, available at http://tao.atmos.washington.edu/pacs/plans.html.

Summary

To predict ENSO over the Pacific Ocean and its effects on surrounding land masses with quantitative accuracy, the annual cycle of the eastern Pacific cold-tongue/ITCZ complex (CTIC) and its interaction with seasonal-to-interannual climate anomalies must be well simulated in coupled ocean-atmosphere models. Intercomparisons of state-of-the-art ocean-atmosphere models and observed data have identified several major deficiencies in our understanding of the processes that determine upper ocean thermal structure and the associated atmospheric patterns of heating and cloudiness over the eastern Pacific. Coupled models tend to produce an unrealistic symmetric circulation with ITCZs north and south of the equator, often associated with unrealistically warm equatorial sea surface temperatures and parameterized boundary layer cloud decks that are less extensive than in observations. The coupled models exhibit considerable sensitivity to changes in parameterization of physical processes in the stratus deck region. Further, the atmospheric components of these coupled models often produce unrealistic atmospheric boundary layer structures over the oceanic cold tongue and significant errors in the strength and location of the northeast Pacific ITCZ. We are, therefore, concerned that we do not have the basic understanding of eastern Pacific ocean-atmosphere coupling that is required to develop reliable seasonal-to-interannual prediction systems for this region and the remote regions influenced by its variability.

The Eastern Pacific Investigation of Climate processes (EPIC) in the ocean-atmosphere is a five year process study to improve the description and understanding of the CTIC and the stratus deck region. It focuses on investigating the key physical processes that must be parameterized for successful CTIC and stratus deck simulation with dynamical ocean-atmosphere models. The pilot phase of the Pan American Climate Study (PACS) conducted field work in the equatorial Pacific at 125°W, where the prevailing September-October surface winds are easterly. EPIC will look at ocean-atmosphere coupling further to the east in the CTIC, between 95°W and 110°W, where southerly surface winds prevail at the equator in September–October, while maintaining an interest in the eastern central Pacific in the oceanographic processes associated with the western part of the cold tongue. EPIC will also work in the stratus deck region off the coasts of Peru and Chile and thus in the upwelling regime that supplies cool water to the eastern end of the cold tongue. EPIC will be part of the CLIVAR VAMOS (Variability of the American Monsoon System)

program and will be conducted in a context defined by longer-running elements of PACS and of the Pacific Basin Extended Climate Study (PBECS).

The scientific objectives of EPIC are:

I. To observe and understand 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, including:
   (a) Mechanisms governing temperature and salinity field evolution in the oceanic cold tongue and in the region of strong meridional gradient in sea surface temperature from the oceanic cold tongue through the ITCZ;
   (b) Atmospheric planetary boundary layer structure and evolution from the equator through the ITCZ, primarily in the southerly monsoonal regime; and
   (c) The processes determining the existence, character and strength of deep convection in the northeast Pacific ITCZ.

II. To observe and understand the dynamical, radiative and microphysical properties of the extensive boundary layer cloud decks in the southeasterly tradewind and cross-equatorial flow regime, their interactions with the ocean below, and the evolution of the upper ocean under stratus decks.

To accomplish these objectives, planning has proceeded with the intent of developing:

- Field studies in the eastern Pacific, to be conducted in 2000–2003, some of which will be brief and target specific locations and/or processes, and some of which will run long enough to capture and study the annual cycle;
- Enhanced monitoring and empirical studies in 1999–2004 that carry on some elements from the PACS pilot phase, initiate new elements, and provide the spatial and temporal context for EPIC;
- Strong links with elements of the CLIVAR Variability of the American Monsoon System (VAMOS) program and with climate studies in the Pacific Ocean and in the Americas; and

- Data analysis and modeling in which results from the enhanced monitoring and process studies are synthesized and prepared for use in model validation and improvement studies.

EPIC will lead to significant improvements in the short-term climate analysis and prediction system for the Americas. The high quality data sets that will be collected in the sparsely observed CTIC and stratocumulus regimes are expected to reveal many quantitative aspects of the ocean-atmosphere structure for the first time. This will result in an improved understanding and simulation of key ocean, atmosphere and coupled processes that are poorly represented in the present generation of ocean-atmosphere prediction models. The results from EPIC will also provide a basis for designing the elements of the clmiate observing system needed for future monitoring and prediction of the eastern Pacific climate variability and its influence on the Americas.

1. RATIONALE FOR AN EASTERN PACIFIC FIELD INVESTIGATION OF CLIMATE PROCESSES IN THE OCEAN-ATMOSPHERE SYSTEM

1.1 Status and Scientific Objectives of CLIVAR-GOALS

The Eastern Pacific Investigation of Climate (EPIC) is designed to observe and understand key ocean-atmosphere processes and the seasonal-to-interannual variability of the climate system over the eastern, tropical Pacific Ocean and adjacent land masses. EPIC will contribute to the study of the variability and predictability of the Global Ocean-Atmosphere-Land System (CLIVAR-GOALS), which is a major component of the World Climate Research Program.

CLIVAR-GOALS builds on the recently concluded Tropical Ocean Global Atmosphere (TOGA) Program (1985–1995). TOGA made significant progress in observing and understanding the ocean and atmosphere as a coupled system, especially the El Niño/Southern Oscillation (ENSO) and its influence on surface air temperature and rainfall over many regions of the globe. TOGA demonstrated the feasibility of quantitative dynamical seasonal-to-interannual predictions of tropical sea surface temperature, and clarified the nature of the remote, planetary scale response to these anomalies. However, many scientific and technical challenges remain in the development of an operational seasonal-to-interannual prediction system.

The recent 1997–98 ENSO illustrates both the successes and shortcomings of our present understanding and predictive capabilities. On one hand, the observing system in the tropical Pacific that is a legacy of the TOGA program provided an unprecedented description of the evolution of the 1997–98 event above and below the ocean surface. On the other hand, numerous experimental prediction models failed to predict both the evolution of the tropical SST patterns for the 1997–98 ENSO event and its remote planetary-scale effects on temperature and precipitation more than one season in advance. Clearly, much work remains to achieve the understanding and capabilities required for the proper initialization of ocean-atmosphere prediction models and the realistic representation of the physics of ocean-atmosphere-land interaction within these models.

The scientific objectives of the CLIVAR-GOALS Program are quite general:

- to describe and understand seasonal to interannual climate variability and predictability through the analysis of observations and modeling of the coupled climate system;

- to improve the accuracy of seasonal to interannual climate prediction through programs of coupled modeling of the upper ocean, atmosphere, land and ice system; and
- to develop and implement appropriate observing, computing and data archiving and dissemination programs needed to understand seasonal-to-interannual climate variability and to predict variations, in cooperation with other relevant climate-research and observing programs.

CLIVAR-GOALS also poses a number of more specific basic science, modeling, and phenomenological questions that are relevant to the present eastern Pacific investigation. These include:

- What are the structure and dynamics of the annual cycle of the coupled ocean-atmosphere-land system, and what are the reasons for its large spatial variability over the globe?

- What determines the low-level convergence of moisture in the tropics over water, land and coasts? More generally, what determines the location and longevity of the thermal heat sources and sinks for the atmosphere?

- What improvements are needed in coupled-model parameterizations for the representation of convection, mixing, radiation-cloud-aerosol interactions, and the processes that determine the coupling of the atmosphere and the ocean for the purpose of seasonal-to-interannual variations?

- What measurements of the global upper ocean and land surface are required to initialize and validate the coupled models of the global ocean-atmosphere land system for prediction of seasonal-to-interannual variations?

- What is the role of synoptic fluctuations in the tropics and the mid-latitudes in seasonal to interannual climate variability and predictability?

Process studies are one of the four major program elements of CLIVAR-GOALS. The development of ocean-atmosphere prediction systems provides a unifying theme for the program.

Empirical studies point to areas in which model improvement is needed and where process studies are necessary. Process studies address basic science questions requiring new observational data. CLIVAR-GOALS places highest priority on process studies that are most likely to contribute toward the improvement of short-range climate prediction.

The overall strategy of CLIVAR-GOALS is to expand the range of its activities as knowledge expands, concentrating initially on the ENSO phenomenon in the tropics. Building on the TOGA observational system in the Pacific, CLIVAR-GOALS investigations will expand to the Indian Ocean and surrounding land masses, and into the Atlantic Ocean and surrounding South American and African land masses. As the program develops, teleconnections with higher latitude regions will be investigated, including the effects of higher-latitude ocean, land and ice on seasonal to interannual climate predictability.

1.2 Ocean-Atmosphere-Land Interactions in the Eastern Pacific Region

One of the strongest, regular features of the sea surface temperature field over the global tropical oceans is the annual appearance of cool water (as shown on the cover image of satellite sea surface temperatures from July 1984) extending out from the west coast of South America westward along, and south of, the equator. The oceanic cold tongue is coupled to the atmosphere through surface wind stress and heat exchange. The surface interactions are coupled to the atmospheric circulation through horizontal gradients of latent heat release in the vicinity of deep east-west bands of ITCZ convection, as well as radiative and sensible heating gradients, especially in the atmospheric boundary layer. The upper ocean heat budget is strongly coupled to radiative effects of the extensive decks of boundary layer clouds in the southeast tradewinds and their extension into the equatorial zone. While horizontal advection by nearly zonal ocean currents is credited with maintaining high sea surface temperature under the ITCZ, mean buoyancy fluxes across the sea surface are sufficient to erase the dynamic topography of these currents in less than a year. Advection and mixing in the ocean, both vertical and meridional, are thought to produce comparably important fluxes, so that three-dimensional ocean processes couple to atmospheric circulation in the eastern tropical Pacific. To predict ENSO over the Pacific Ocean and its effects on surrounding land masses with quantitative accuracy, the annual cycle of the cold-tongue/ITCZ complex (CTIC) and its interaction with seasonal-to-interannual climate anomalies must be well simulated in coupled ocean-atmosphere models.

The rainfall climatology of the eastern tropical Pacific is dominated by the ITCZ and the continental monsoons (Figure 1.1). The northeasterly and southeasterly tradewind belts, which occupy most of the eastern tropical and subtropical Pacific, are noted for fair weather and a large excess of evaporation over precipitation, while narrow ITCZs which separate them are marked by heavy and persistent rainfall. The positions and intensities of the ITCZs are highly sensitive to the underlying sea-surface temperature distribution. Rainfall over the tropical and subtropical Americas and the adjacent oceans is dominated by seasonally dependent monsoonal circulations, that produce widespread rain in the summer hemisphere. The major monsoonal rain areas are marked by conspicuous upper-level anticyclones in the upper tropospheric flow. Monsoonal influences are not as overwhelming within the Americas as they are in the Austral-Asian sector of the tropics, but there is a prevalence of westerlies in the upper troposphere over the eastern equatorial Pacific, whose existence allows for a higher degree of interaction between the northern and southern hemisphere circulations than occurs elsewhere in the tropics.

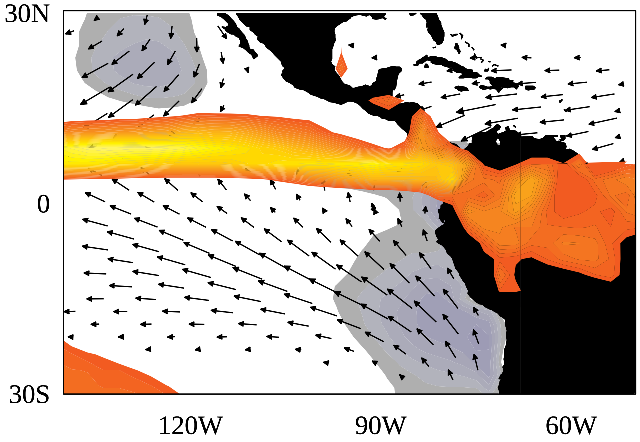


Figure 1.1. Annual mean surface wind vectors, precipitation (orange-yellow), and stratus decks (gray-blue).

The annual, mean climate in the eastern tropical Pacific is marked by strong equatorial asymmetries that cannot be explained on the basis of simple considerations of sun-earth geometry. The heavy and persistent rainfall associated with the ITCZ is centered, not on the equator, but at 5–10°N. Stratiform cloud decks in both the northern and southern hemisphere cool the underlying ocean by shielding it from incoming solar radiation. The greater extent of these cloud decks in the Southern Hemisphere contribute to its relative coolness. The highest sea surface temperatures are observed not along the equator, but at 5–10°N, more or less coincident with the annual mean position of the ITCZ in the western part of the region shown in Figures 1.1 and 1.2, and at 10–15°N in the eastern part of the region. The warm water coincides with the eastward flowing North Equatorial Countercurrent in the central Pacific, which is forced by the strong meridional gradient of zonal wind stress across the ITCZ there. In the eastern Pacific, the warmest water is found on the north side of the ITCZ in the mean, where winds are weak. Near the equator, easterly surface winds drive divergent (poleward) flow due to the meridional gradient of the Coriolis parameter. The induced equatorial upwelling of large volumes of cold, nutrient-rich water leads to the pronounced ‘equatorial cold tongue’ evident in SST and ocean color (CZCS) imagery. The strong equatorial asymmetry in the mean climate appears to be a manifestation of coupled ocean-atmosphere interactions no less intricate than those involved in ENSO. For example, the ITCZ may be viewed as a response to the underlying belt of warm sea surface temperatures, but the warm water can equally be viewed as a response to the ITCZ. In the context of the coupled atmosphere-ocean system, the ITCZ and the underlying warm water can both be viewed as elements of a response to the land-sea geometry. Surface winds, ocean currents, upwelling, deep convection, and stratus cloud decks all appear to be involved in these interactions, and circulations in the meridional plane appear to be at least as important as the circulations in the zonal plane that have been emphasized in connection with ENSO. It is not clear whether the large equatorial asymmetry in the annual mean climate derives from oceanic processes related to the northwest-southeast orientation of the west coast of South America or from planetary waves induced by the differences in orography and the land-sea distribution in the northern and southern hemispheres; nor is it clear to what extent it depends upon the superimposed seasonal march.

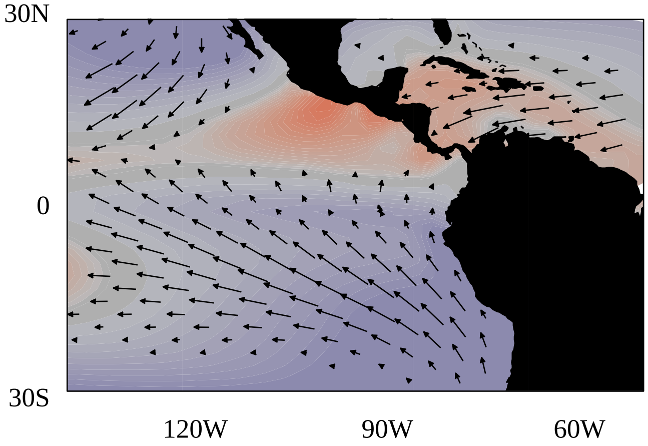


Figure 1.2. Annual mean sea surface temperature (red, warm) and surface wind vectors.

Within the eastern Pacific cold tongue region there exist two rather different regimes that prevail within different ranges of longitude that will be referred to as "the easterly regime" and "the southerly regime" on the basis of the direction of the prevailing winds along the equator as illustrated in Figure 1.3. The dividing line, near 110°W, corresponds to the ridge in the equatorial sea-level pressure profile. Westward of 110°W, the zonal pressure gradient along the equator drives easterly surface winds that comprise the lower branch of the Walker Circulation. The easterlies induce a distinctive, equatorially symmetric upwelling signature in the SST pattern: a reflection of surface Ekman divergence, partially balanced by an opposing geostrophic convergence due to the eastward directed pressure gradient force that sets up in response to these winds. The divergence represents the upper branch of a pair of wind-driven circulation cells in the meridional plane, symmetric about the equator, whose convergent, lower branch is at the depth of the thermocline and the core of the Equatorial Undercurrent. The strongest and most coherent SST fluctuations that occur in association with the ENSO cycle lie within this easterly regime. Seasonal variations are also observed, but they are weaker than those in the southerly regime farther to the east. Eastward of 110°W the strong equatorial asymmetry in the American coastline induces northward cross-equatorial flow in the atmospheric planetary boundary layer, whose curvature is in cyclostrophic balance with the zonal sea-level pressure gradient along the equator. The cold tongue, centered near 1°S, cannot be interpreted as an equatorial upwelling signature induced by westerly wind stress, since the zonal wind at these longitudes is quite weak.

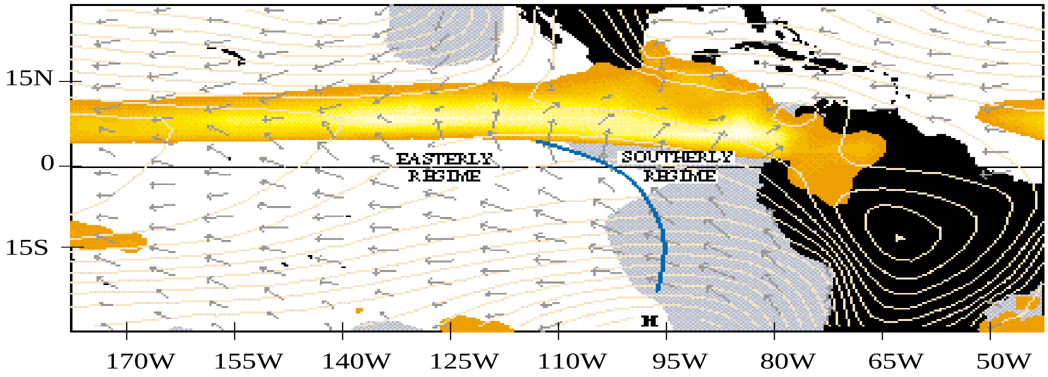


Figure 1.3. Equatorial wind regimes superimposed upon the average September-October climatology. Arrows represent surface winds; orange shading represents rainfall in excess of 20 cm/mo based on microwave satellite imagery over the oceans and rain gauge data over land; gray shading represents the stratus decks, defined as the region in which the albedo exceeds 0.3, and the contours represent sea-level pressure (SLP: contour interval 1 mb). The heavy line represents the "ridge line" in the SLP field; i.e., the highest SLP at each latitude. Climatological winds from the Comprehensive Ocean-Atmosphere Data Set (Woodruff *et al.*, 1987); SLP from Sadler et al. (1987); ocean rainfall from Spencer (1993); and land rainfall from Legates and Willmott (1990).

It may simply be the surface signature of the ridge in the thermocline above the equatorial undercurrent, rendered visible in the SST pattern by wind driven entrainment. Alternatively, it could be a manifestation of upwelling to the south of the equator induced by the southerly surface winds, or it might be the signature of the plume of cold water upwelled along the coast of Peru.

The march of the seasons over the Americas contains some elements, such as year-round rainfall in the upper reaches of the Amazon, summer monsoons over Central and South America, and rainy winters in the Pacific Northwest and southern Chile, that are relatively well understood. However, it also contains some that are not understood, such as the single rainy season in northeast Brazil and coastal Ecuador and the asymmetry of the March-April and September-October climates over the oceans in the eastern tropical Pacific (Figure 1.4).

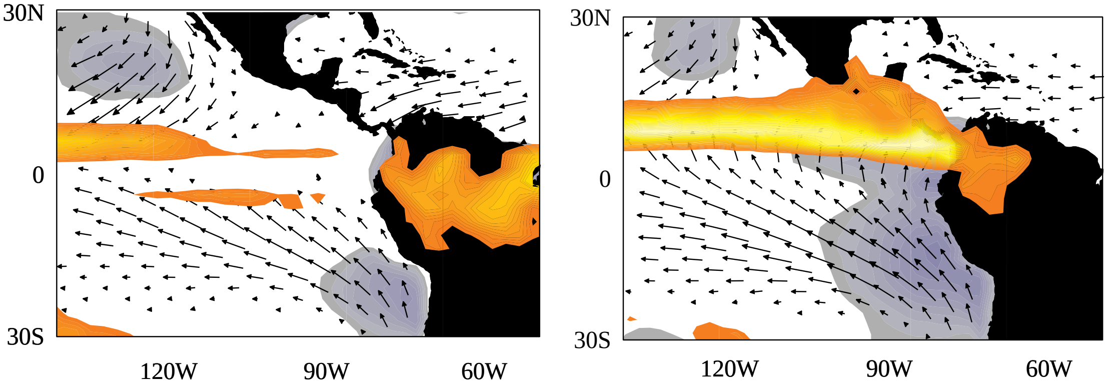


Figure 1.4. March-April (left) and September-October (right) heavy rainfall locations (orange-yellow), surface wind vectors, and stratus decks (blue-gray).

Convection in the east Pacific is typically organized into a ragged east-west line which is located a few degrees north of the equator in the northern winter to 9–12° N in the northern summer, as illustrated in Figure 1.4. In March and April a southern hemisphere counterpart is sometimes seen, but it is weaker and more transient than the northern hemisphere line. The dominant northern hemisphere convective band is usually identified as the ITCZ. However, the feature in the far eastern Pacific is actually more like the Asian monsoon trough than the mid-Pacific ITCZ in that there is a dominant seasonal cycle, and strong southwesterly flow occurs south of the line in the northern summer. We shall refer to this phenomenon here as either the “east Pacific monsoon trough” or the northeast Pacific ITCZ.

March–April is the time of the heaviest rainfall in the equatorial belt: the double ITCZ, symmetric about the equator, is often observed. In contrast, September–October is marked by the strongest equatorial asymmetry, with the ITCZ in the northern hemisphere and large stratus decks in the southern hemisphere. At the same time, there is a strong cycle in the sea surface temperatures in the cold tongue (Figure 1.5) and in the eastern Pacific warm pool (Figure 2.1). These sea surface temperature cycles are remarkably regular from year to year, even in the presence of El Niño. Considerations of sun-earth orbital geometry do not explain the strength of this annual cycle and would instead indicate a semiannual cycle.

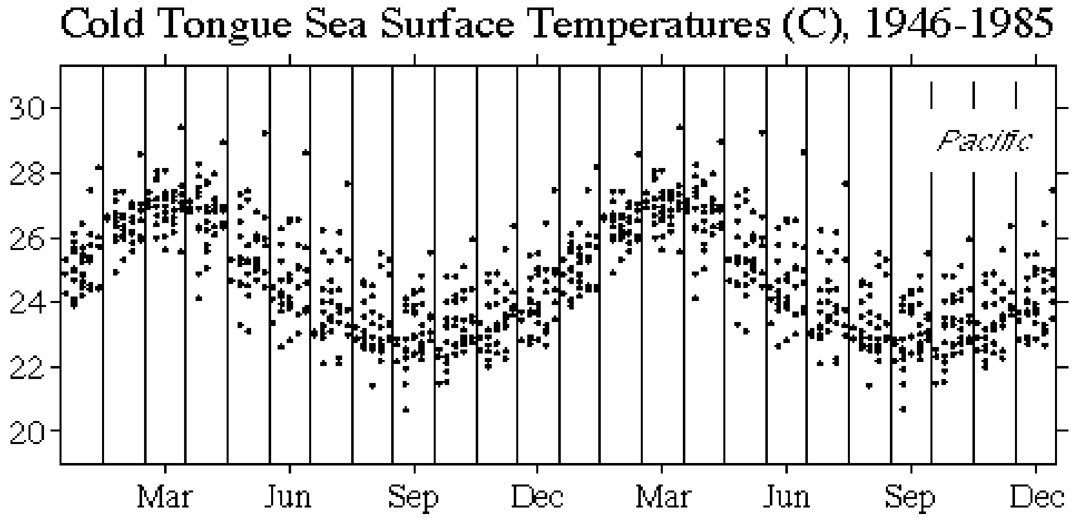


Figure 1.5. Annual cycle of sea surface temperature in the cold tongue.

The seasonal march of rainfall, temperature, wind, and ocean currents in the cold tongue/ITCZ complex seems surely to be linked to the American monsoon, but the mechanisms by which the coupling occurs are still unclear. The oceanic seasonal march near the equator does not follow any simple model for the oceanic response to atmospheric forcing: cold sea surface temperatures are present typically nine months of the year, with the warming confined to a period of less than three months ending in March; the usual westward surface flow reverses from April through June even though the wind continues to blow from the east; and the eastward flow in the subsurface equatorial undercurrent is at a maximum in May-June, following the period of weakest surface easterly wind stress. It is notable that the maximum sea surface temperature in March precedes the onset of the period of eastward flow that advects warm water eastward. The notion that a reduction in easterly wind stress leads to reduced upwelling and so to a deeper thermocline and warmer sea surface temperature does not appear to be applicable to the seasonal march: the seasonal variations in thermocline depth and sea surface temperature (Figure 1.6) do not exhibit the well-defined inverse relation characteristic of the ENSO cycle. Hence, it appears that the processes responsible for the sea surface temperature variations in the seasonal march and the ENSO cycle may be quite different.

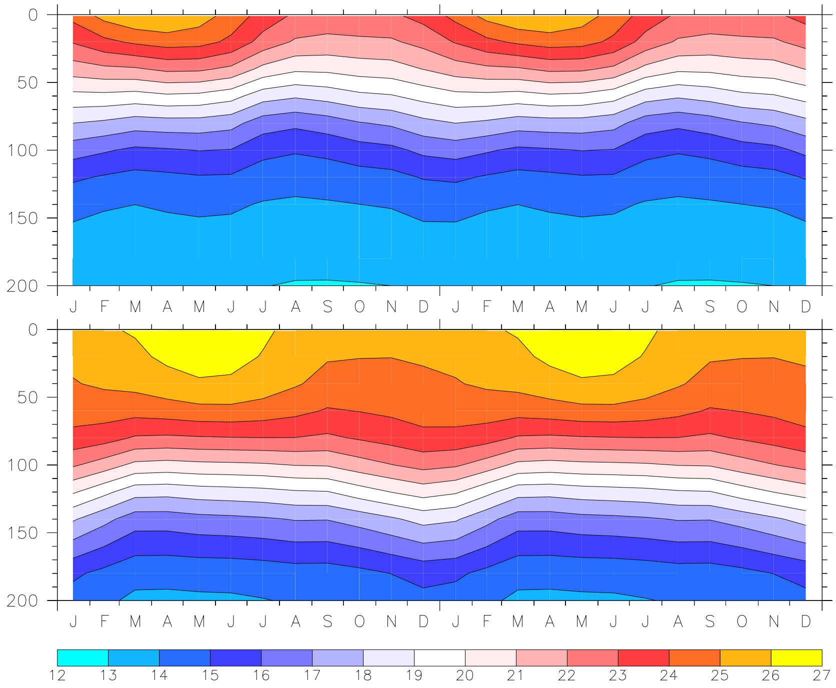


Figure 1.6. Climatological mean temperatures (°C) at 100°W (top) and 140°W (bottom) on the equator.

Over the tropical eastern Pacific the seasonal march is more pronounced and more regular from year to year in the meridional wind stress than in the zonal wind stress because the meridional wind component is more directly tied to the seasonal march of the monsoon convection over Central America. Seasonal variations in the meridional wind stress can induce a seasonal march in surface temperatures on or near the equator in several ways: wind speed affects the net sensible and latent heat flux at the air-sea interface and the amount of wind-induced mixing and entrainment in the mixed layer; wind stress curl can induce upwelling or downwelling; meridional stress can force meridional flow and change the rate of upwelling and meridional temperature advection, etc. The relative importance of these processes in the seasonal march of sea surface temperature has yet to be determined.

It has been suggested that the modulation of the strength of the cold tongue may be an important factor in accounting for the absence of a rainy season at the time of the September equinox over much of equatorial South America. The seasonal march in the latitude of the ITCZ may also contribute to the southward displacement of the jet stream over the United Sates in springtime relative to autumn which favors heavier rainfall and a higher frequency of occurrence of severe thunderstorms to the east of the Rockies in springtime.

Just as east-west thermal contrasts and circulations in the atmosphere and upper ocean play a dominant role in the ENSO cycle, it appears that north-south thermal contrasts and the related circulation cells in the atmosphere and ocean may be instrumental in producing the distinctive features of the seasonal march in the eastern tropical Pacific. They may also account for some of the interannual variability.

Another intriguing feature of the seasonal march over the Americas is the abrupt onset of the summer monsoon over much of northwestern Mexico and the southwestern United States around July 1. This event is accompanied by decreases in rainfall over the northern Rockies, the U.S. Great Plains, and parts of the Caribbean and Central America and it coincides with an abrupt rise in sea level pressure over Mexico. The increased pressure gradient across Central America is accompanied by a freshening of the northeast trades at some locations. The reversal of the surface winds over the Gulf of California from northwesterly to southeasterly is accompanied by an abrupt increase in low-level moisture. In view of the modest change in the climatological mean insolation from June to July, the magnitude, abruptness, and year-to-year regularity of this shift in rainfall and associated circulation pattern is quite remarkable.

1.3 Challenges in Modeling the Eastern Pacific

Basic to the plan for EPIC is the intent to build toward improved ability to predict seasonal-to-interannual variability in the eastern tropical Pacific and its impact on the Americas. The challenges to modeling in the eastern Pacific are reviewed here as background for the development of the plan for EPIC.

1.3.1 Atmospheric General Circulation Models

One of the common flaws in the atmospheric general circulation models (AGCMs) is the underestimation of wind stress in the equatorial belt. It indicates the lack of grid resolution to resolve the poleward eddy momentum flux and representation of topographic effects on the low-level flow. The Andes, for example, may play a crucial role in maintaining the prevailing along-shore surface winds off Peru and the associated oceanic upwelling in that region. The models also underestimate the coverage of oceanic boundary layer stratus clouds, which play an important role in the energy balance of the atmospheric boundary layer and the oceanic mixed layer and are believed to be responsible for much of the equatorial asymmetry of SST in the tropical eastern Pacific. Furthermore, the cumulus parameterizations of deep convection in AGCMs are not adequate to simulate the precipitation in the ITCZ.

The AGCMs often produce unrealistic atmospheric boundary layer structures which are crucial for the simulations of both deep convective processes in the ITCZ and the boundary layer stratus clouds. This will also lead to unrealistic surface fluxes calculated in AGCMs in the ITCZ/ cold tongue complex. Increasing the horizontal resolution and improving the physical parameterizations, especially the treatments of the deep convective clouds and boundary layer stratus clouds are required to improve the prediction scale in the AGCMs.

1.3.2 Mesoscale Atmospheric Models

Understanding and simulating the detailed distribution of rainfall over the Americas and in the oceanic ITCZs will not require resolving mesoscale processes over the entire globe. Incorporating nested high resolution mesoscale models that resolve mesoscale phenomena within AGCMs and coupled GCMs can be an effective tool. Preliminary experiments with high resolution mesoscale models have yielded more realistic depictions of the near-surface circulation and rainfall than AGCM simulations. Mesoscale model simulations have demonstrated the importance of resolving the complex terrain along the Mexican coast to the rainfall distribution in the region. Experiments with varying grid resolutions in the mesoscale models have also indicated that the precipitation in the oceanic ITCZ region is sensitive to changes in grid resolutions and representation of deep convection as well as the physical processes in atmospheric boundary layer. However, there are very little, if any, observations in the ITCZ/cold tongue region to initialize and validate these high resolution mesoscale models.

1.3.3 Ocean General Circulation Models

The processes that determine the annual march of SST in the eastern equatorial Pacific Ocean are only partly known, yet this is a crucial fact of the climatology in the PACS domain, particularly with respect to the annual march of the ITCZ and the northwestward shift of the American monsoon from equatorial South America to Central America and Mexico in boreal summer. Although the annual march is largely a reflection of coupled air-sea interactions, there remain a number of important questions concerning the processes that contribute to SST variability in this region that could be addressed in the context of OGCM experiments in which the ocean is forced by specified atmospheric fluxes. There are large uncertainties in the surface forcing fields and few observational studies of ocean processes in the eastern Pacific. As accurate air-sea flux fields for the eastern Pacific become available and the important components of the ocean response become better understood, improvement of coupled models will be expedited.

The mechanisms that control the annual march of SST in the monsoon regime of the eastern tropical Pacific appear to be fundamentally different from those in the trade wind regime of the central Pacific, upon which much of the prior OGCM development effort has been focused. In the central Pacific, zonal wind variations are a dominant mode of forcing, and SST often appears tied to thermocline depth variations, which are dominated by the interannual variability. In the east, by contrast, the fact that the annual cycle of cold tongue SST variability is much more regular than that of thermocline depth suggests that remotely forced equatorial ocean wave activity might not be the pacemaker for the annual march. The lack of correspondence between fluctuations in SST and thermocline depth in the east attests to the importance of other processes such as insolation and other surface fluxes, upwelling, horizontal advection, and vertical mixing in the heat balance. Vertical mixing influences SST not only by entraining cold water into the upper layer, but also by changing the mixed layer depth over which the surface heat and momentum fluxes are distributed. The thermocline can be quite shallow in this region, trapping this complex set of processes in a thin layer. Therefore, very fine vertical resolution may be necessary to model these processes accurately, and proper accounting for changes in mixed layer depth is crucial.

Ocean models have been able to simulate some aspects of annual variability in the eastern equatorial Pacific, particularly features with large zonal scale such as the basin-wide pressure gradients and zonal currents, yet they have had trouble simulating the annual cycle of SST in the eastern Pacific without resorting to parameterizations that to some extent predetermine the result through either relaxation terms or particular specifications of the heat fluxes. It is unclear to what extent these unsatisfactory results are due to incomplete model physics or insufficiently well-observed surface forcing functions. Efforts to improve these models have often focused on parameterization of mixed layer physics, upwelling and entrainment. One of the major motivations for the EPIC field studies is the need for improved estimates of the surface fluxes for testing the various OGCM parameterizations.

As in the atmosphere, an issue that remains unresolved is the rectification of high-frequency forcing and internal instabilities into the low-frequency variability. Such forcing includes the equatorial intraseasonal waves, and instabilities that are prominent particularly north of the equator at periods near 20–30 days; both these signals are modulated by the annual cycle and by ENSO. Model results suggest that the vertical velocity field can fluctuate rapidly in connection with these and other phenomena. Since mixing is an irreversible process, the net effect of high-frequency signals on the annual cycle might be quite different than would be deduced from low frequency averages alone.

There also appears to be important smaller-scale regional variability that escapes the resolution of basin scale OGCMs but that may be significant for understanding the heat, mass, and momentum budgets over the eastern tropical Pacific. The region up to a few hundred km of the Central American coast is generally very warm but can cool rapidly in response to winter northerlies blowing through gaps in the American cordillera. South of the equator, the annual coastal upwelling signal has been cited as important for the development of much larger-scale phenomena, but the processes by which the narrow coastal features might influence the larger scale have not yet been clearly elucidated. Present basin-scale OGCMs handle these near-coastal signals poorly.

The question of closure of the equatorial and tropical current systems in the east Pacific remains obscure. The fate of water flowing eastward in the North Equatorial Countercurrent and Equatorial Undercurrent is not known. To date, these current systems have been largely understood as a feature of the dynamics of the broad central Pacific, far from boundaries, where the zonal scales are very long. Similarly, the source of water upwelled in the equatorial cold tongue, the depth from which it originates, and the meridional extent of the upwelling water can be traced back to the surface in extratropical regions, as has been suggested from theory. These and other questions about the closure of the current systems in the east speak to the most fundamental aspects of the ocean circulation in the PACS region; they will become tractable as the community develops confidence in the performance of OGCMs in the tropical eastern Pacific.

1.3.4 Coupled Ocean-Atmospheric Models

Coupled models tend to produce an unrealistic symmetric circulation with ITCZs north and south of the equator, often associated with unrealistically warm equatorial sea surface temperature and lack of extensive boundary layer cloud decks compared to the observations. The coupled models exhibit considerable sensitivity to changes in parameterization of physical processes in the stratus deck region. The feedback between SST and the stratus deck is complex and not well represented in the coupled models.

A number of important technical issues in the design of coupled models have yet to be resolved. Typically, the ocean component of coupled models used for simulating seasonal to interannual variability in the tropics has considerably higher horizontal resolution than the atmospheric component. The fluxes of momentum, heat, and fresh water at the interface between the model components are calculated on the coarser atmospheric model grid. This grid incompatibility implies that while the ocean model grid may resolve the complex coastal geometry reasonably well, the surface forcing to the ocean model in the vicinity of the coastal regions does not adequately represent the complexity of the coastal geometry. This problem can lead to relatively large SST errors along the tropical American coast lines. Furthermore, simulations of the feedbacks between the atmosphere and the ocean is compromised to some extent because the atmosphere component is incapable of responding to the fine structure in the SST field such as the equatorial cold tongues and narrow coastal upwelling zones. The technology of incorporating nested high-resolution atmospheric mesoscale models in global models is needed to explore the effect of grid resolution in the coupled models.

The complex terrain and geometry of the tropical Pan American region in many ways dictates the need for high resolution coupled models. The importance of regional topographic features can be seen during the Mexican monsoon when the rainfall is heaviest along the narrow western slopes of the Sierra Madre Occidental. The June through September rainfall along the western slope of the Sierra Madre Occidental can exceed 65 cm, whereas less than 200 km directly to the west the wet season rainfall is over 40 cm less. This mesoscale structure in the mean Mexican Monsoon is strongly influenced and modulated by the complex surface characteristics of the region from Gulf of California in the west to the Mexican Highlands in the east. However, these complex surface features are absent or are severely under resolved with current coupled GCMs. The narrow Andes mountains also play a profound role in the monsoon circulation over Ecuador, Colombia and Central America. The classic mountain/no-mountain experiments with the R40 atmospheric GCM and the 80 km Eta model have shown that the GCM underestimates the importance of the topography in influencing the circulation and rainfall during the tropical South American wet season. While it is clear that the continental monsoons are closely linked to the details of the orography, it is also becoming more apparent that the continental monsoons are further complicated by interactions with the oceanic ITCZs. Simulating and predicting the physical processes which drive these monsoons is more complex than just modeling the response to orographic forcing and requires models that resolve the mesoscale details of the orography and the physics and dynamics of the monsoon circulation as well as the complex interaction with the oceanic ITCZs.

While the structure of the topography and the coastal geometry indicates the need for high resolution component models, simulating the oceanic ITCZs also dictates the need for high resolution coupled models. For example, the northern branch of the Pacific Ocean ITCZ extends across much of the basin, merges with the continental monsoons of central and northern South America, but is meridionally confined to only a few degrees of latitude between 5°N and 10°N. The highest SST, also exhibiting a range of spatial scales, is observed to be more or less coincident with the ITCZ in the eastern Pacific. Associated with the small meridional scales in the ITCZ precipitation and SST are strong meridional gradients of wind and wind stress which drive the narrow North Equatorial Counter Current (NECC) and the equatorial upwelling that helps maintain the sharp cold tongue to the south. Very high resolution coupled ocean-atmosphere models are needed to simulate these features.

Coupled models tend to be more sensitive to small perturbations and to display more complex behavior than their OGCM and AGCM components. Hence, to promote a better understanding and improved modeling of various physical processes, it will be necessary to consider the coupling between the ocean and atmosphere over a wide spectrum of time scales, ranging from diurnal to seasonal, and out to decades or longer.

Coupled models will provide the ultimate test of any theory of why the ITCZ/cold tongue complexes exist, why they tend to be asymmetric about the equator, and why they exhibit a strong annual cycle and interannual variability. These models will be the principal tool for prediction of the seasonal-to-interannual variability of the eastern Pacific and the Americas and their influence on global climate. To improve the coupled models requires a better description of the seasonal-to-interannual variability and understanding of the physical processes responsible for the variability.

1.4 Objectives of the Eastern Pacific Field Investigation of Climate Processes

Based on the discussions in Section 1.3, it is clear that we do not have the basic understanding of the ocean-atmosphere coupling in the eastern tropical Pacific required for development of the capability to make reliable seasonal to interannual predictions in this region and to explore the remote influences of the eastern tropical Pacific.

EPIC is planned to address this lack of understanding. Its scientific objectives are:

I. To observe and understand 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, including:
   (a) mechanisms governing temperature and salinity field evolution in the oceanic cold tongue and in the region of strong meridional gradient in sea surface temperature from the oceanic cold tongue through the ITCZ;
   (b) atmospheric planetary boundary layer structure and evolution from the equator through the ITCZ, primarily in the southerly monsoonal regime; and
   (c) the processes determining the existence, character, and strength of deep convection in the northeast Pacific ITCZ.

II. To observe and understand the dynamical, radiative and microphysical properties of the extensive boundary layer cloud decks in the southeasterly tradewind and cross-equatorial flow regime and their interactions with the ocean below.

Achieving these scientific objectives will provide knowledge and observations crucial to the improvement of model parameterization schemes. To achieve the scientific objectives a field plan is presented here that consists of activities that include monitoring to be sustained for many (~5) years, investigations of processes spanning a season or the annual cycle (~6 to 18 months), and high intensity process studies to be concentrated within one month. Specific activities are presented to illustrate that the scientific objectives of EPIC can be met. This plan is not meant to be exclusive, and additional field efforts are encouraged.

EPIC process studies will be conducted in the equatorial Pacific west of 95°W with an atmospheric focus between 95°W and 110°W, in the southerly regime, and in the stratus deck region off the coast of South America. Oceanographic studies will have a broader extent in order to investigate the contributions to the formation and maintenance of the cold tongue by upwelling and other processes along the equator west of 110°W. Furher extensions of the spatial coverage of the EPIC field work toward Central and South America are being sought through international collaboration facilitated by VAMOS. Some elements of the process studies will focus on the seasonal cycle, and the air-sea coupling and oceanic and atmospheric processes governing the CTIC and stratus deck regions over the course of a year; such elements will collect data for periods of several months up to two years, and be deployed in 2000 to 2003. Other elements of the process studies will be intense, localized in time and/or space, to focus on understanding and parameterizing specific processes; such work is anticipated to be conducted in field campaigns lasting approximately one month.

The eastern Pacific is a region that is essentially without operational in-situ data (the TOGA TAO array of equatorial moored buoys being an exception). Enhanced in-situ and satellite-based monitoring of the eastern Pacific ocean and atmosphere is needed to provide context for the more focussed process studies. Overlap in enhanced monitoring in support of EPIC objectives as well as continuation of enhanced monitoring begun in the pilot phase of PACS are desirable. These monitoring activities should also be developed in coordination with VAMOS, in order to exploit and foster linkages to other climate studies in the Pacific and over the Americas.

2. SCIENTIFIC BASIS FOR EPIC

Two focal points have developed for EPIC: the cold tongue-ITCZ complex and the stratus deck regions. This section reviews the scientific issues associated with each.

2.1 Coupled Ocean-Atmosphere Dynamics in the Cold Tongue-ITCZ Complex (CTIC)

A successful theory of the climate system in the eastern Pacific region must explain why the cold-tongue/ITCZ complex (CTIC) exists, why it tends to be asymmetric about the equator, and why it exhibits a strong annual cycle. Coupled ocean-atmosphere models will provide the ultimate test of such a theory, but the coupling between the Intertropical Convergence Zone (ITCZ) and equatorial current systems in the region of the cold tongue has neither been well documented nor understood, even though such knowledge is crucial to the ability to predict ENSO and the seasonal cycle over the Pacific and surrounding land masses.

The eastern Pacific's ‘Southerly Regime,’ includes both the coolest equatorial surface waters as well as a wide zone of high SST north of the equator (see cover figures). Winds in this region blow nearly directly across the most intense SST front in the tropical ocean during the season of cool equatorial SSTs. This SST front just north of the equator is often extremely sharp and is distorted by oceanic tropical instability waves. Immediately to the north of the equatorial front is a region of strong air mass modification, where northward moving air that has just crossed the equatorial cold tongue flows over warmer surface waters. The transition is marked by an abrupt increase in surface wind speed and a decrease in surface humidity. The boundary layer becomes unstable and drier as faster-moving air is mixed down toward the surface. Stratocumulus clouds form, and are analogous to those that develop when continental air flows over the Gulf Stream during wintertime. These surface meteorological conditions and the underlying SST pattern exhibit substantial seasonal and interannual variability, as does the location, structure, and intensity of the ITCZ. The eastern tropical Pacific ITCZ fluctuates seasonally between raining more intensely than anywhere else in the basin and splitting into a pair of weak convergence zones astride the equator.

The interplay of atmospheric forcing and oceanic dynamic and thermodynamic response is what makes the problem of eastern Pacific ocean-atmosphere coupling both interesting to study and important to understand. The conventional oceanographer's view is that the equatorial current system is almost entirely the result of wind stress forcing by the atmosphere, while the meteorologist's view has been that the distribution of sea surface temperature (SST) determines the location and strength of atmospheric convection, hence the wind stress pattern. The equatorial current system in the central Pacific is largely wind-forced, yet the winds themselves are determined at least in part by the SST pattern. In the eastern Pacific, air-sea fluxes of heat and moisture compete with wind stress to force the ocean. The connections between thermocline structure and SST are not known sufficiently well for the purposes of predicting the location and strength of the ITCZ and its associated wind pattern. The EPIC program focuses on observing and understanding key elements of the connections between the ocean and atmosphere in the CTIC.

2.1.1 Upper Ocean CTIC Processes

The present generation of ocean general circulation models has difficulty maintaining the correct balance of heating, mixing, and advection to sustain vertical thermal structures like those observed, especially in the eastern third of the Pacific Ocean. The strongly non-zonal character of trade winds in the eastern tropical Pacific induces exchanges of heat and moisture with the ocean that differ with exchange processes further west in the Pacific basin.

The evolution of eastern Pacific SST patterns depends on complex interactions between the surface fluxes and upper ocean structure. Upper ocean stratification and shear varies considerably with latitude and in time, especially in the meridional direction. These underlying features set the background against which air-sea fluxes of heat, moisture, and momentum act to modify near-surface structure. Substantial surface heating and downward mixing of heat are needed to balance the equatorial upwelling of cold water driven by Ekman divergence induced by the surface easterly wind stress in the cold tongue. Between the cold tongue and the ITCZ, surface fluxes cool the ocean, while they heat it between the ITCZ and the Central American coast. Meridional alternation of the direction and magnitude of surface heat flux is sufficient to induce a surface dynamic height change in less than a year equal and opposite to that of the observed dynamic topography associated with zonal mean currents. A combination of zonal advection by the nearly zonal equatorial current, vertical and meridional advection induced by easterlies near the equator, meridional exchange via the seasonally appearing tropical instability waves, and vertical mixing redistribute the heat and moisture exchanged across the sea surface.

Scientific Issues:

The temporal and spatial evolution of eastern tropical Pacific Ocean structure depends on the combined effect of a number of prominent processes. Dynamic and thermodynamic forcing, mixing, and advection (both horizontal and vertical) are at work, and the details of their interplay is the crux of understanding the oceanic linkages between large scale oceanic structure and SST.

The balance of advective effects in causing changes in upper ocean temperature and salinity differs substantially with location in the eastern tropical Pacific. Zonal advection, while generally credited with causing the North Equatorial Countercurrent surface temperatures to be warm and those of the South Equatorial Current to be cool by virtue of the sources of these flows, can only induce minor changes in upper ocean temperature. Scaling arguments demonstrate that meridional and vertical advection are potentially more powerful agents of change. In the cold tongue region, vertical advection is believed to be the dominant effect to balance surface heating with meridional advection playing a smaller but still important role. Downward air-sea heat flux, if absorbed between the surface and the pycnocline, heats this region at a few W m^{-3}, enough to raise upper ocean temperatures by about one degree Celsius in 10 days. Upwelling and poleward near-surface flow offset this potent tendency in the cold tongue. In the eastern Pacific warm pool, also a region heated at a rate of a couple of W m^{-3} on average by surface fluxes, meridional advection tends to cool the upper ocean by exporting heat equatorward. In the zone between the cold tongue and the warm pool, where surface heat fluxes are upward tending to cool the upper ocean, downwelling effects heating while meridional advection may act in either sense to change upper ocean temperature. Slight imbalances in surface heating, advection, and downward mixing are enough to cause upper ocean temperatures to evolve seasonally and interannually at rates of one degree Celsius per 100 days or less. The nature of the imbalances that cause seasonal and ENSO changes has never been observed in the eastern Pacific. Briefly, for the various processes, the issues are reviewed.

Surface forcing: The upper ocean heats and cools diurnally, seasonally, and interannually under the influence of radiation, sensible heating and evaporation. All of these signals are strong in the eastern Pacific compared with elsewhere in the tropical ocean (Figure 2.1). A variety of cloud patterns influence the surface radiative budget, from cumulus towers to stratus decks. Cumulus convection is concentrated in the ITCZ, while stratus decks are found over the cool pool along the equator, and south of it, east to the South American coast. There are, at present, large uncertainties in the climatological and model-based air-sea flux fields in the CTIC.

Mixing: The relative roles of shear and buoyancy-driven mixing need to be examined. Nighttime convection depends not only on surface conditions (both SST and sea surface salinity (SSS)), but also on upper ocean stratification and shear structure. Surface mixed layer depths are thin in the eastern tropical Pacific and tend to vary in thickness in proportion to pycnocline depth (Figure 2.2). The depth to and from which buoyancy is transported vertically has large dynamical consequences because comparatively weak horizontal pressure gradient forces balance strong geostrophic currents at low latitude.

The cross-frontal structure of mixing is expected to be particularly prominent in the Southerly Regime because spatial gradients are relatively stable. While upper ocean fronts in such places as subtropical and polar convergences meander considerably and break into eddies, the equatorial front between the Cold Tongue and the ITCZ is a more seasonally persistent feature and tends to meander relatively regularly due to tropical instability waves. Spatial variations in heat, fresh water, and momentum fluxes are induced by frontal structure, particularly when winds blow across it, as they do in boreal autumn (Figure 2.1). These variations can be expected to influence mixing processes and control upper ocean stratification, SST, and SSS.

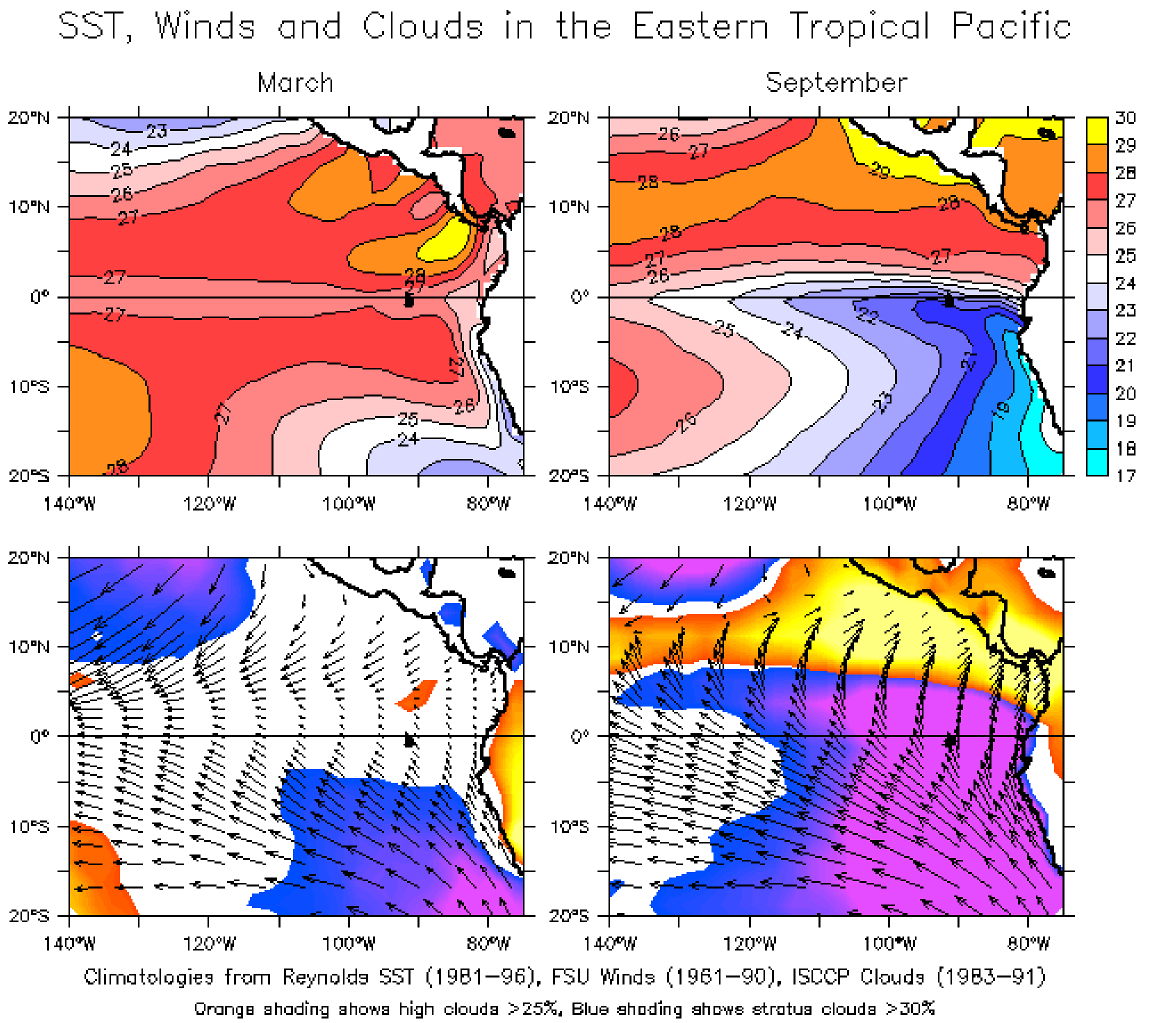


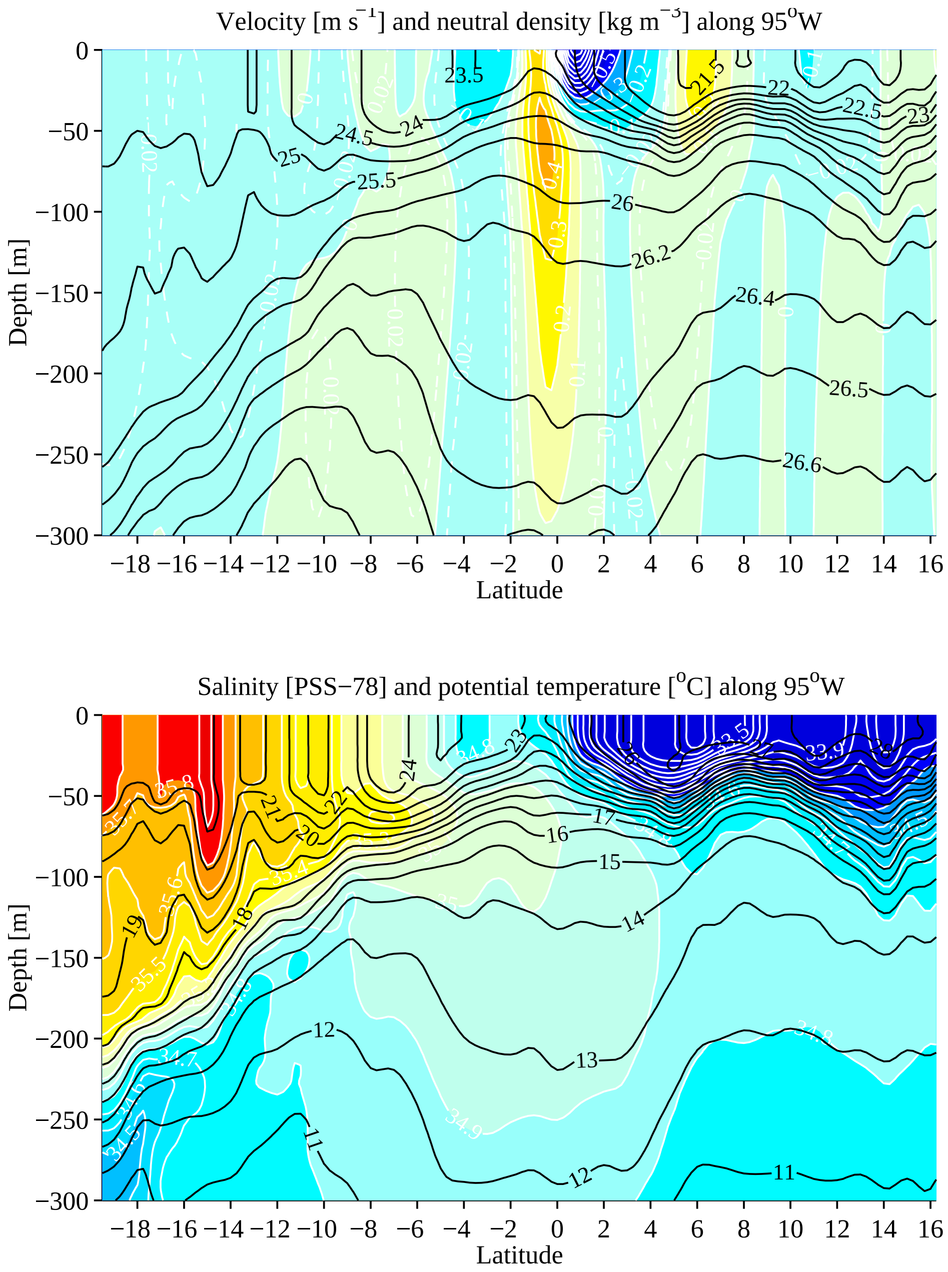
Figure 2.1. Climatological SST (°C, upper panels) and wind vectors and cloud cover (relative scales, bottom panels) for March (left) and September (right) in the eastern tropical Pacific.

Episodic events that cause mixing in the eastern tropical Pacific include tropical cyclones and wind bursts through the mountain gaps of central America. Both kinds of events can lead to large changes in upper ocean structure, including SST and SSS. While cyclones are likely to deposit fresh water at the ocean surface, gap wind events probably enhance evaporation and destabilize the layer.

Horizontal advection: Mean and seasonally varying currents are powerful agents of horizontal advection particularly in the eastern tropical Pacific, and their role in maintaining the spatial gradients in SST needs to be examined. Warm water is imported from the west, north of the equator, by the North Equatorial Countercurrent (NECC) (between 5°N and 8°N at 95°W, upper panel, Figure 2.2). This water is often associated with the location of the ITCZ. The freshest SSS is found there, while the highest SST is found further north (lower panel, Figure 2.2). The seasonal modulation of the NECC presumably accounts for much of SST variation in the warmest zone north of the equator (compare top panels in Figure 2.1 from 5°N to 15°N). The South Equatorial Current (SEC), by contrast, imports colder water from the eastern boundary and the subtropical gyre to the south. Its transport fluctuates seasonally by a large fraction of its mean. Deeper, the Equatorial Undercurrent (EUC) carries colder water eastward and deposits it at ever shallower depths to the east. Both the SEC and the EUC tend to import cooler water to the upper ocean in the eastern tropical Pacific. The thermocline is found as shallow as only a few tens of meters below the surface in the eastern tropical Pacific. The effects of these persistent, nearly zonal, currents on upper ocean stratification is profound. Stratification evolves not only dynamically as changes in the ocean's pressure field spread or contract isopycnals, but also due to importation of water of different temperature and salinity from afar.

Horizontal variation in wind stress and upper ocean stratification combined with lateral gradients of temperature and salinity results in Ekman transports of heat and salt that contribute to advective evolution of property distributions. The details of Ekman spiral structure determine wind forced advection of heat and fresh water. The close proximity of the thermocline and its associated shear make Ekman dynamics a potentially powerful contributor to horizontal advective change.

The equatorial wave guide supports the now well-known trapped free modes, forced by the wind principally in the form of Kelvin, Rossby, and Rossby-gravity waves. While much of tropical ocean dynamics appears explicable via free wave behavior, the relevance of free waves in the eastern tropical Pacific is less clear because of reflection from the complicated geometry of the coast together with local forcing. Tropical instability waves arise from meridional and vertical shear inherent in the equatorial current system. While they are less prominent in the eastern tropical Pacific than farther west, they may still constitute a potent mechanism for mixing heat and fresh water meridionally across the frontal zone found just north of the equator. At the very least, their variability must be resolved.



Velocity [m s^{-1}] and neutral density [kg m^{-3}] along 95^{o}W

Salinity [PSS−78] and potential temperature [^{o}C] along 95^{o}W

Figure 2.2. Oceanic zonal velocities and properties along 95°W. All available CTD data between 85°W and 102.5°W are averaged on neutral density surfaces in 1° latitude bins. Zonal geostrophic velocity estimates are relative to a 500 dbar level of no motion and are filtered with a 2° latitude half-width Blackman filter. Top panel shows zonal velocity [m s-1] in color with white contours and labels and neutral density [kg m-3] with black contours and labels. Bottom panel shows salinity in color with white contours and labels and potential temperature [°C] with black contours and labels.

Vertical advection: The pattern of zonal currents and winds in the eastern tropical Pacific is similar but significantly weaker than those found further west. By contrast, the pattern of air-sea buoyancy fluxes is stronger in the eastern than in the central tropical Pacific, with mean downward heat fluxes as large as 100 W m^{-2} in the cold tongue and the ITCZ and upward fluxes of as much as 50 W m^{-2} in the narrow region between. Heating of the regions where the thermocline is shallow and cooling of those where it is deep has the tendency to erase the consistently observed pattern of zonal currents and their dynamic topography in a relatively short time. These surface fluxes must be compensated by other processes, and to the extent that they are not, the structure of dynamic topography and sea surface temperature must evolve. Upwelling is thought to provide the compensating heat flux in the cold tongue region, while downwelling and meridional advection may be providing the necessary warming of upper ocean waters in the region of the dynamic height ridge separating the North Equatorial Countercurrent and the South Equatorial Current. Mean vertical-meridional flow found in models (Figure 2.3) suggests that three dimensional advection is very important to the circulation of the eastern tropical Pacific.

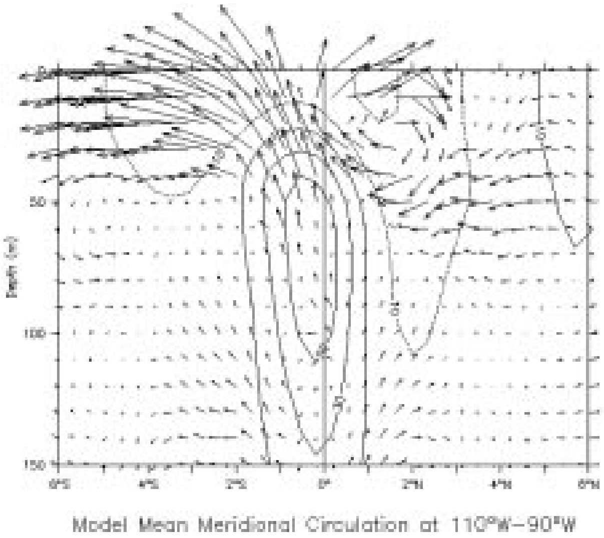


Figure 2.3. Mean circulation in the meridional/vertical plane calculated by a numerical model. Arrows indicate inclination of flow. Contours indicate zonal speeds (cm s^{-1}), solid eastward, dashed westward.

Hypotheses:

Consideration of the processes that contribute to maintenance and evolution of upper ocean structure, SST, and SSS in the eastern tropical Pacific suggests a number of distinct hypotheses. Not all of these offered below can be simultaneously true, but identifying and quantifying the degree to which each hypothesis holds will constitute understanding of the oceanic system. In turn, increased understanding will improve predictive ability.

The hypotheses to be considered in the oceanic budgets component of the proposed work are:

1) High SST is found near the ITCZ due to:
    - a) advection by the NECC
    - b) weak wind speeds that cause weaker mixing than elsewhere
    - c) precipitation that stabilizes the surface boundary layer
    - d) wind stress curl that deepens the pycnocline north of the NECC.

2) The sharp SST front found north of the equator is maintained and seasonally modulated by:
    - a) horizontal advection by the NECC and SEC
    - b) variations in surface fluxes of heat, fresh water, and momentum
    - c) vertical advection induced by Ekman convergence
    - d) horizontal mixing by tropical instability waves.

3) The cool water of the cold tongue results from several processes:
    - a) cross-equatorial winds induce meridionally asymmetric upwelling and cool SST
    - b) strong, local wind-driven mixing and/or strong shear in the equatorial currents that together with a shallow thermocline support entrainment of cool water from below.
    - c) cool, upwelled water from the coast of South America that is advected into the cold tongue.

These hypotheses together ask how the processes of advection and mixing contribute to produce the observed mean and seasonal behavior of upper ocean and surface layer structure in relation to major features of the atmospheric circulation in the eastern tropical Pacific.

2.1.2 CTIC Atmospheric Boundary Layer Structure and Evolution

The SST distribution in the eastern equatorial Pacific provides a unique lower boundary for the atmospheric planetary boundary layer (ABL). As air moves northward over the cold tongue in SST, turbulent mixing within the ABL is substantially suppressed as surface buoyancy fluxes become downward (Wallace et al., 1989). The boundary layer in this region is often capped by very dry air that can further affect boundary layer evolution through entrainment. But as the flow continues northward over the SST front on the north side of the cold tongue the evolution of the PBL responds to increased surface fluxes followed by a change in forcing due to strong, sometimes sharply defined, convergence at the ITCZ. These extreme (by tropical standards) variations in surface conditions and large-scale forcing are significant over distances of 500–1000 km and on time scales of 1–2 days.

The combined influences of the CTIC on ABL structure and evolution challenge our understanding and modeling capabilities as reflected by the poor representation of the ABL over the eastern Pacific by current operational analyses and numerical weather prediction (NWP) models. These shortcomings are significant since the ABL structure is an important factor in determining the surface fluxes, hence the feedbacks between the oceanic mixed layer. For example, the equatorial cold tongue is characterized by pronounced divergence in the surface wind fields (Figure 2.4) with strong and persistent anticlockwise turning of the wind with height, from southerly at the surface, to easterly at the top of the planetary boundary layer. Strong backing is not well simulated in boundary layer parameterization schemes in the current operational weather prediction models. In the absence of surface wind observations, these schemes tend to bring easterlies at the top of the planetary boundary layer down to the surface, thereby creating an unrealistic surface wind field for driving ocean models. In addition, proper representation of the ABL over the cold tongue/SST front is necessary for correct specification of the southerly inflow into the ITCZ and the associated moisture convergence that can help fuel deep convection.

Balloon soundings and wind profiler observations from ships during TAO buoy operations in the eastern Pacific and from the Galapagos Islands have provided some fuzzy snapshots of ABL structure in the region (Bond, 1992). Notably, the ABL tends to be stratified (non-mixed) over the cool water, suggesting that the vertical profiles of turbulent fluxes are non-linear. Although the TAO moorings provide continuous, long-term monitoring of some meteorological conditions just above the surface, the results from this monitoring will remain tentative and incomplete until more detailed process-type field measurements are made. Such measurements and the associated process studies should provide (1) a better understanding of the mechanisms responsible for PBL evolution, (2) guidance for improved parameterizations of these mechanisms in models, (3) the observations needed to validate models of boundary layer structure, and (4) a context for interpreting the extent in time but more limited in scope observations from the TAO array.

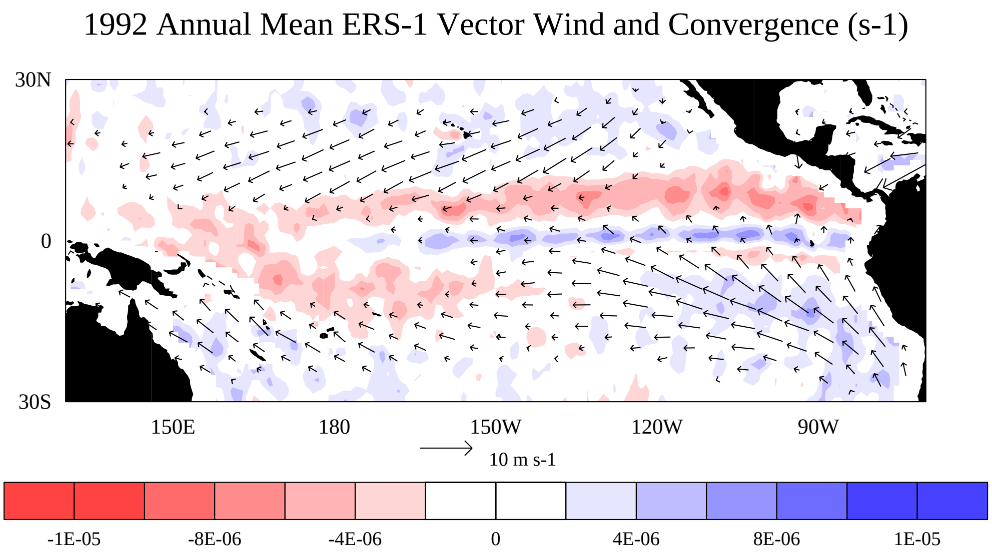


Figure 2.4. 1992 annual mean 10 m wind vectors from ERS-1 with the divergence field in color; convergence is red and divergence is blue.

The specific scientific issues that need to be addressed with process-oriented field work are framed as questions below, with brief supporting discussion.

What is the relative role of fluxes at the surface versus the top of the ABL (entrainment) on ABL structure and evolution? Since SST gradients can be large, the ABL is often in a state of disequilibrium with the surface. Flux profiles of momentum, heat and moisture over the entire depth of the ABL need to be determined to deduce how the profiles respond to temporal and spatial changes in both the lower and upper boundary conditions. It will also be necessary to obtain a better understanding of entrainment processes and the mechanisms and processes responsible for the formation and maintenance of decoupled boundary layers.

What processes are important for the formation and evolution of the low-level southerly jet across the cold tongue? This low-level jet is an especially important aspect of the ABL because of its role in forcing the ocean and as a source for the ITCZ. It is unclear how much the jet depends on vertically-varying (horizontal?) pressure gradients versus momentum fluxes.

Are the radiative effects of ABL clouds important to the surface energy budget of the CTIC? As the boundary layer air moves equatorward the fractional coverage of clouds decreases over the cold tongue and increases sharply over the higher SSTs to the north of the equator followed by a decrease over the ITCZ. It is unknown, however, if these systematic variations in the radiative forcing at the surface are important for the surface energy budget. The exact nature of the clouds in the CTIC has not been documented. It is unclear whether these clouds are classic stratocumulus associated with well-mixed boundary layer conditions or if the clouds are cumulus rising into stratus that are associated with deeper decoupled boundary layers.

What are the origin and implications of the extremely dry air found above the ABL at the cold tongue? This dry air has a direct impact on downward longwave fluxes, and indirect ramifications for turbulent and cloud properties near the top of the ABL through entrainment. The effects of this layer on the evolution of boundary layers in the CITC and the source of this dry layer has not been established.

What is the interaction between ABL characteristics and the ITCZ? The depth, speed, temperature and humidity of the ABL flow will both depend on and help control the convection at the ITCZ. For example, a thicker ABL might tend to promote low-level mass flux into the ITCZ, but would tend to include a lower surface equivalent potential temperature and Convective Available Potential Energy (CAPE), since the surface heat and moisture fluxes would be distributed over a greater depth. It remains to be determined how much the ABL outside the ITCZ depends on not just local effects but remote forcing by the ITCZ.

What controls the ABL structure in the cloud-free regions within the ITCZ? Because the overall environment of the ITCZ is much different than over the warm pool in the western Pacific, it is likely that the ABL's response to deep convection nearby will also differ. Illuminating comparisons could be made with some of the results from TOGA COARE. Previous studies in the central and eastern Pacific indicate that the cloud-free areas in the ITCZ are associated with low-level inversions at about 800 mb that inhibit deep convection (Firestone and Albrecht, 1986; Kloesel and Albrecht, 1989). But the factors that control the formation, maintenance, and the weakening of these inversions are not well understood. The relative role of local vs. remote controls (Schubert et al.,1995) on inversion heights and strengths is unclear.

2.1.3 Factors Affecting the Location, Strength and Variability of the Northeast Pacific ITCZ

Deep convection is a key player in the coupled ocean-atmosphere system in the eastern tropical Pacific. Though such convection is generally known to occur over and near the warmest ocean waters, we do not understand the laws governing its precise location, strength, and temporal variability. Furthermore, this convection is a key part of the atmospheric circulation that drives the oceanic flows in this region.

Over the eastern Pacific, rain falls from clouds whose tops do not show up as cold in infrared imagery as those associated with convection over and near the tropical land masses over the ‘warm pool’ region of the western Pacific. The lack of a strong relationship between cloud top temperature and rainfall is consistent with the finding in GATE (GARP Atlantic Tropical Experiment) that the vertical profiles of vertical velocity and latent heat release in synoptic-scale disturbances peak 2–3 km above sea level, compared to 5–10 km over the ‘warm pool’ region of the tropical western Pacific. Strong boundary layer convergence evidently plays a critical role in maintaining the shallow but extremely persistent convection in the ITCZ. Operational weather prediction models and climate models have had difficulty simulating the intensity of the ITCZ rainfall and the diversity of the convective heating profiles observed in different parts of the tropics. Existing model parameterizations of radiative transfer in clouds, cloud microphysics, and convection will need to be reconsidered in light of this problem.

The northern hemisphere preference exhibited by east Pacific deep convection is clearly related to the existence of a large pool of warm surface water to the north of the equator, with the warmest waters occurring immediately adjacent to the Mexican and Central American coastline in the northern summer. The heat source represented by the summertime Mexican plateau and Central American highlands may also play a role. Curiously, the strongest convection often occurs not over the warmest waters but on the warm side of the steep north-south gradient in sea surface temperature that bounds this ‘east Pacific warm pool’ to the south.

Deep convection in the east Pacific monsoon trough is not steady, but is strongly modulated on diurnal to decadal time scales. Modulation on time scales of a few days to a week is thought by some to be related to the impingement of African easterly waves on the eastern Pacific while others believe it to be an intrinsic instability. This modulation is intimately related to the development of east Pacific tropical storms. Indeed, the region is the most prolific producer of tropical cyclones per unit area in the world. Modulation on intraseasonal time scales could conceivably be related to the Madden-Julian oscillation. We have already mentioned the strong annual cycle. Interannual variations are clearly related to the sea surface temperature anomalies of El Niño.

Many of our questions about the east Pacific monsoon trough relate to its temporal variability. The diurnal oscillation of east Pacific convection is clearly associated with the daily cycle of insolation, but whether this is a local phenomenon or a process involving larger scale dynamics is not known. The mechanism by which easterly waves modulate convection is unknown as well. Do these waves change the surface fluxes or the thermodynamic profiles or is there a more subtle mechanism? There is evidence that intraseasonal variations in the north-south gradient of low level potential vorticity in the Caribbean correlate with east Pacific cyclone production, but the operative mechanism is obscure.

Convection in the monsoon trough is fed at low levels primarily by a cross-equatorial flow. As this air flows toward the north, it gains energy through fluxes from the increasingly warmer sea surface north of the equator. The modulation of convection could be caused by the modulation of the strength of this flow. Alternatively, changes in the thermodynamic characteristics of the flow or of the convective environment could alter the strength of convection. Variations in the strength of the inflow and the sea-air fluxes into it thus become crucial factors in understanding the modulation of convection, as do variations in the profiles of temperature, humidity, and horizontal wind in the convective region. Monitoring these factors on time scales compatible with those of the variabilities of interest is thus needed. An intensive field program of about 4 weeks duration could investigate changes on the easterly wave time scale and shorter scales. Extended monitoring by upgraded TAO buoys and other means could address longer time scales such as those of the Madden-Julian oscillation and seasonal cycle.

Fundamental research on convection over the past 30 years is beginning to pay off in terms of our knowledge of the morphology and behavior of convection as a function of environmental conditions. This research is now having an impact on the development of convective parameterizations for large scale atmospheric models. Though patterns of convective behavior are becoming clearer, we still cannot predict with complete confidence the characteristics of convection which will develop for any given set of environmental conditions.

Recent observational work with shipborne radars in the west Pacific in COARE and near 125°W in the 1997 PACS Tropical Eastern Pacific Process Study are expected to shed light on the nature of the convection in these two regions. However, the convection in the ITCZ at 125°W is significantly different from that in the monsoon trough at 95°W, where land masses to the north and east undoubtedly influence the circulation. Comparison of the characteristics of convection at 95°W with that in the west Pacific and the ITCZ convection near 125°W will be very useful for testing our ideas about convective parameterization.

Scientific Issues:

With the above comments in mind, we propose in EPIC to address the following scientific issues:

What are the conditions related to the existence, character, and strength of deep convection in the east Pacific monsoon trough?

How do the characteristics of convection in this region compare with those found in ITCZ convection at 125°W and warm-pool convection in the west Pacific?

Answering the first question will help us understand to what degree the annual and interannual variability of the east Pacific monsoon trough is due to local sea-air interactions, and to what degree it is a consequence of changes in the global atmospheric circulation, that may or may not be directly related to local changes in SST. Given the roughly two-dimensional character of the monsoon trough, determination of cross-trough sections of thermodynamic profiles, winds, convergence, sea surface temperature, and surface fluxes, along with measurements of convective characteristics, should satisfy the above objectives. Since waves in the trough propagate from east to west, a time series of measurements would give us pseudo-three-dimensional coverage of trough characteristics. The diurnal cycle of the monsoon trough needs to be explored by sampling at different times of day. This is important because a better understanding of this cycle will help us estimate and possibly correct diurnal biases in the remote sensing of precipitation.

2.2 Air-Sea Interaction Processes in the Eastern Pacific Stratus Cloud Deck Regions

The expansive and remarkably persistent oceanic stratus cloud decks to the west of Peru exert a strong cooling influence in the local and global heat balance, as verified in recent experiments with ocean models and coupled models. They occur in regions of large-scale subsidence and their variability is governed by the interplay between radiative transfer, boundary-layer turbulence, surface fluxes, and cloud microphysics. They expand and contract on weekly, annual, and interannual time scales in response to changes in sea surface temperature and in winds and temperatures in the overlying air. They also follow a pronounced diurnal rhythm of nighttime thickening and daytime thinning. The variability of these decks is particularly large along their western edge, which marks the transition from stratiform cloudiness to tradewind cumulus as air parcels move downstream in the trades. Within these transition zones there appears to be some potential for positive feedbacks in the interactions between cloud amounts and the underlying sea surface temperatures: an increase in cloud amount should tend to cool the ocean and a cooler ocean leads to a shallower boundary layer in which the balance is shifted from cumulus clouds towards stratiform clouds, which tend to cover a larger fraction of the sky.

Coupled ocean-atmosphere processes in the eastern tropical Pacific are significantly influenced by marine stratocumulus clouds. This includes the classical subtropical stratocumulus, which for simplicity we will refer to as “California” (NE Pacific) and “Peru” (SE Pacific) regimes, and equatorial stratocumulus occurring in the region of the strong N–S sea surface temperature gradient around 85–110°W (Deser et al., 1993). The persistent stratocumulus decks off the coast of Peru play an important role in the equatorial asymmetry of SST and winds in the eastern Pacific. Prediction of cloud fraction and optical depth is difficult because relatively small changes in boundary layer conditions can substantially affect the character of the cloud field. The presence or absence of clouds makes a large difference to the net radiation balance at the sea surface and hence the SST.

Stratocumulus clouds still present great difficulty for GCM's which must attempt to capture complex physical processes with crude spatial resolution. However, in recent years high-resolution PBL models, such as Large Eddy Simulations (LES) and Cloud Resolving Models (CRM), have shown considerable success (e.g., Krueger et al., 1995). These models generate realistic subtropical stratocumulus cloud fields and simulate their life cycle from low stratus (e.g., off Oregon) to trade cumulus clouds (e.g., off Hawaii). Thus, besides the traditional method of advancing models by comparing them with spatially diverse climatologies (such as satellite data), much work is being done to apply field results from process studies to verify/improve high-resolution models. These are then averaged to GCM scales to develop and test parameterizations (e.g., Moncrieff et al., 1997). While there are still a number of small-scale issues confronting high-resolution models, most notably the entrainment rate (Moeng et al., 1996), their representation of stratocumulus clouds in the regions that have been heavily studied to date (e.g., northeast Pacific and northeast Atlantic) is far superior to the typical GCM. Based on this, it is our conclusion that near-future eastern tropical Pacific monitoring and process-oriented field work should not attempt to “solve” the stratocumulus problem. Rather, measurements should focus on demonstrating that the essentially unstudied regions in the eastern tropical Pacific (i.e., the equatorial and Peruvian regimes) can be handled as effectively by our present understanding and models.

Scientific Issues:

Boundary layer clouds depend largely on cloud top entrainment, drizzle, long wave and short wave radiative flux divergence within the boundary layer, and the surface fluxes of heat and moisture (Albrecht et al., 1995). The relative importance of these processes depends largely on the wind speed, sea surface temperature, subsidence, and the radiative properties of the free atmosphere. For example, the rate of entrainment is inversely proportional to the strength of the inversion, so that a large temperature inversion, associated with a region of subsidence, implies relatively weak mixing between the free atmosphere and the boundary layer. High boundary layer winds enhance the surface fluxes, which may in turn increase the cloud liquid water content. Many of the problems associated with stratus and stratocumulus clouds are beyond the scope of the proposed eastern tropical Pacific study; however, the program can benefit from the results of previous studies to focus on the processes that are unique to the eastern Pacific.

Similarities in the radiative characteristics of the boundary layer, for example, might obviate the need for extensive microphysics measurements in the Peruvian stratus and stratocumulus. Alternatively, if small changes in the sea surface temperature lead to large changes in the cloud structure, extensive mapping of the cloud field and mean boundary layer properties may be required. An assessment of the earlier work, combined with a relatively limited set of observations from the eastern tropical Pacific, could provide the rationale and scope for intensive field effort directed towards air-sea interaction in the region of stratus decks.

It is generally accepted that stratus and stratocumulus play an active role in determining the thermodynamic structure of the marine atmospheric boundary layer. Once formed, stratus clouds are often decoupled from the subcloud layer, which is immediately adjacent to the sea surface (Rogers and Koracin, 1992). This decoupling takes the form of a small temperature discontinuity, which forms due either to the radiative heating of the cloud layer, to the entrainment of dry, warm air from aloft, or to drizzle (Albrecht, 1989). The effects are interdependent and several processes may coexist. The net effect changes both the thermodynamic and dynamic structure of the boundary layer by limiting the effects of the surface fluxes to a shallow mixed layer. The depth of this layer is approximately the depth of the original stratus or stratocumulus subcloud layer. The continued warming of the cloud layer will lift cloud base forming a stable transition layer between the subcloud and cloud layers. The lower layer, which is sometimes referred to as the surface mixed layer, continues to moisten due to the surface latent heat flux. If air parcels at the sea surface are sufficiently buoyant they may reach their lifting condensation level and continue to rise through the transition layer as individual cumulus clouds (Martin et al., 1995). This often occurs where the surface forcing is strong, due to either high winds or large sea-air temperature differences or both, and when the boundary layer is capped by a subsidence inversion.

These penetrating cumulus clouds have several important effects on boundary layer cloud development. Since these are convective clouds, drops will grow more vigorously than in the stratus or stratocumulus. Large drops result in a decrease in the optical depth of the cloud and hence a decrease in the reflectance. However, since the cumulus clouds form at a lower altitude than the stratus, they tend to have a higher liquid water content, which increases the optical depth. The combined effect is uncertain. If penetrating cumulus clouds remain capped by the subsidence inversion, the cumulus clouds tend to maintain the stratocumulus. If the cumulus clouds are more energetic, however, or if the inversion is weak, the transport of air out of the boundary layer will produce local regions of enhanced subsidence. This descending motion will effectively break up the stratus or stratocumulus into isolated cells (Martin et al., 1997).

The satellite view of a nearly uniform stratus deck often belies the complex vertical structure of the clouds within the boundary layer. A model that fails to capture the effect of these interactions will tend to produce a uniform cloud layer that will be much shallower than the observed cloud deck. The surface response will be an overestimate of the incoming shortwave radiation and an underestimate of the downwelling longwave radiative flux.

Several questions need to be addressed:

What is the effect of the cloud layer on the net radiative flux at the sea surface? How does it vary with time? Are there feedbacks between the ocean and the cloud deck

What are the radiative properties of the cloud layer? How does the cloud field vary with time and why?

How does the boundary layer evolve as the air moves to the northwest from the stratus to the equatorial cold tongue?

What are the primary controls on the boundary layer structure? For example, how does the large-scale subsidence vary and what is the impact of this variation on the cloud field?

Hypotheses:

Our observational strategy for an eastern tropical Pacific stratocumulus study is based on three simple hypotheses:

1. High-resolutions PBL models developed on California/Azorian stratocumulus are equally applicable to equatorial and Peruvian stratocumulus.

2. Bulk parameterizations of radiative transfer properties (i.e., solar optical thickness and longwave emissivity versus integrated liquid water content and droplet or CCN number density), developed on northeast Pacific and northeast Atlantic stratocumulus (e.g., White et al., 1995; Gultepe et al., 1996), are applicable to equatorial and Peruvian stratocumulus clouds.

3. The stratocumulus cloud deck and cool SST underneath mutually reinforce each other through coupled fluxes.

While we do not expect the laws of physics to be different in the hemispheres, we are partly concerned about the parameterized nature of some aspects of cloud representations and partly concerned about apparent differences in the balance of physical processes forcing the clouds. For example, the two main subtropical marine stratocumulus banks in the northern hemisphere have an annual cycle that peaks in June, July, August while the two main banks in the southern hemisphere peak, not in December, January, February, but in September, October, November. Klein and Hartmann (1993) show that the existence of subtropical stratocumulus is most highly correlated with PBL stability (i.e., the difference in 700 mb potential temperature and the SST) rather than the standard textbook index of large-scale divergence. The generation of stratocumulus by the strong SST gradient on the equator is a mechanism that has not been studied with high-resolution PBL models; by Hypothesis 1 we believe that they will work, but this must be tested.

Hypotheses 1 and 3 can be effectively tested with a limited process study in the stratus region, linked with the oceanographic and meteorological studies of the equatorial region. Hypothesis 2 should be examined within a complete processes study (as above) and together with hypothesis 3 with a more modest but spatially and temporally extensive monitoring study.

3. THE EPIC PROGRAM

3.1 Program Elements

The eastern Pacific investigation of climate processes (EPIC) is a five year program of ocean-atmosphere process research to improve the description and understanding of the cold-tongue/ITCZ complex (CTIC) and stratus deck region. EPIC is endorsed by the CLIVAR Variability of the American Monsoon (VAMOS) Program and will be strongly linked to other climate studies in the Pacific Ocean and pan-American region.

The specific scientific objectives of the program are:

Objective I. To observe and understand 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, including

(a) mechanisms governing temperature and salinity field evolution in the oceanic cold tongue and in the region of strong meridional gradient in sea surface temperature from the oceanic cold tongue through the ITCZ;

(b) atmospheric planetary boundary layer structure and evolution from the equator through the ITCZ, primarily in the southerly monsoonal regime; and

(c) the processes determining the existence, character and strength of deep convection in the northeast Pacific ITCZ.

Objective II. To observe and understand the dynamical, radiative and microphysical properties of the extensive boundary layer cloud decks in the southeasterly tradewind and cross-equatorial flow regime and their interactions with the ocean below.

The research plan to achieve these scientific objectives builds on the eastern tropical Pacific PACS pilot field studies that have been conducted along 125°W (Fig. 3.1). EPIC process studies will study on the coupled monsoonal regime further to the east and the cold tongue, as shown schematically in Figs. 3.2 and 3.3.

EPIC will have the following elements:

- field work involving a combination of sustained and intensive observations of ocean-atmosphere processes in the eastern Pacific CTIC and stratus deck regions, to be conducted during the 2000-2003 period;

- data analysis and modeling activities that prepare and synthesize the results from the field work for use in ocean-atmosphere model validation and improvement;

- enhanced monitoring, modeling and empirical studies of the annual cycle and interannual variability of the CTIC and stratus deck regions throughout the five year program (1999-2003) to provide the spatial and temporal context for process studies and to explore connections with climate variability over the Pacific and pan-American regions.

EPIC process research will include diverse types of field work. Basically, however, two coordinated strategies are required to achieve the scientific objectives. First, the description of the seasonal-to-interannual evolution of the cold-tongue/ITCZ complex and the stratus deck region will require field activities of a sustained nature over a period of several annual cycles. Sustained observations are expected to be based on instrument deployments of durations ranging from 6 to 24 months and repeated ocean-atmosphere transects. Second, the detailed examination of key physical processes in the CTIC and stratus deck region will require intensive observations during short campaigns, typically of 4-6 weeks duration. Intensive observations will

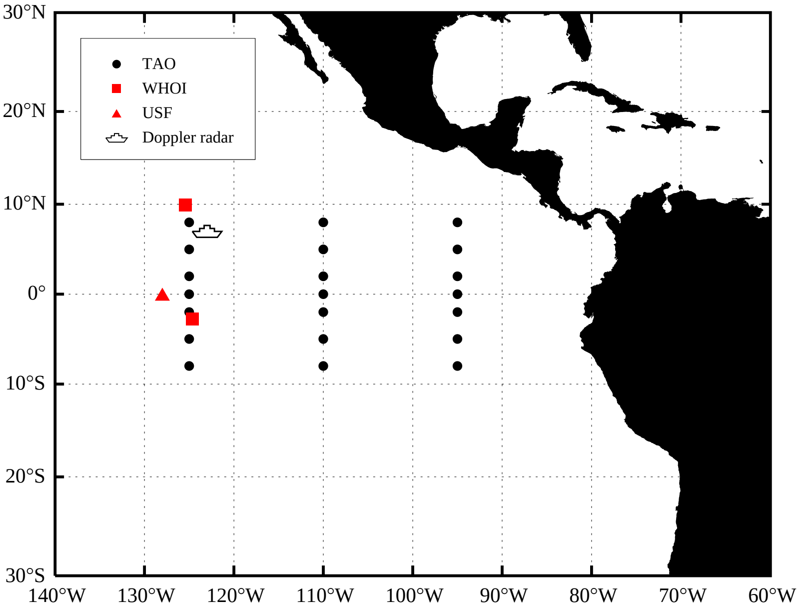


Figure 3.1. Summary of the location of process studies during the pilot phase of PACS. Shipboard studies were done from the R/V Ron Brown in August 1997, and moorings were deployed by the University of South Florida (USF) and the Woods Hole Oceanographic Institution (WHOI) between April 1997 and September 1998. The existing TAO (Tropical Atmosphere Ocean) buoy array is also shown.

sample phenomena such as atmospheric and oceanic turbulence and convection at high spatial and temporal resolution to explore the scientific questions identified in the EPIC science plan and to learn how the effects of the smaller-scale phenomena might be more successfully parameterized in ocean-atmosphere models. Enhanced monitoring and sustained observations will provide the context for the intensive field campaigns. Coordination between the field campaigns and sustained observations will be essential to achieving the EPIC scientific objectives.

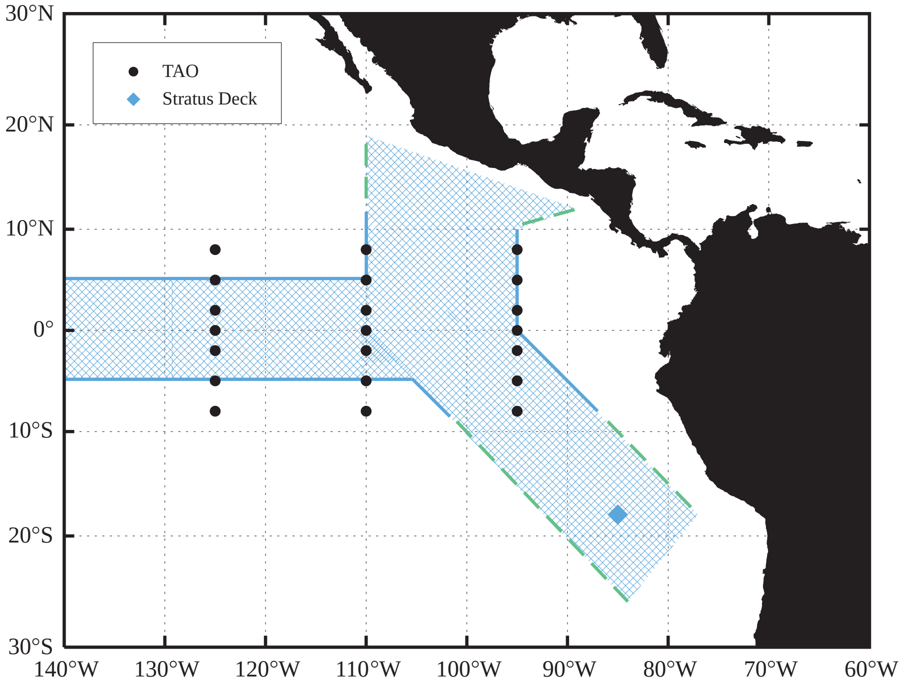


Figure 3.2 Summary of the regions where EPIC field studies will be concentrated. The blue lines and blue shading indicate the region where process studies will occur, with the blue diamond as an indicator of the studies of the stratus deck region. The green dashed lines extending to the southwest and to the northeast toward South and Central America, respectively, indicate the intent to develop international collaborative activities under VAMOS that will extending the observational region toward the coasts.

The EPIC program will involve scientists at operational and experimental climate prediction centers. Their participation will be sought in the planning and analysis of field observations, and particularly in the those research activities designed to improve the parameterizations of ocean mixing and atmospheric convection, radiation and boundary layer processes.

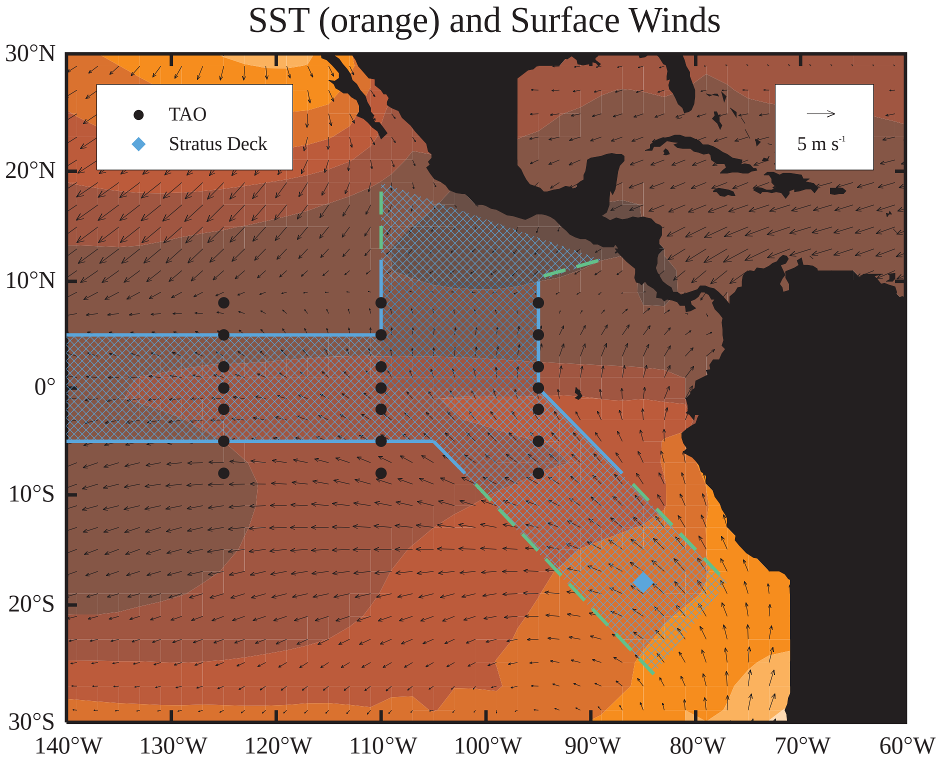


Figure 3.3. The annual mean sea surface temperature and surface wind fields superimposed on the region where EPIC will conduct field programs.

Enhanced monitoring, modeling and empirical studies focussed on EPIC objectives will be accomplished primarily through collaboration with closely related national and international programs. The US PACS program and the CLIVAR VAMOS program seek a better understanding of CTIC and stratus deck processes and their connection with seasonal-to-interannual climate variability over the pan-American region. The Pacific Basinwide Extended Climate Observation System (PBECS) and the Consortium on the Oceanπs Role in Climate (CORC) plan long-term observations of the upper Pacific Ocean for use in studies of seasonal-to-decadal climate variability. EPIC seeks collaboration with Central and South American scientists and organizations interested in eastern Pacific climate processes and observations.

As in the TOGA program, the EPIC observational activities are an essential part of the development of a global climate observing system. The eastern Pacific is a large data-sparse region with very few potential island sites for conventional meteorological systems and a limited number of ocean-atmosphere platforms of opportunity from shipping and aviation activity. It is likely that the data required to initialize, validate and improve operational climate analysis and prediction systems will come from a combination of satellite systems, autonomous atmospheric and oceanic probes and moored buoys. The EPIC field observations will provide a basis for designing the observing systems required for the eastern Pacific.

3.2 Process Studies in the CTIC

Investigation of CTIC structure and evolution will require a combination of process oriented field work, data analysis and modeling in the context of regional enhanced monitoring. The specific scientific objectives for CTIC process studies are organized into:

- an ITCZ component
- an atmospheric boundary layer (ABL) component
- an upper-ocean component

The three components are tightly coupled. Deep atmospheric convection is coupled to the temperature and salinity structure of the upper ocean through surface heat, freshwater and momentum fluxes across the ITCZ and into the northeastern Pacific warm pool region. ABL processes couple the ocean to the atmosphere in the equatorial zone and the ITCZ, and couple the regions of ascent associated with the ITCZ heat source to the regions of subsidence and strong radiative cooling in the stratocumulus decks to the south. Oceanic mixing and large-scale advective processes play an important role in the upper-ocean temperature and salinity budgets that feed back on the atmospheric motions through the sea surface temperature.

Location and timing of CTIC field work

Based on the CTIC scientific objectives and practical considerations, highest priority will be given to open-ocean CTIC field work in the vicinity of 95°W. The science plan calls for a focus on CTIC meridional structure and the physical processes that govern the evolution of the atmospheric heat and moisture sources in the southerly monsoonal regime. The southerly regime is distinctly different than the equatorial cold tongue and ITCZ regime further west, related in part to coupling with the annual march of heating patterns over Central and South America. CTIC field work must take place far enough to the east to capture the unique interplay between equatorial ocean-atmosphere circulation and the cloud field, involving both ITCZ deep convection and the equatorial stratocumulus decks.

From a practical perspective, the 95°W longitude line is the location of existing TAO moorings that can provide context for the more intensive process-oriented observations. In addition, research aircraft are expected to play a critical role in understanding CTIC atmospheric boundary layer and deep convection processes. Proximity to Mexican and Central American air bases near 95W make it feasible to reach the ITCZ and cold tongue region with the necessary instrument systems.

The period of sustained observations is expected to begin in Year 2000 and extend into 2003 (see Fig. 3.8). Although the observational period will be too short to separate the annual march from interannual CTIC variability, the extended period is necessary to sample the full range of conditions associated with the annual march of the CTIC meridional structure in the upper ocean and ABL. During strong ENSO warm events that may occur during the EPIC period, for example, the meridional gradient of SST across the oceanic front will be significantly reduced and displaced.

Intensive field campaigns, the ITCZ and ABL Intensive Observing Periods (IOPs) are expected to take place during the July-September 2001 period. During the latter half of the July-September period, the climatological contrasts between the cold tongue and the ITCZ region are greater, and the cross-equatorial ABL flow is stronger; the stratocumulus decks are more developed in the equatorial zone. Transient atmospheric disturbances in the ITCZ and warm pool region to the north of the equator, however, are stronger earlier in the July-September period. The period of intensive field campaigns will represent a balance between these scientific considerations.

3.2.1 The ITCZ Component

The focus of the ITCZ component is the ITCZ IOP (Intensive Observing Period) expected to take place during a 4-6 week period during July-September 2001. Observations taken over the ITCZ and the northeastern Pacific warm pool region will be designed to describe and understand the processes that determine the existence, character and strength of deep cumulus convection in the region. The major challenge of the ITCZ component is to properly sample key physical processes in transient atmospheric disturbances. Satellite imagery shows that variability of convective activity occurs on daily, weekly, monthly, and seasonal time scales. The daily fluctuations clearly correspond to the diurnal cycle of solar heating, while the seasonal cycle is linked to (among other things) the seasonal variations in sea surface temperature (SST).

Fluctuations of intermediate time scale may be related to tropical cyclogenesis, impingement of west African easterly waves on the eastern Pacific region, and to a number of remote monthly time-scale influences that are not yet well understood, including intraseasonal oscillations in the Caribbean and the western equatorial Pacific.

The observational strategy is to coordinate a series research aircraft missions with research vessels operating in the ITCZ, supported by enhanced monitoring by moored buoys, satellite remote sensing and other observational platforms. Figure 3.4 indicates the observational strategy and the region of interest. Critical atmospheric measurements are vertical profiles of wind, temperature and humidity; radiative heating estimates in clear and cloudy air at several levels; cloud macrophysical and microphysical structures; and turbulent fluxes in the atmospheric boundary layer. A research vessel and supporting platforms will be deployed in the ITCZ to provide continuous time series near a fixed location. Research aircraft will provide the mobility required to measure atmospheric vertical structure and a representative sample of cloud systems with high resolution and extended spatial coverage

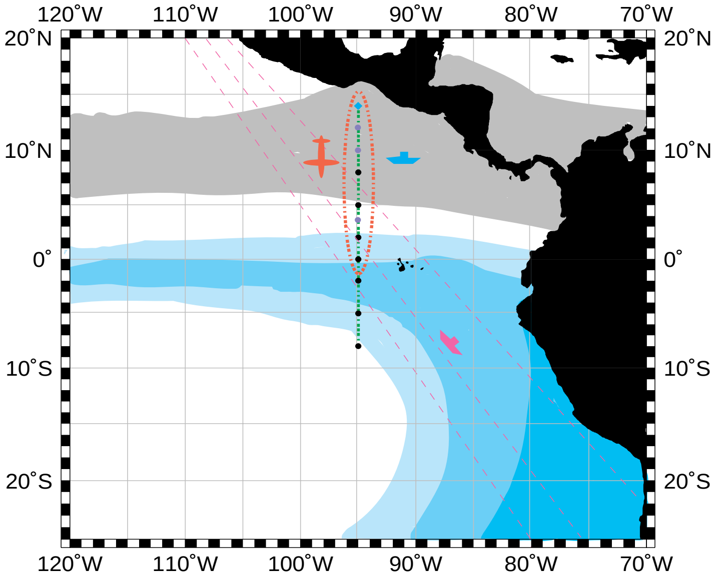


Figure 3.4. Summary of the ITCZ field studies. The mean northern summer locations of the cold tongue and cold water of the coastal upwelling region are shown in blue and of the ITCZ in gray. The 95°W TAO buoys are shown as black dots, with additional TAO buoys recommended as enhancements to 95°W in purple. International collaboration is sought to provide buoys, such as shown as a blue diamond, off the coast of Mexico. Aircraft flights (red plane and area enclosed by dashed line) would work in the ITCZ along 95°W in coordination with a research ship (blue) with a Doppler radar. VOS (pink dashed lines and ship) could be instrumented to obtain addtional data on a regular basis.

The data set that emerges from the ITCZ component is expected to provide high quality observations of four types:

- Detailed ITCZ IOP time series of atmospheric vertical structure and doppler radar descriptions of convective systems and their interactions with the upper ocean over a mesoscale region near a fixed point at the expected center of ITCZ convection. A research vessel with Doppler radar capability is required to anchor this portion of the data set. High-quality wind, temperature and humidity data at the surface and aloft are critical to success. This element of the data set will support case studies and quantitative analysis of the ITCZ convective systems, interpretation of detailed physical processes using cloud resolving models and data for assimilation and validation studies with ocean-atmosphere models.

- Supporting surface and upper-ocean observations from moored buoys and ocean probes in the vicinity of the research vessel, giving detailed time histories of air-sea fluxes and upper-ocean temperature, salinity and current structure during the passage of the atmospheric disturbances. High priority will be placed on closing the upper-ocean temperature and salinity budgets in the vicinity of the research vessel. (See the Upper-Ocean Component description below.)

- Research aircraft observations from a series of missions from southern Mexico along 95°W, across the warm pool and through the ITCZ in the vicinity of the research vessel during the IOP. The aircraft will complement the research vessel observations in the ITCZ by documenting the meridional variation of atmospheric vertical structure and convective system properties along 95°W. Doppler radar capability is required. Missions will sample the full diurnal cycle. High priority is placed on obtaining a representative sample of convective systems with detailed descriptions of the structure and microphysics of convective and stratiform elements. In the ABL and middle troposphere, observations are required to describe the meridional variability of wind and thermodynamic structure and to estimate vertical convective fluxes of heat and water. These observations are designed to guide improvements in theories and parameterizations of convective control in the ITCZ region.

- Supporting observations from satellite remote sensing, the TAO 95°W mooring line, in situ observations at fixed sites and platforms of opportunity in the eastern Pacific ITCZ and warm pool region. Estimates of surface wind, SST, precipitation, cloudiness, water vapor and sea level from satellite remote sensing are expected to play a critical role in providing spatial and temporal context for ITCZ and warm pool observations taken along 95°W during the IOP. The special EPIC observations from enhanced monitoring and the ITCZ IOP will be made available for data assimilation by ocean-atmosphere models to synthesize remotely sensed and in situ data for use in eastern Pacific empirical and prediction studies.

3.2.2 The ABL component

The ABL component is designed to describe and understand the evolution of atmospheric planetary boundary layer structure across the cold tongue and into the ITCZ in the southerly monsoonal regime. Field observations will involve both a 4-6 week ABL Intensive Observing Period in the July-September 2001 period, and sustained observations throughout the EPIC.

The observational challenges for the ABL IOP are: (1) to obtain statistically meaningful meridional cross sections of the cross-equatorial ABL flow, including the structure of the low-level jet across the cold tongue and the vertical thermodynamic structure from the surface to the middle troposphere, and (2) to improve the description of key physical processes - turbulence, convection, cloud structure and microphysics, and radiation - that control the ABL structure and evolution. The sustained observations will focus on describing the annual march and interannual variability of the ABL, especially the air-sea fluxes, precipitation, surface winds, cloud cover and radiative properties, and, wherever possible, the vertical wind and thermodynamic structure from the surface to the middle troposphere. Deployments of ABL instrumentation for sustained observations will build on existing enhanced monitoring opportunities from satellite remote sensing, moored buoys and ocean-atmosphere platforms of opportunity in the EPIC process study region, with priority given to observations along 95°W.

The observational strategy for the ABL IOP is illustrated in Fig. 3.5. North-south transects by a research vessel would be coordinated with a series of missions by research aircraft missions and autonomous atmospheric probes, and would be supported by enhanced monitoring by moored buoys, satellite remote sensing and observational platforms of opportunity. As in the case of the ITCZ Component, the ABL IOP is expected to take place during a 6 week period during July-September 2001. It is desirable that the ITCZ and ABL Intensive Observing Periods coincide to

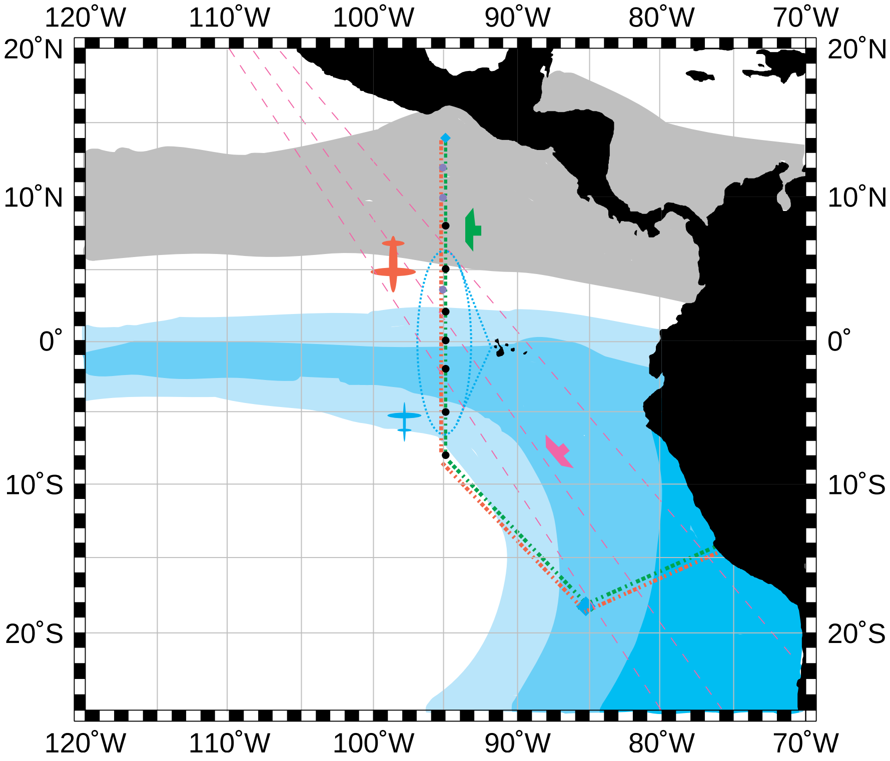


Figure 3.5. Sketch of the proposed ABL studies. The northern summer locations of the cold tongue and coastal upwelling regions are shown in blue and the ITCZ in gray. Research aircraft (red plane) flights and research ship (green ship) tracks along 95°W would continue to the location of the enhanced monitoring buoy at 18°S, 85°W and then to the west coast of South America to sample the ABL through the CTIC and stratus regimes. Unmanned aircraft (blue plane and elliptical region) could be launched from the Galapagos, and additional sampling could be done form the VOS (pink dashed lines and ship).

maximize ABL observational resources across the ITCZ into the cold-tongue region, but it is not an absolute requirement of the program.

The ABL IOP will place high priority on observing the transitions of the ABL and upper-ocean structure across the cold tongue into the ITCZ, and obtaining an observational basis for improving ABL parameterizations of surface fluxes that are essential to representing the observed changes in meridional structure. The north-south research vessel transects will provide detailed data on air-sea fluxes, cloud structure, including radiative properties of the clouds, vertical wind, temperature and humidity soundings and surface meteorological data. The research aircraft missions with turbulence and cloud microphysics probes, cloud radar and oceanic profilers will provide more synoptic sampling of ABL vertical structure from southern Mexico along 95°W across the ITCZ to the equator. Autonomous aircraft operating continuously out of the Galapagos are expected to document ABL wind, temperature and humidity across the cold tongue between 5°S and 5°N.

The data sets expected to emerge from the ABL IOP include:

- Cross sections of boundary layer wind, temperature and humidity structure across the cold tongue and into the ITCZ during the IOP. Soundings from the research vessel and aircraft will be combined to describe the evolution of the low-level southerly jet from the cold tongue into the ITCZ.

- Observations of air-sea fluxes and cloud structure and radiative properties from cruises of the research vessel along 95°W. The suite of radar, radiation and surface meteorological measurements will be used to describe the interactions between the ABL structure and clouds and of the effects of clouds on the ocean from the cold-tongue boundary layer cumulus regime to the ITCZ deep convective regime.

- Supporting surface and upper-ocean observations from moored buoys and ocean probes along 95°W, giving detailed time histories of the air-sea fluxes and upper-ocean temperature, salinity and current structure during the ABL IOP.

Sustained ABL component observations will be designed to describe the annual march and interannual variability of key parameters over the entire EPIC field study area (see Fig. 3.2). The observational strategy for sustained observations is to build on EPIC enhanced monitoring activities. Multiyear data sets from sustained observations are expected to include:

- Time series of surface meteorological parameters, air-sea heat and freshwater flux estimates, and upper-ocean temperature and salinity structure from the enhanced TAO array along 95°W.

- Spatial fields of surface meteorological parameters required for the computation of air-sea turbulent fluxes and the description of surface boundary layer dynamics. These data sets would be extracted from available satellite remote sensing and in situ data sets. Key parameters include sea surface temperature, surface wind and wind stress estimates from satellite remote sensing, and surface wind, temperature, humidity and sea-level pressure data from in situ platforms of opportunity.

- Spatial fields of ABL cloud amount, type, heights, and radiative properties. It is expected that the cloud information will be produced from satellite remote sensing methods and by extracting information from cloud data sets based on surface observer reports.

- Episodic observations of air-sea fluxes, ABL cloud structure and radiative properties, wind, temperature and humidity soundings, and surface meteorological data from the TAO array tender along 95°W and 110W.

3.2.3 The Upper-Ocean Component

The objective of the upper-ocean component is to observe and understand the mechanisms governing the structure and variability of the temperature and salinity fields across the cold tongue and into the ITCZ. The observational strategy involves upper-ocean Intensive Observing Periods, coinciding with the ITCZ and ABL IOPs during the July-September 2001 period, and sustained observations based on autonomous instrument deployments of 6-24 months and periodic research vessel cruises to document oceanic structure over two full annual cycles.

The observational approach will be to:

- Describe the physical processes that drive the evolution of upper-ocean structure and couple it to the atmosphere at select, fixed locations, including the ITCZ, the equatorial front, and the cold tongue.

- Document the annual march and interannual variability of the CTIC upper-ocean temperature and salinity structure, looking at the meridional structure across the CTIC and also at the western branch of the cold tongue and the connection of the eastern end of the cold tongue to the coastal upwelling region.

- Document the spatial and temporal variability of surface fluxes, horizontal and vertical advection, and mixing across the CTIC region and relate the physical processes to variability in the upper-ocean temperature and salinity structure.

A schematic observational plan for all the EPIC ocean studies, including the upper-ocean component of the CTIIC studies, is shown in Fig. 3.6.

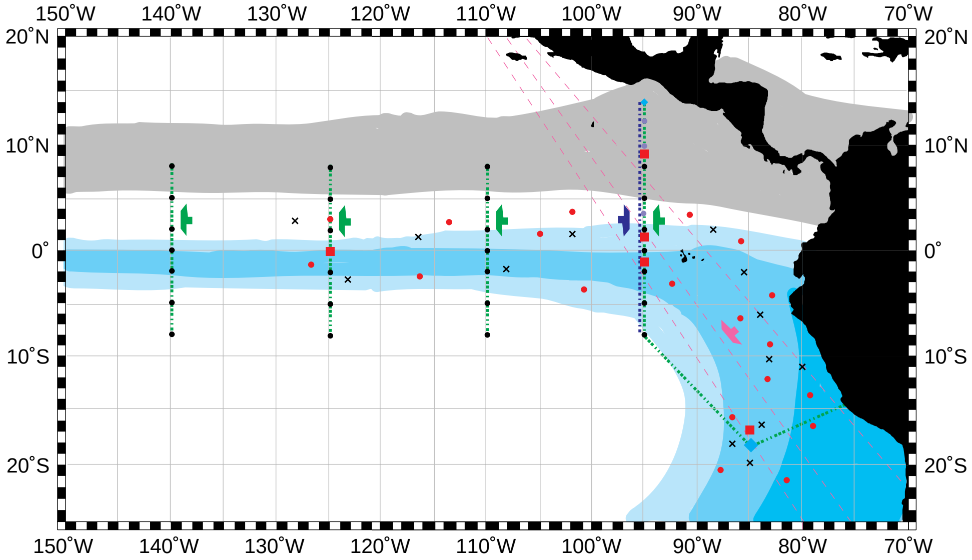


Figure 3.6: A schematic plan for study of ocean processes in EPIC. Process studies are recommended at specific sites as indicated by red squares: cold tonue upwelling (square at 125°W, 0°), ITCZ (~12°N, 95°W), equatorial front (~2°N, 95°W), and cold tongue (~2°S, 95°W). These process studies would employ shipboard, Lagrangian (floats, profilers, and gliders), andmoored instrumentation. Regular, dedicated shipboard studies (purple ship and dashed line)over two annual cycles along 95°W would examine the seasonal cycle of the upper ocean inthe CTIC. Additional shipboard studies would link 95°W to the stratus (18°S, 85°W) and coastal regions. Surface drifting buoys (red dot) and profiling floats and gliders (black x) would be deployed broadly in the CTIC and stratus regions. Exisitng (black dots) amd recommended addtional (purple dots) TAO moorings and additional air-sea flux moorings (light blue diamonds) are shown. Ships servicing these moorings (green ships and dashed lines) as well as VOS (pink ship and dashed lines) provide platforms for regular sampling.

High priority is placed on closing the upper-ocean budgets of temperature and salinity at several select locations. Key observations include the measurements required to evaluate the surface heat, freshwater and momentum fluxes and continuous monitoring of the current, temperature and salinity structure. The objective would be to obtain budget estimates representative of a 50km-by-50km region at a fixed location in the ITCZ (see description of atmospheric ITCZ component above), at the equatorial front, at a contrasting site in the cold tongue along 95°W, and at an upweeling site inthe cold tongue to the west. Based onthe success seen in TOGA COARE, intensive shipboard, float, and moored array measurments are planned to coincide with atmospheric studies in the CTIC. Seasoar, shipboard ADCP, ship-deployed turbulence profilers, high vertical resolution physical and optical measurments made in the upper 50 m, and air-sea fluxes from buoys and ships would be combined to close the heat, freshwater, and momentum budgets at these select sites. It is anticipated that the budegt will be closed as done in COARE and that the processes controlling the evolution of the upper ocean at those sites will be identified. The contributions of horizontal and vertical advection, mixing, surface heat, freshwater, and wind stress forcing (including absorption of sunlight as a function of depth) will be quantified. Based on the experience of COARE, particular attention should be paid to shallow thermohaline structure and depth-dependent absorption of insolation. Shallow profiling floats will provide a method to collect data in the upper 50 m that was not available in COARE. The northern site in the ITCZ will be occuppied coincidentally with the atmospheric IOP at 95°W in July-September 2001. The other sites would be done in conjunction with ABL work and between 2001 and 2003.

Studying the upper ocean response to an coupling with the atmosphere over the broader area and over the annual cycle requires a coordinated set of observations from moored autonmous platforms, moving research vessles or autonomous gliders. TAO and IMET moorings and shipboard surface meteorological measurements are expected to provide the required surface flux information. Estimates of oceanic horizontal and vertical advection of mass, temperature and salinity as required to close the heat and freshwater budgets will come from either an array of moored buoys with acoustic Doppler current profilers (ADCPs) or by an array of autonomous oceanic gliders centered on the fixed sites of interest. The research vessel servicing the ITCZ and equatorial array may provide an additional source of upper ocean structure information.

High priority for the moored array and Lagrangian drfiter studies is placed on documenting the annual march of merdional temperature and salinity structure across the CTIC over two full annual cycles. The individual elements (surface buoyancy flux, advection and mixing) need to be observed concurrently and over a range of locations that encompasses the warm pool and the cold tongue. The TAO moorings provide the background, and require supplements to observe the surface forcing and resolve merdional and zonal gradients in the ocean. Additional moorings are possible. However, autonmous profiling floats or gliders (floats with wings, able to progress along a track or keep station using GPS navigation) should be ready and offer an alternate apporach. The moored buoy and float observations will be supplemented by at least two research vessel cruises per year during a 24 month period to document year-to-year variations in the fine structure and details of meridional T-S structure along the buoy lines, and to examine physical processes in the regions of most intense vertical mixing. Additonal moored elements and/or Lagrangian instruments would be used to document large scale horizontal and vertical advection of mass, temperature and salinity. Observations in the western branch of the cold tongue and those made in the coastal upwelling regime (see the description of the stratus deck program below) will sample the annual variability in the open ocean and coastal upwelling regimes.

The data sets that are expected to emerge from the upper-ocean component are:

- Detailed time series of upper-ocean temperature, salinity and current structure from arrays of moored buoys and oceanic probes deployed along 95°W, across the cold tongue and through the ITCZ, during two full annual cycles beginning in year 2000 and extending through the IOP. The arrays will be designed to permit the calculation of heat and salt budgets for locations in the ITCZ (with priority on the ITCZ IOP), the equatorial front, and the equatorial zone. Additional time series suitable for upwelling calculations will come from ADCP and/or virtual moorings in the western branch of the cold tongue.

- Detailed meridional cross sections of upper-ocean temperature, salinity and current structure from periodic research vessel cruises across the cold tongue and through the ITCZ along 95°W and 110°W beginning in year 2000. The data set will include information on small scales (meter to 10km). Ocean microstructure measurements of limited duration may be coordinated with the surveys in regions of strong ocean mixing activity for the ITCZ, the oceanic front and the cold tongue along 95°W.

- Detailed analyses of the upper ocean heat, freshwater, and momentum budgets from month-long occupations of sites in the ITCZ, at the equaotrial front, and in the cold tongue. The data would include surface forcing from ships and buoys, profiles of physical (including turbulence) and optical properties, and detailed information about the vertical and horizontal structure of the upper ocean at the 50km x 50km sites. The higher spatial and temporal resolution of these studies would complement the longer-running moored array and float studies and support analyses of processes they do not resolve.

- Supporting atmospheric observations from moored buoys and research vessels giving time series and meridional structure of air-sea fluxes across the cold tongue and into the ITCZ. High priority will be placed on obtaining detailed time series required for closing the upper-ocean temperature and salinity budgets at the ITCZ, cold tongue, and frontal sites of intensive oceanographic studies.

3.3. Process Studies in Stratus Deck Regions

The second major objective of EPIC process research focusses on marine stratiform clouds (MSC) in the atmospheric boundary layer and their interaction with the upper ocean. At least two MSC regimes can be identified. The first is an extensive region centered near 18°S, 85°W, where the MSC cloud cover is most persistent, extending toward the equator in the southeast tradewinds. The second is the region of vigorous stratocumulus convection in the vicinity of of the oceanic front and the ITCZ to the north of the equator. This equatorial regime is characterized by rapid changes in cloud cover and properties as the air flows across the cold tongue and oceanic frontal region toward the ITCZ. Both the subtropical and equatorial regimes are integral parts of CTIC structure and variability.

3.3.1 Strategy and timing of field observations

The equatorial MSC regime will be addressed as an integral part of CTIC process studies described in Section 3.2 above. Observational activities related to the subtropical and equatorial MSC regimes will be coordinated whenever possible. Since there are few measurements of either equatorial or subtropical MSC decks in the eastern Pacific, the investigation of the MSC regimes will take a two-phase approach.

Phase 1. Qualitative measurements are required to determine cloud types in the eastern Pacific between 20°S and 5°N. Figure 3.7 summarizes the Phase 1 program. The frequent transects of Volunteer Observing Ships (VOS) offer an opportunity to obtain routine surface fluxes, surface

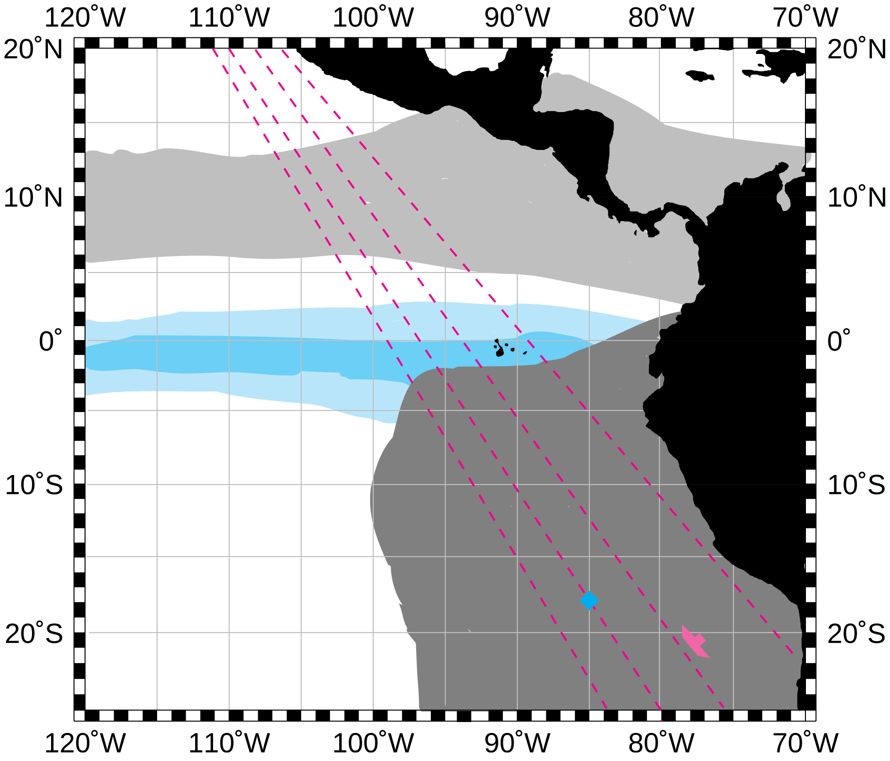


Figure 3.7 The northern summer low cloud cover (dark gray shading), ITCZ (light gray shading), and oceanic cold tongue (blue shading) are shown togther with the observational elements of Phase 1. A surface mooring equipped to measure air-sea fluxes and with a ceilometer would be installed and maintained at 18°S, 85°W. Additional sampling would be done using platforms of opportunity, such as the VOS (pink ship and dashed lines).

measurements of downwelling shortwave and longwave radiation, cloud base height, and boundary layer depth. This information is sufficient to determine the basic cloud structure and mean characteristics of the boundary layer to resolve the detailed structure and evolution of the cloud field using high-resolution boundary layer or large eddy simulation models.

Details of the subtropical regime can be determined from long time series measurements from an IMET mooring located at 18°S, 85°W, with the addition of a ceilometer to measure cloud base and inversion base height.

A high-resolution boundary layer model can be initialized with an idealized profile based on the surface conditions and boundary layer depth. As a diagnostic tool, the model can provide information on the cloud structure, the radiative flux divergence within the boundary layer and the evolution of the cloud field. Changes in the diurnal structure of the cloud are likely to be important since changes in the drop distribution are not likely to be cyclical. The model test runs will help to identify the processes that are least certain and the focus of Phase 2 of the study.

Phase 2. This is an intensive observing phase coincident with the other major field efforts of EPIC. The extent of the observations depends largely on the results of Phase 1. However, as a minimum it will be essential to obtain information on the basic boundary layer structure along a trajectory from the Peruvian coast to the equatorial cold tongue. It is important to resolve the vertical flux divergence of both the turbulent and radiative fluxes and the microphysical structure of the cloud field. Coincident measurements of the upper ocean structure will also be required. Measurements are required to determine the spatial evolution of the stratus and stratocumulus decks from the Peruvian coast along a northwesterly trajectory to about 5°N near 95°W. Three separate regimes can be identified. Different conditions are anticipated in each of subtropical and equatorial regimes and, where possible, measurements should be obtained in the same season to verify the evolution of the stratus along the northwesterly trajectory. It is desirable to obtain measurements in contrasting seasons. The stratus is least extensive in March and April, and most extensive in August and September.

3.3.2 Observational Activities During Phase 2

Figure 3.8 summarizes the observational activities in the atmosphere during stratus Phase 2; Figure 3.6 includes oceanographic elements of the work in the stratus region.

Atmospheric observations

Aircraft sampling will be required to resolve the vertical flux divergence of both the turbulent and radiative fluxes and the microphysical structure of the cloud field. A platform

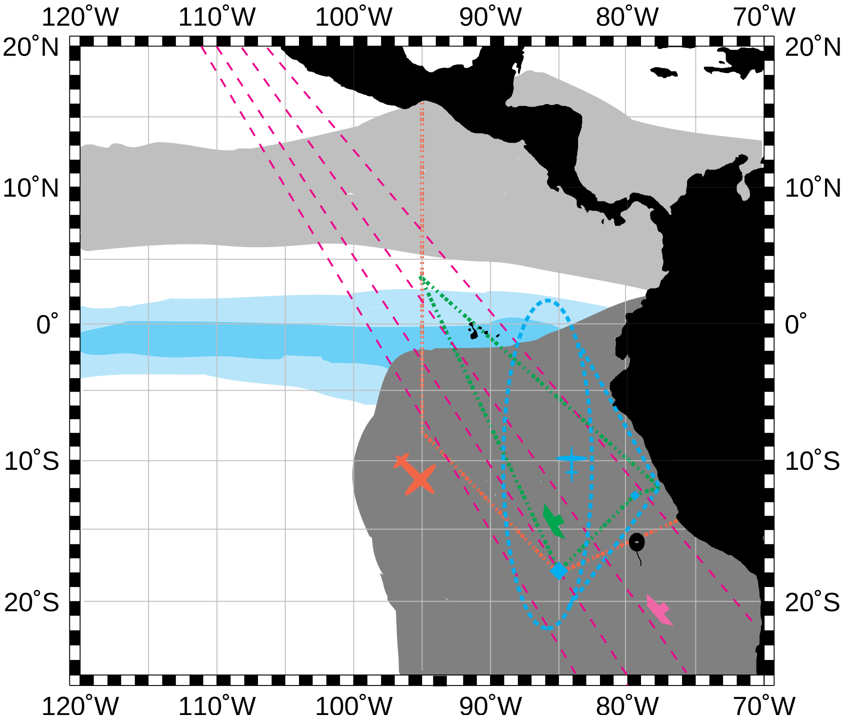


Figure 3.8. The northern summer low cloud cover (dark gray shading), ITCZ (light gray shading), and oceanic cold tongue (blue shading) are shown togther with the observational elements of Phase 2. A surface mooring equipped to measure air-sea fluxes and with a ceilometer is maintained at 18°S, 85°W. Research aircraft flights (red plane and dashed line) would sample the ABL and clouds out to the equator at 95°W; planes could either continue north to Mexico in coordination with CTIC work or return to South America. Process study cruises with the research vessel with Doppler radar (green ship and dashed line) would study the coastal and equatorial stratus regimes. Unmanned aircarft (blue plane and elliptical sampling domain) could be launched from South America, as could profiling balloons (black balloon). Additional sampling would be done using platforms of opportunity, such as the VOS (pink ship and dashed lines).

such as the NCAR C-130 has the required range, endurance and instrumentation to make such measurements. Coincident measurements of the upper ocean structure may also be obtained from AXBTs, AXCTDs and AXCPs. The mean vertical structure of the boundary layer and lower free atmosphere will be obtained directly using dropsondes and aircraft profiling.

Shipboard measurements will provide higher temporal resolution of the boundary layer structure and evolution. A Class I research ship is required to support an extensive suite of remote sensing instrumentation. Remote sensing techniques are sufficiently advanced to be able to provide detailed information on the vertical structure of the boundary layer, cloud microphysics, and vertical mixing. Coordinated, the aircraft and ship measurements will be sufficient to determine the processes controlling the evolution of the stratus and stratocumulus cloud decks.

The long trajectories and remoteness of the eastern tropical Pacific operating area make observations using traditional techniques, though necessary, difficult. Sampling the radiative properties of the atmosphere is essential and can be accomplished using the new technological devices, such as robotic balloon aerovehicles (aerobots) which have the ability to profile between predetermined altitudes while moving with the mean wind. Autonomous aircraft such as the aerosonde should also be exploited where possible to obtain frequent, detailed measurements of the boundary layer structure in the remotest regions.

Oceanic observations

Oceanic observations for Phase 2 will focus on the subtropical marine stratiform cloud (MSC) regime. A well-instrumented surface mooring (IMET) will be deployed at 18°S, 85°W. Current meters and salinity/temperature recorders on the mooring will resolve the variability in the depth of the mixed layer and thermocline as well as the temperature, salinity, and velocity fields in the upper ocean. Links between SST and upper ocean structure and the stratus deck will be examined. The reduction in incoming shortwave radiation may not only reduce surface heat gain but also decrease the stability of the upper ocean, making cooling of the mixed layer by entrainment at its base more likely. If cooler SST reinforces the stratus cloud cover, then there is positive feedback.

Because of the prevalent cloud cover in the region, the uncertainties in present sea surface temperature fields there may be large. SST will also be sought from VOS and surface drifters. Upper ocean profiling floats could be used to complement the surface mooring and expand the area under the stratus deck where information about the vertical structure of the upper ocean is obtained. With sufficient drifter, VOS, and float coverage and with the possible addition under VAMOS of additional moorings along the Chilean and Peruvian coasts, the role of horizontal advection of cool water upwelled at the coast as well as of the surface forcing and one-dimensional upper ocean physics in governing SST could be considered.

Subsurface temperature and surface salinity measurements at the surface flux mooring at 18°S, 85°W would allow gross estimates of advective oceanic fluxes at 95°W between it and the TAO mooring at 8°S and at 18°S between it and coastal measurements. These temporally resolved interior estimates would complement the spatially resolved hydrographic transects.

Strong and variable upwelling and longshore currents off South America presumably play a role in the East Pacific oceanic heat budget. A few gliders at 18°S making repeat coastal hydrographic sections or a small moored array within the region of strong and variable upwelling and longshore currents would quantify the role of coastal upwelling and longshore currents in the budget. Together with subsurface temperature from the mooring at 18°S, 85°W, such coastal measurements would allow for gross but temporally resolved estimates of interior advective fluxes along 18°S, complementing the few spatially resolved hydrographic transects.

3.4 Enhanced Monitoring in the Eastern Tropical Pacific

Enhanced monitoring of ocean-atmosphere processes will provide the context for the intensive observational activities during EPIC. Enhanced monitoring is seen as being long-term observations, with emphasis on developing a continuous record over a five year period, nominally 1999–2004. The observations would be both oceanographic and meteorological and span the whole eastern tropical Pacific region. EPIC will build on the TOGA observing system, a collection of sparse in-situ observations from research and voluntary observing ships and island stations, anchored by the TAO array of moored buoys and satellite based observations. EPIC will encourage cooperative activities among U.S. agencies and international partners to improve the quality and availability of in situ observations in the region for scientific and operational use. In addition to providing context for the intensive observations, in situ and remotely sensed data from enhanced monitoring activities will be used to uncover and correct systematic errors in coupled model fields. For example, atmospheric profiles from a data assimilation cycle of an operational coupled climate prediction model (CCPM) in the stratus regime may be compared with observed profiles to determine if the model atmospheric boundary layer quantities are biased high (or low) and correctly captures the phase and amplitude of the seasonal cycle. Or, observations of air-sea fluxes may be used to identify CCPM biases in the zonal distribution of surface heat and fresh water fluxes. Without enhanced monitoring over a large region, and continuous in time over several years, such model validations would be impossible.

3.4.1 Space-Based Observations

Space-based observations will play an important role in providing the large-scale context for EPIC intensive observing periods in the eastern tropical Pacific. Satellite data analyses provide some key atmospheric and oceanic fields that cannot be obtained by other methods. Moreover, satellites provide a spatial resolution that cannot be obtained from the sparse distribution of in situ observations and the limitations of present operational data assimilation models in the eastern tropical Pacific ocean and the overlying atmosphere. Methods for obtaining fields of sea surface temperature, near-surface wind velocity and sea level are well advanced. Methods for obtaining quantitative estimates of the components of the surface radiation budget and of precipitation are developing rapidly.

Satellite observations will be most useful if they can be continued uninterrupted during the entire EPIC program in order to provide simultaneous, dense observations in both the eastern Pacific. As summarized in Appendix II, most of the satellite needs will be met during EPIC.

However, maintaining satellite programs beyond the EPIC period poses serious practical difficulties. Long, continuous time series, exceeding the typical 3-year lifetime of individual satellite missions or instruments, are extremely difficult to acquire outside of operational programs. While many of the needed satellite-based observations of key atmospheric and solar forcing variables are already incorporated into U.S. and international operational meteorological satellite programs, the situation is far less secure for ocean variables. Of particular concern for applying the research results from EPIC is assuring long records of scatterometer observations of near-surface vector winds and altimeter observations of sea level since these are available only from research satellites.

3.4.2. *In-Situ* Observations

Enhancing the in-situ climate observing system over the eastern Pacific is essential for achieving the scientific objectives of EPIC, for improving coupled climate prediction models and monitoring their performance over time, and for proper calibration and use of satellite based observations. The remoteness of the area over much of the equatorial and southeastern Pacific present a major challenge to the ingenuity of observational oceanographers and meteorologists. EPIC will encourage cooperative activities among U.S. agencies and international partners to improve the quality and availability of in situ observations in the region. These efforts include:

(1) TAO: The NOAA TOGA TAO array will provide upper ocean temperature data and surface winds over a band extending from 8°S to 8°N across the Pacific. The addition of meteorological sensors to buoys at 95°W and 110°W is needed to provide downwelling shortwave and longwave

radiation, precipitation, and barometric pressure measurements in addition to the regular TAO observations. The addition of temperature, salinity, and velocity sensors to provide good temporal and vertical resolution of the upper ocean may be needed if the array is to be used in conjunction with other elements of EPIC to explore upper ocean processes.

(2) PACS: The Pan American Climate Studies Program (PACS) provided the impetus and focus for EPIC. PACS enhanced monitoring activities will continue during the EPIC process study. PACS currently supports a number of field studies to build a better description of the background climatology of the cold-tongue/ITCZ complex. The atmospheric boundary layer structure above the cold tongue is being studied with atmospheric soundings collected aboard ships during TAO mooring recovery and deployments. Air-sea fluxes and associated upper ocean structure are being studied from two moorings at 125°W, one at the equator and one at 10°N in the vicinity of the ITCZ. A third effort measures vertical profiles of currents, temperature and salinity in the equatorial cold tongue.

PACS is supporting work to improve the upper air sounding network in the eastern Pacific and surrounding land areas. Currently, the only operational atmospheric soundings in the eastern Pacific are taken at the Galapagos. Several different approaches are being considered: establishing routine soundings at the remaining three islands (Clipperton, Cocos, Malpelo); the use of ship-based soundings; the use of dropsondes from manned aircraft; and the direct use of flight level data from autonomous aircraft or robotic balloons. An enhanced VOS sounding activity could improve basin-scale coverage, while fixed location soundings would provide long term monitoring with higher temporal resolution at selected sites around the basin. These could be pilot balloons, radiosondes (RAOBs), microwave sounders, or integrated systems. Aircraft sampling could contribute to enhanced monitoring east of 100°W with P-3 and G-4 aircraft. Wind Profilers could be deployed on Galapagos and Piura islands for winds up to 3 km altitude. Other possibilities are tethered balloons (Peru and Ecuador) and recoverable radiosondes for PBL observations. Aerosondes and robotic balloons are currently being tested and may be available in time for PACS. An aerosonde could be based in Galapagos or Peru. Clipperton Island is identified as a PACS special site for enhanced monitoring under the ITCZ where observations could be made during the intensive observing period.

(3) CORC: Starting in 1998, the Scripps-Lamont Consortium for Ocean Role in Climate (CORC) will conduct enhanced monitoring in the eastern tropical Pacific (Figure 3.9). The plans included upgrading selected VOS XBT lines with IMET sensors to make air-sea flux

measurements. In addition, surface drifters and P-ALACE floats will be deployed and monitored within the PACS region. These observations are sponsored independently of PACS.

(4) VAMOS: The variability of the American monsoon system is being studied by the VAMOS Program, a component of CLIVAR-GOALS. It is anticipated that VAMOS will play a crucial role in coordinating the efforts of EPIC scientists in North, Central, and South America. In addition to improving land-based atmospheric sounding systems in the region, VAMOS may assist in the upgrading of VOS XBT, enable Peru and Chili to redeploy moorings in the Pacific, to occupy CTD transect and maintain sea level and coastal monitoring. The VAMOS Science Panel has endorsed the scientific plan for EPIC as a VAMOS/CLIVAR field study. Under discussion are coincident VAMOS field work in the Amazon, the Andes, and the altiplano of South America that would work with EPIC to examine links between Amazonian convection, subsidence in the stratus deck region off Peru, and Pacific SSTs. In addition, VAMOS will help address onshore moisture flows from the EPIC region, such as through the Gulf of California region. A VAMOS Field Planning Workshop was held in Sao Paulo, Brazil, in April 1998 to coordinate these efforts.

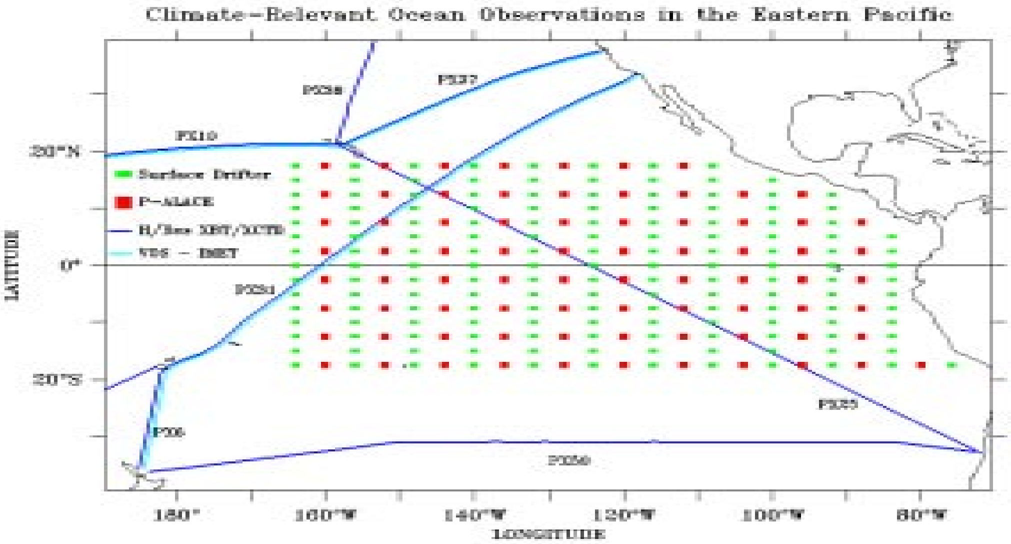


Figure 3.9. Summary of measurements to be made under CORC.

5) PBECS - The Pacific Basin-wide Extended Climate Study: the goal of PBECS is to describe and understand climatic variability within and between the tropical and subtropical Pacific Ocean. PBECS will examine the hypothesis that an important element of that variability is associated with meridional circulation that carries cool thermocline water to the equator from the subtropics. At the equator in the eastern Pacific that water upwells, forming the cold tongue. PBECS will focus on the pathways of these shallow overturning cells, on decadal modulation of ENSO, on the decadal variability of the North Pacific, and on the coupled ocean-atmosphere exchanges and transports of heat and freshwater. The science of PBECS is in many ways complementary to that of EPIC, with the major difference between the programs being that of time scales of interest. EPIC seeks to understand the annual cycle of the coupled system in the eastern Pacific, while PBECS looks out as long as the decadal signal. Because of the commonality between the science, plans to coordinate the start-up of PBECS and EPIC are being developed.

3.5. Synthesis: Data Analysis and Modeling Activities

The diverse nature of the EPIC field observations and the availability of additional data from programs such as PBECS will require a effort to synthesize a comprehensive picture of ocean-atmosphere structure and variability over the EPIC domain. Large numbers of field variables will come from instrument systems having a variety sampling patterns and resolution in space and time. Atmospheric and oceanic modeling and data assimilation in support of EPIC will provide a useful framework for testing the scientific hypotheses about the CTIC and subtropical stratiform cloud regimes discussed in Section 2. The primary objective of these activities will be physical understanding, not simply the development of modeling and data assimilation techniques.

Atmospheric analysis and modeling

High priority will be placed on working with NCEP and other major weather and climate prediction centers to obtain the best possible large-scale atmospheric analyses of the EPIC data set through the application of state-of-the-art 4D atmospheric data assimilation systems. Data that may be usefully assimilated into large-scale models from EPIC enhanced monitoring and process studies will be provided in real time whenever possible. The purpose of the reanalyzed data sets are to support empirical studies and to provide initial fields and boundary conditions for numerical experiments and data assimilation using nested high resolution cloud resolving models.

Cloud resolving models are expected to play an important role in understanding the nature of the controls on atmospheric convection in the eastern Pacific ITCZ and in understanding the reasons for the differences between the eastern Pacific convective systems and the convective systems further west in the ITCZ near 125°W and in the TOGA COARE warm pool region. Data from atmospheric soundings, shipborne radar and ABL observations during the IOP will provide ground truth for numerical experiments. Mesoscale variational data assimilation methods may reach a mature stage during the EPIC period, providing a quantitative means for analyzing the nature of ITCZ convection and its variability over a mesoscale atmospheric domain during the ITCZ intensive observing period.

Cloud resolving models are also expected to play an important role in the design and interpretation of EPIC field observations of boundary layer clouds. High priority is placed on understanding the transitions in the structure and properties of boundary layer cloud decks following large-scale trajectories from the Peruvian and Chilean stratocumulus across the cold tongue into the ITCZ. Successful numerical simulations of the cloud field transitions may provide a basis for understanding the systematic errors in the atmospheric components of coupled models and improving boundary layer cloud parameterizations.

Ocean analyses and modeling

The unprecedented density of observations along 95°W, in the context of larger scale ocean observations provided by EPIC enhanced monitoring, are expected to provide an opportunity for data analysts and ocean modelers to sort out the quantitatively mechanisms by which the CTIC mass, heat and salinity budgets are satisfied. EPIC will seek collaboration with NCEP and other groups insure that observed data from EPIC and PBECS investigators are fully utilized in the analysis of large-scale upper-ocean structure using state-of-the-art ocean data assimilation systems. One dimensional ocean modeling is expected to play a key role in the interpretation of heat and salinity budgets in the vicinity of moored buoys with high quality air-sea flux estimates.

The interpretation of EPIC upper-ocean observations will require the use of high resolution ocean models. Intraseasonal waves and instabilities near the equator, the complex CTIC current and upwelling structures, and the effect of coastal geometry are expected to be important contributors to the upper-ocean heat and salinity budgets in the CTIC and subtropical stratus deck regions. Collaboration with PACS and GOALS investigators will be essential to the success of this activity.

Ocean-atmosphere modeling and analysis

A major goal of EPIC is to provide a basis for improving the performance of coupled models in simulating the ocean-atmosphere climate of the eastern Pacific. The EPIC domain is characterized by large gradients of atmospheric heating and cloud-radiative effects and complex ocean current, temperature and salinity structures. It is not clear the extent to which these detailed features are crucial for the annual march and seasonal-to-interannual variability of the larger scale features of the ocean and atmosphere. High resolution coupled models are expected to play a key role in testing the hypotheses identified in Section 2 and developed further from the analysis of EPIC field observations. Collaboration between EPIC investigators and scientists at major climate analysis and prediction centers during the period of EPIC field observations and enhanced monitoring will be essential to timely improvements in seasonal-to-interannual climate prediction systems for the pan-American region. The EPIC data sets will also provide a basis for further numerical experimentation and hypothesis testing by PACS and GOALS investigators during the latter half of the CLIVAR program.

3.6 Timeline

EPIC is a five year process study, beginning with enhanced monitoring in 1998 and ending in 2004. A timeline is shown in Figure 3.10. The intensive observational periods are expected to occur in 2000–2003. The process study elements aimed at seasonal to interannual variability will span much or all of those years. High intensity, one-month elements of the process studies will occur within the 2000–2003 period (Figure 3.10). July-September 2001 is the target date for high intensity process studies in the CTIC.

The timeline shoes that EPIC has sustained (3-year) observations in both the CTIC and Stratus elements in 2000-2003 that are supported by the longer-running existing and new (1999-2004) enhanced monitoring elements of PACS. By 2005 PACS interest will shift to the tropical

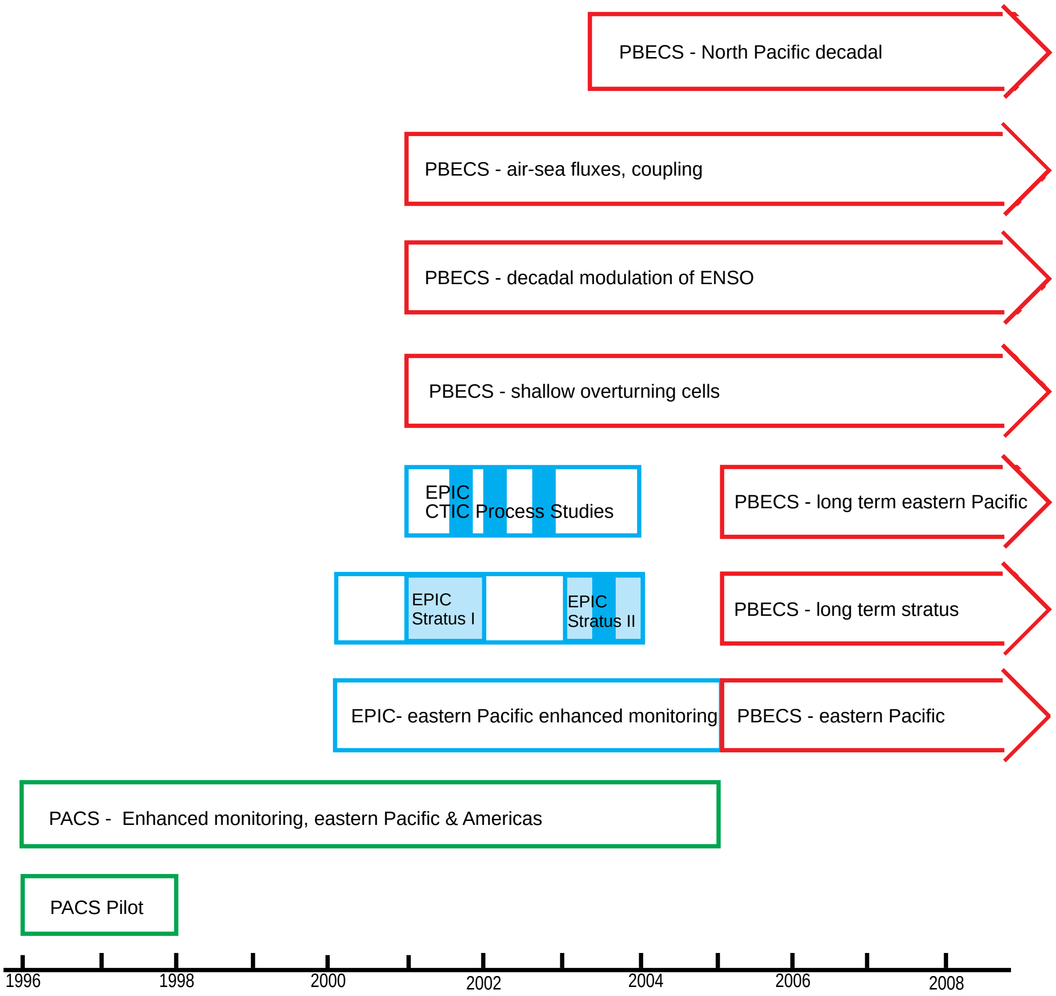


Figure 3.10: Timeline summarizing filed activities during EPIC. The shaded, one-month duration boxes indicate that intense limited duration process studies will be carried out in addition to longer running process studies. Coordinated Pacific studies focussed on longer time scales are indicated by the activities labeled as PBECS.

Atlantic. Thus, the continuation of studies of variability of the coupled ocean-atmosphere system in the tropical Pacific will be under PBECS; and the timeline has been drawn to indicate the potential that some EPIC observations will transition to PBECS. In addition, the timeline reflects the desire to start EPIC and PBECS at roughly the same time, so that each program may benefit from and support the other.

4. THE IMPACT OF EPIC

EPIC will have significant impact. Improved understanding of the key ocean, atmosphere, and coupled processes of the eastern Pacific will result from the program. High quality data sets that will, for the first time, illuminate the structure and seasonal-to-interannual variability of the ocean and atmosphere in the region will be collected. Improvement to our ability to predict the evolution of the SST in the eastern tropical Pacific on seasonal-to-interannual time scales will be a key step toward gaining skill in predicting the impact of SST variability in this region on weather and climate over the Americas. EPIC will also provide the basis for designing the climate observing system needed for future monitoring of the eastern Pacific.

4.1 Contributions from EPIC

The field work described in this scientific plan was motivated by and aimed at resolving the challenges encountered in modeling the region and its impacts on the Americas. These challenges were summarized in Section 1.3. Here, the anticipated contributions of the EPIC field studies are summarized, highlighting how they will address the issues raised in Section 1.3.

Considerable difficulty stems from our present lack of spatial (horizontal and vertical) and temporal resolution in the observations available for understanding physics and benchmarking models of the eastern tropical Pacific. As a result, the available descriptions of the fields and structures that are being modeled are often rudimentary. Similarly, the quantitative understanding of the relative importance of various processes to the evolution of those fields and structures is at present deficient. The EPIC process studies will provide the accurate, well-resolved observations that are needed.

There will be both short, high intensity process studies and longer running process studies that capture seasonal-to-interannual variability. The contributions anticipated from each are discussed below.

4.1.1 Contributions from High Intensity Process Studies

Oceanic, atmospheric, and coupled models employ parameterizations of processes whose physics they cannot fully represent. High intensity process studies will be used to examine processes and structures in sufficient detail to address questions about the parameterizations used in models.

A major difficulty in present-generation ocean models is properly accounting for vertical exchanges of heat, salt and momentum in, and through, the ocean mixed layer. A variety of parameterizations for these processes are used, but we have little sense of how well they represent the real ocean. Vertical exchanges are likely to be particularly important in the eastern Pacific where near-surface vertical gradients are so large. Ordinary TAO moorings poorly resolve the mixed layer vertical structure. Historical, hydrographic, and XBT data are aliased in time, especially under relatively short timescale events like ITCZ storms and wind bursts through the mountain gaps, whose episodic mixing may be a significant contribution to the low-frequency evolution. Detailed, local studies of upper ocean physics, similar to those done in TOGA COARE, can be used to examine the physics of mixing in the upper ocean. Such EPIC process studies will help improve model parameterizations by examining the ocean response to wind and freshwater forcing at high space and time resolution. In addition, these measurements will help to understand coupled feedbacks that need to be modeled. For example, when ITCZ storms cool SST by vertical mixing, does that change feed back to modify the development of convection?

Recent theory and simple models of the ITCZ point to an important role for the meridional SST gradient and the associated southerly cross-equatorial wind. However, we have little quantitative idea of how, and on what time and space scales, the SST gradient affects the southerly winds. We know that there is usually a sharp SST front, and that both the front and the southerlies are strongest near 95°W. Are these things related, or do the southerlies respond mostly to the much larger scale gradient? On what time and space scales do the southerlies change in response to changes in the SST gradient? Aircraft and ship-based studies in EPIC will diagnose the connection between changes in the SST front and southerly winds. In-situ observations are necessary because, first, TAO buoys do not resolve the front in space, and second, because satellite AVHRR (Reynolds SST) is aliased by not seeing through clouds, a severe problem in this region of often heavy cloud cover.

Cross-equatorial southerlies generate a meridional cell consisting of upwelling south of the equator, northward surface flow, and downwelling north of the equator. In models, the sum of this cell and the symmetric upwelling due to the zonal wind produces upwelling centered south of the equator and a shallow recirculating cell to the north. This probably accounts for the mean southward displacement of the cold tongue, and is an important aspect of the heat balance in the eastern Pacific. However, we do not know the meridional or vertical extent of this cell, and therefore cannot evaluate how well models represent the actual ocean. Shipboard and profiling float observations will be used to examine SST and other property changes in association with variations of the southerly winds, and contribute to better understanding of this circulation.

Atmospheric GCMs underestimate cloud cover in the stratus decks; their cumulus, deep convection, and boundary layer stratus parameterizations need improvement. Mesoscale atmospheric models are more successful at simulations over complex topography and in regions such as the ITCZ. However, further work on them requires the data sets that will be used to initialize such models and as benchmarks for their success.

Satellite observations (e. g., Raymond et al., 1998) show that the east Pacific ITCZ is in a sense a statistical fiction, in that intense deep convection there is concentrated in episodic bursts of convection associated with the passage of easterly waves and the genesis of east Pacific tropical cyclones. As seen in Figure 4.1, the mean time between these outbursts varies between 5 and 10 days. In between these outbursts, deep convection is weak to non-existent.

If deep convection in the east Pacific ITCZ is so strongly modulated by the passage of synoptic waves, what role does the strong north-south SST gradient play in the generation of convection there? Since the SST pattern does not radically change over the period of a few weeks, the convection is not just a simple response to an atmospheric thermal gradient imposed by the ocean. However, easterly wave forcing is not the entire answer either, because if that were so, there would be much more episodic deep convection in the southern Caribbean as African easterly waves crossed this region. We suspect that east Pacific deep convection is the result of a synergy between easterly waves and the SST gradient, but the nature of this synergy is uncertain.

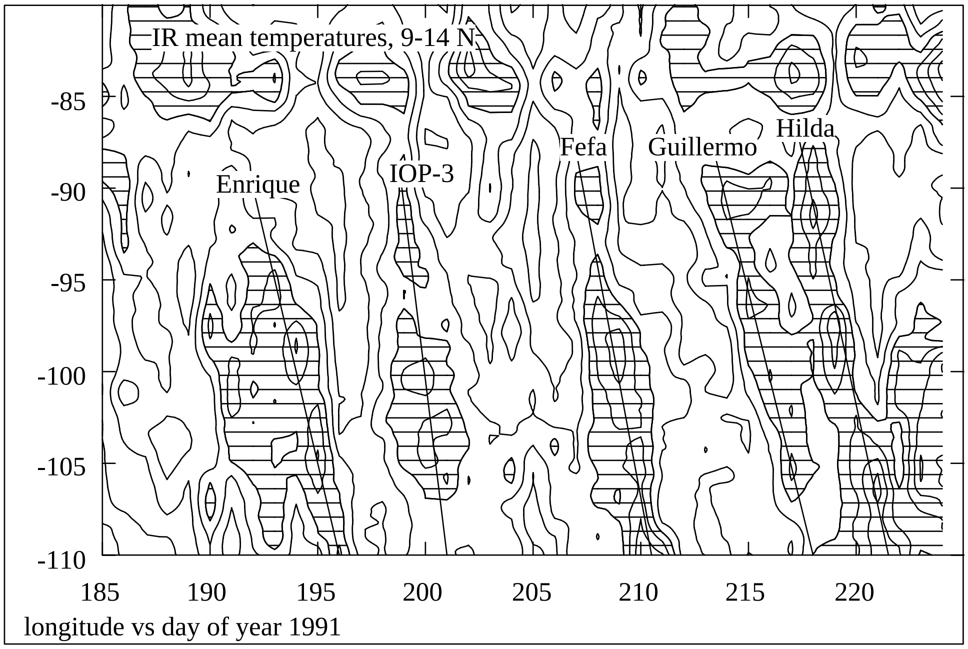


Figure 4.1. Infrared brightness temperature from GOES-7 averaged over the latitude range 9–14°N for summer, 1991. The contour interval is 10 K and horizontal hatching indicates temperatures less than 260 K. The names indicate easterly waves which developed into tropical storms.

The above dilemma is symptomatic of a larger problem in tropical meteorology: Precisely what is it that forces tropical deep convection? Diverse assumptions about convective forcing have been made in different models, with widely diverging results. Further progress in this area requires that the convective forcing issue be resolved.

Ultimately, convection responds to change in its local environment. Some of the factors which are known to influence convection in varying degrees are the amount of convective instability available in the free troposphere, the humidity and wind profiles in the troposphere, the degree to which convection is inhibited by a stable layer near cloud base, the entrainment of dry tropospheric air into the boundary layer, and the strength of sea surface energy fluxes.

Two things need to be done; first, the relative importance of each of the above factors in producing deep convection needs to be evaluated. Second, the role of SST gradients, easterly waves, and other large scale phenomena in setting up these conditions needs to be determined. Remote and in-situ aircraft and ship observations of environmental conditions accompanying deep convection in conjunction with synoptic scale observations of easterly waves should be able to answer these questions. Of particular importance are boundary layer observations taken systematically through disturbed and suppressed conditions. Attention needs to be paid to atmospheric thermodynamic measurements in rainy conditions, something which has not been done before.

The payoff for a successful execution of this phase of PACS will be a better understanding of how to treat deep convection in large scale models of the PACS region. Since the deep convection in the east Pacific ITCZ is a key part of the coupled ocean-atmosphere system in this region, learning more about convection there is essential to the program's success.

4.1.2 Contributions from Seasonal-to-Interannual Process Studies

The eastern tropical Pacific is a data sparse region. We have little basis for describing the seasonal cycle in the vertical structure of the atmosphere across the CTIC and for accurate quantification of the air-sea fluxes in the CTIC and under the stratus deck. Atmospheric GCMs underestimate the wind stress in the equatorial region and more generally have difficulty with the surface fluxes and in producing realistic boundary layer structure. Time series of the wind and the surface heat and moisture fluxes from moorings will be used to benchmark the performance of AGCMS and guide improvements to them. Together with data from the VOS and satellites, surface mooring data will be used to provide accurate flux fields over the region for the duration of the experiment. As a result there will be a high quality surface flux data set for forcing oceanic models as well as for comparison with atmospheric and coupled model flux fields.

Ocean general circulation models have difficulty at producing a realistic annual march of SST in the eastern tropical Pacific. This may be either because their physics are deficient or because the surface flux fields used to force them are inaccurate. The longer running surface mooring deployments will provide both high quality surface fluxes and well-resolved (in time and in the vertical) descriptions of the upper ocean. Surface moorings deployed in combination with virtual moorings (profilers) and subsurface moorings for 18 months would allow, at select locations, the balance of processes governing the annual cycle in the upper ocean to be evaluated and compared to the physics of the ocean models. Eulerian and Lagrangian observations of the horizontal velocity field will be used to quantify the role of advection. The moored data is also well-suited to addressing whether models must resolve high frequency surface forcing and oceanic variability, such as tropical instability waves, in order to properly simulate the lower frequency response of the ocean.

For coupled and atmospheric general circulation models, simulating the annual march of the upper ocean and the atmosphere in the eastern tropical Pacific has also proven to be difficult. The longer-running process studies will document the evolution of the atmosphere and ocean over the annual cycle, thus helping to pinpoint the deficiencies in the models. Ordinary TAO moorings poorly resolve the mixed layer vertical structure and are not instrumented to observe the surface fluxes. The additional observing elements fielded by the longer-running EPIC process studies are thus critical elements of the effort to benchmark and improve model performance.

The surface radiative fluxes are poorly known and links between SST, the surface radiative fluxes, the ABL, and the cloud cover will be explored and documented at select locations. These observations and information about such links will be used to improve the models. One such improvement would be to the ocean models, which have suffered from a lack accurate shortwave and longwave radiation data in their surface forcing fields. Another improvement would be to the atmospheric models, where improvements to simulations of the coupling between the ocean and the clouds would be sought.

4.2 Linkages to modeling activities

The climate in the EPIC region is characterized by the equatorial cold tongue and by climate asymmetries about the equator. The latter include a single northern ITCZ, except for a brief period around the March equinox where there seems to be a southern ITCZ. The flow over the eastern sector of the cold tongue is affected by the monsoonal circulations over the Americas. There are persistent stratocumulus decks along the coastlines. The study of this complex flow will requires the use of a hierarchy of models, ranging from coupled atmosphere-ocean general circulation models (CGCMs) to single-column models. The EPIC domain, with its strong atmosphere-ocean interactions, provides an attractive test bed for such models.

Links with PACS and GOALS. These programs encourage the development of CGCMs, whose performance must be improved in the EPIC region. Here, these models tend to produce a too strong, narrow and westerly-elongated equatorial cold tongue, to simulate a rather persistent double ITCZ and to overestimate SSTs along the coast of Peru and California. One of the keys to the CGCM deficiencies seems to be the poor model performance in the simulation of marine stratocumulus. The goal is to improve the simulation of the seasonal cycle, which appears crucial for the period, phase and a periodic nature of ENSO. This intimate dependency of anomalies on the mean state and seasonal cycle presents a major challenge to coupled GCM modelers.

PACS also encourages AGCM studies aimed to gain insight on the remote effects of SST anomalies. In the EPIC region, one of the common flaws of AGCMs is the underestimation of wind stress in the equatorial belt. It is also important to gain a better understanding of the effects on the low-level flow of coastal mountain ranges. The Andes mountains, for example, may play a crucial role in maintaining the prevailing along-shore surface winds off Peru and the associated oceanic upwelling in that region. The PACS and EPIC efforts will pave the way for the development of realistic AGCMs and eventually of improved CGCMs.

PACS and GOALS encourage work with OGCMs, particularly on those ocean processes that influence the behavior of the coupled system. This research addresses the varied roles of insolation and other surface fluxes, upwelling, horizontal advection and vertical mixing. Efforts to improve OGCMs focus on the parameterization of those physical processes, the better understanding of the rectification of high-frequency forcing (e.g., equatorial intraseasonal waves) and internal instabilities into the low-frequency variability, and on the question of closure of the equatorial and tropical current systems in the east Pacific. These topics are of high relevance to EPIC.

In addition, PACS is encouraging the development of mesoscale models for detailed examination of the seasonal to interannual variability along the coasts and over the mountainous terrain of the Americas. The research with these models addresses the role of mesoscale convective systems in organizing precipitation land and in the ITCZs. The issues under investigation concern the sensitivity of model performance to resolution and physical parameterizations, as well as the techniques employed to nest the mesoscale models in global models. This task includes determining the impact of mesoscale surface wind fluctuations on the thermodynamical and dynamical structure of the underlying ocean. PACS is also exploring the potential of “window models,” in which a selected region is examined at higher resolution. In the EPIC region, mesoscale atmospheric models coupled to coastal models can focus on the rapid ocean cooling along the Central American that develops in response to winter northerlies blowing through gaps in the American cordillera.

Links to NCEP. The improved understanding of the physical processes responsible for the variability of the tropical oceans and the improved ability to predict them with CGCMs will be directly relevant to the methodologies used in operational prediction centers. EPIC will emphasize the links with NCEP in several aspects. First, GCM improvements will be made available to NCEP for operational activities. Second, NCEP can provide the testbed for parameterization schemes developed as part of EPIC. In this regard, PIs will be encouraged to test model improvements developed under EPIC in the operational prediction (medium range as well as seasonal predictions). Third, EPIC will encourage collaborative efforts with NCEP to assess the impact of special observational network related to EPIC on the operational atmospheric/oceanic assimilation and prediction on medium range and seasonal time scales. The initialized fields in operational numerical weather prediction models are subject to large uncertainties and systematic biases in the data sparse region of the eastern Pacific, which are as yet largely undocumented. The impacts of these errors and biases upon the accuracy of forecasts are not well understood. In situ atmospheric data gathered by EPIC will be compared with operational analyses in order to get an indication of the errors and biases in these data sparse regions. The possible impacts on the seasonal time scale will be through the impact of special oceanic observing network on the analysis of the ocean initial state (salinity etc.). Impact on medium range atmospheric prediction can focus on assessment of tropical storm genesis and evolution and propagation of easterly wave disturbances in the Eastern Pacific.

Links with DOE/ARM. The primary objective of the Atmospheric Radiation Measurement (ARM) Program is the improved treatment of atmospheric radiation in climate models. ARM's approach is based on a combined measurement and modeling program. EPIC will interact with these program components, particularly with ARM's Single Column Modeling effort for validation against the special observational network related to EPIC. Some scientific questions, among others, may include: how do the low level observed profiles of T and q etc. compare with observations; how do the heating rates in the model compare with either observed or diagnosed heating rates; how does the temporal variability of convection predicted in the models compare with the observations; role of large scale forcing related to easterly waves in initiating convection; structure and comparison of PBL.

5. THE IMPLEMENTATION OF EPIC

In the spring and summer of 1998 this document was distributed to potential investigators and to funding agencies, including NOAA, NSF, NASA, ONR, and DOE. Discussions followed and culminated in the EPIC Workshop in Tucson in October 1998. Revisions were made that reflected the Tucson meeting and discussions with funding agencies and the U.S. CLIVAR Scientific Steering Committee. The intent of this revised document is to outline the scientific objectives of EPIC and to present the initial draft of an implementation plan for a program that will successfully address those objectives. An EPIC Scientific Steering Committee was formed to assist in revising this document and further development of the program.

It is anticipated that potential Principal Investigators will submit proposals for participation in EPIC beginning in 1999. In 1999, following the first round of proposal submission and funding, and in advance of field work that would begin in 2000, an Implementation Workshop will be held. The purpose of this workshop will be to coordinate the activities within EPIC and the activities of EPIC with VAMOS, CORC, PBECS, GEWEX, and other related programs. During EPIC, a workshop of active and potential investigators will be held yearly to provide ongoing coordination.

Because the detailed plans for the field program are evolving in response to continued planning and dialog with other programs, especially PACS, VAMOS, and PBECS, detailed discussion of the implementation is done in **Appendix V**, which will be periodically rewritten to stay current.

REFERENCES

Albrecht, B. A., 1989: Aerosols, clouds microphysics and fractional cloudiness. *Science*, **245**, 1227-1230.

Albrecht, B. A., C. S. Bretherton, D. W. Johnson, W. H. Schubert, and A. S. Frisch, 1995: The Atlantic Stratocumulus Transition Experiment ASTEX. *Bull. Amer. Meteorol. Soc.*, **76**, 889-904.

Bond, N.A., 1992: Observations of planetary boundary-layer structure in the eastern equatorial Pacific. *J. Climate*, **5**, 699-706.

Deser, C., J. J. Bates, and S. Wahl, 1993: The influence of sea surface temperature gradients on stratiform cloudiness along the equatorial front in the Pacific Ocean. *J. Climate*, **6**, 1172-1180.

Firestone, J., and B.A. Albrecht, 1986. The structure of the atmospheric boundary layer in the central equatorial Pacific during FGGE. *Mon. Wea. Rev.*, **114**, 2219-2231.

Gultepe, I., G. A., Issac, W. R. Leaitch, and C. M. Banic, 1996: Parameterizations of marine stratus microphysics based on in situ observations: Implications for GCMs. *J. Climate*, **9**, 345-357.

Klein, S. A., and D. L. Hartmann, 1993: The seasonal cycle of low stratiform clouds. *J. Climate*, **6**, 1587-1606.

Kloesel, K.A., and B.A. Albrecht, 1989: Low-level inversions over the tropical Pacific - Thermodynamic structure of the boundary layer and the above-inversion moisture structure. *Mon. Wea. Rev.*, **117**, 87-101.

Krueger, S. K., G. T. McLean, and Q. Fu, 1995: Numerical simulation of the stratus-to-cumulus transition in the subtropical marine boundary layer. Part I: Boundary-layer structure. J*. Atmos. Sci.*, **52**, 2839-2850

Legates, D. R., and C. J. Wilmott, 1990. *Int. J. Climate.*, **10**, 111-127.

Martin, G. M., D.W. Johnson, D. P. Rogers, P. R. Jonas, P. Minnis, and D.A Hegg, 1995: Observations of the interaction between cumulus clouds and warm stratocumulus clouds in the marine boundary layer during ASTEX. *J. Atmos. Sci.*, **52**, 2902-2922.

Martin, G. M., D.W. Johnson, P. R.Jonas, D. P. Rogers, and I. M. Brooks, 1997: Effects of airmass type on the interaction between cumulus clouds and warm stratocumulus clouds in the marine boundary layer. *Quart. J. Roy. Met. Soc.*, **123**, 849-882.

Moeng, C.-H., W. R. Cotton, c. Bretherton, A. Chlond, M. Khairtoutdinov, S. Krueger, W. S. Lewellen, M. K. MacVean, J. R. M. Pasquier, H. A. Rand, A. P. Siebesma, B. Stevens, and R. I. Sykes, 1996: Simulation of a stratocumulus-topped planetary boundary layer: Intercomparison among different numerical codes. *Bull. Am. Met. Soc.*, **77**, 261-278.

Moncrieff, M. M., S. K. Krueger, D. Gregory, J.-L. Redelsperger, and W.-K. Tao, 1997: GEWEX cloud system study (GCSS) working group 4: Precipitating convective cloud systems. *Bull. Am. Met. So*c, **78**, 831-845.

Raymond, D. J., C. Lopez-Carrillo, and L. Lopez Cavazos, 1998: Case studies of developing east Pacific easterly waves. *Quart. J. Roy. Meteor. Soc.*, in press.

Rogers, D. P. and D. Koracin, 1992: Radiative Transfer and Turbulence in the Cloud-topped Marine Atmospheric Boundary Layer. *J. Atmos. Sci.*, **49**, 1473-1486.

Sadler *et al.*, 1987. University of Hawaii, Department of Meteorology, Reports 98-01 and 98-02.

Schubert, W.H., P.E. Cieslielski, C. Lu and R.H. Johnson, 1995. Dynamical adjustment of the trade wind inversion layer. *J. Atmos. Sci.*, **52**, 1-11.

Spencer, R.W., 1993: Global oceanic precipitation from the MSU during 1979-91 and comparisons to other climatologies. *J. Climate*, **6**, 1301-1326.

Spencer, R.W. and J.R. Christy, 1993: Precision lower stratospheric temperature monitoring with the MSU: Technique, Validation, and Results 1979-1991. *J. Climate*, 6, 1194-1204

Spencer, R.W. and J.R. Christy, 1990: Precise monitoring of global temperature trends from satellites. *Science*, **247,** 1558-1562.

Wallace, J.M., T.P. Mitchell, and C. Deser, 1989. The influence of sea-surface temperature on surface wind in the eastern equatorial Pacific: Seasonal and interannual variability. *J. Climate*, **2**, 1492-1499.

White, A. B., C. W. Fairall, and J. B. Snider, 1995: Surface-based remote sensing of marine boundary-layer cloud properties. *J. Atmos. Sci.*, **52**, 2827-2838

Woodruff, S. D. *et al.*, 1987. *Bull. Amer. Meteor. Soc.*, **68**, 1239-1250.

APPENDIX I: ACRONYMS

PBL	Planetary boundary layer
SST	Sea surface temperature
CLIVAR	Climate Variability, a WCRP research program
GOALS	Global Ocean-Atmosphere-Land System, the seasonal to interannual component of CLIVAR
CTIC	Cold Tongue, Intertropical Convergence zone complex
ITCZ	Intertropical Convergence Zone
EPIC	Eastern Pacific Investigation of Climate processes in the coupled ocean-atmosphere system
BECS	Basin-wide Extended Climate Study
PACS	Pan American Climate Study
PBECS	Pacific Basin-wide Extended Climate Study
ENSO	El Niño Southern Oscillation
VAMOS	Variability of the American Monsoon System, an element of CLIVAR
TOGA	Tropical Ocean-Global Atmosphere
TAO	Tropical Atmosphere Ocean
SSS	Sea surface salinity
NECC	North Equatorial Countercurrent
SEC	South Equatorial Current
EUC	Equatorial Undercurrent
ERS-1	European Remote Sensing Satellite
COARE	Coupled Ocean Atmosphere Response Experiment
CAPE	Convective available potential energy
GATE	GARP Atlantic Tropical Experiment
GARP	Global Atmospheric Research Program
CCN	Cloud condensation nuclei
LES	Large eddy simulation
CRM	Cloud resolving model
GCM	General circulation model
NOAA	National Oceanic and Atmospheric Administration
NCAR	National Center for Atmospheric Research
GOES	Geostationary operational environmental satellite
AVHRR	Advanced very high resolution radiometer
IMET	Improved Meteorological system, a complete package for ships or buoys
AXBT	Airborne expendable bathythermograph
CCPM	Coupled climate prediction model
DMSP	Defense Meteorological Satellite Program
TRMM	Tropical Rainfall Measuring Mission
NASDA	National Space Development Agency (of Japan)
NASA	National Aeronautics and Space Administration
GEWEX	Global Energy and Water Experiment
GOOS	Global Ocean Observing System (NOAA)
GCIP	GEWEX Continental-Scale International Project
NPOESS	National Polar-orbiting Operational Environmental Satellite System
IRI	International Research Institute for SCPP

APPENDIX II: Spaced-Based Observations During EPIC

A. Prospects for space-based observations during EPIC

The atmospheric and oceanographic variables of most interest to EPIC are listed below, together with summaries of the histories and future of satellite instruments for measuring these variables.

1. Near-Surface Winds

a. Scatterometers provide accurate, global, high-resolution measurements of near-surface wind velocity (both speed and direction) under all weather conditions. With the development of numerical atmospheric general circulation models containing realistic boundary layer parameterizations, the operational meteorological community has found that assimilation of scatterometer surface vector wind measurements can yield improved operational weather forecasts. For this reason, NOAA invested in the telecommunication, data reduction, and data assimilation hardware and software needed for operational acquisition and utilization of scatterometer measurements from the research-mode NASA scatterometer.

History of Scatterometry:

July–October 1978	NASA Seasat-A Satellite Scatterometer (SASS)
April 1992–May 1996	European Space Agency ERS-1 Scatterometer
August 1995–present	European Space Agency ERS-1 Scatterometer
October 1996–June 1997	NASA Scatterometer (NSCAT)

Future of Scatterometry:

November 1998 (approved)	NASA Quick Scatterometer (QSCAT)
August 2000 (approved)	NASA SeaWinds-1 Scatterometer
August 2000 (proposed)	NASA SeaWinds-1B Scatterometer
2002	European Space Agency METOP Advanced Scatterometer

b. The Defense Meteorological Satellite Program (DMSP) has launched an operational series of passive microwave radiometers (the Special Sensor Microwave/Imager, SSM/I) since the late 1980s. The primary application of the SSM/I data is to study polar sea ice processes. However, the instrument also measures all-weather wind speed over the ocean, but with no directional information. An SSM/I is included on each of the operational DMSP Polar Orbiters, of which there are generally two in orbit at any given time.

History of SSM/I:

July 1987–December 1991	SSM/I on DMSP Platform F08
December 1990–present	SSM/I on DMSP Platform F10
December 1991–present	SSM/I on DMSP Platform F11
May 1995–present	SSM/I on DMSP Platform F13
May 1997–present	SSM/I on DMSP Platform F14

Future of SSM/I:

1998 (approved)	SSM/I on next DMSP Platform

2003+	SSM/IS (improved SSM/I)
2007+	Conical Scanning Microwave Imager/Sounder (CMIS) on NPOESS

c. Cloud drift winds produced from geostationary sensors have been used routinely in operational forecast models for some time. More recently techniques have been developed for producing water vapor drift winds, which do not rely on the presence of clouds to produce wind vector estimates

2. Sea Level

Altimeter measurements of the precise distance between the satellite and the ocean surface include important climate signals such as steric heating and cooling of the upper ocean and upper-ocean geostrophic currents. Satellite altimeter measurements provide unprecedented coverage and accuracy of the long, baroclinic tropical Kelvin and Rossby waves associated with seasonal and intraseasonal variability and interannual signals such as El Niño. These waves play a critical role in coupled ocean-atmosphere interaction in the eastern tropical Pacific region of interest to EPIC.

History of Altimetry:

July–October 1978	NASA SEASAT altimeter
November 1986–December 1989	U.S. Navy GEOSAT altimeter
April 1992–May 1996	European Space Agency ERS-1 altimeter
September 1992–present	NASA/CNES TOPEX/POSEIDON altimeter
August 1995–present	European Space Agency ERS-2 altimeter

Future of Altimetry:

December 1997	U.S. Navy GEOSAT Follow-On altimeter
1999 (approved)	European Space Agency ENVISAT altimeter
May 2000 (approved)	CNES/NASA Jason-1 altimeter
2004 (proposed)	CNES/NASA Jason-2 altimeter

3. Sea Surface Temperature

Satellite infrared measurements of SST have been available from the NOAA operational satellites since 1973, with high quality SST estimates from the Advanced Very High Resolution Radiometer (AVHRR) available since 1979. The AVHRR measures SST in cloud-free conditions. 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 several European and Japanese satellites.

With the launch of GOES-8 and 9, we now also have the capability to obtain SST measurements from geostationary satellites. Though the accuracy and resolution are slightly poorer than that possible from the AVHRR, the instruments enable detailed measurements of diurnal variations in SST that were not previously possible. These measurements will be very valuable to the planned air-sea interaction studies. The more frequent measurements provided by geostationary satellites also provide a much greater likelihood of obtaining cloud-free SST retrievals in regions of persistent cloud cover such as the stratus cloud decks.

History of NOAA AVHRR

February 1979–January 1980	AVHRR on TIROS-N satellite
January 1980–August 1981	AVHRR on NOAA-6 satellite
August 1981–February 1985	AVHRR/2 on NOAA-7 satellite
July 1985–September 1985	AVHRR on NOAA-8 satellite
February 1985–November 1988	AVHRR/2 on NOAA-9 satellite
December 1986–September 1991	AVHRR on NOAA-10 satellite
November 1988–September 1994	AVHRR/2 on NOAA-11 satellite
September 1991–present	AVHRR/2 on NOAA-12 satellite
March 1995–present	AVHRR/2 on NOAA-14 satellite

Future of NOAA AVHRR

Fall 1997 and beyond (approved)	AVHRR/3 on NOAA-K, L and M

Future Sources: Additional high quality SST measurements will be possible from the NASA MODIS following its launch scheduled for 1998.

4. Ocean Color

Estimates of near-surface chlorophyl can be obtained from ocean color measurements. These data are good tracers of upper-ocean currents, as well as a measure of the biological response to wind forcing and ocean dynamics. The chlorophyl distribution is, also, often correlated with the geographical distributions of fish populations.

History of Ocean Color:

October 1978–June 1986	NASA Coastal Zone Color Scanner (CZCS)
October 1996–June 1997	Japanese ADEOS Ocean Color Temperature Sensor (OCTS)
October 1997 –present	NASA SeaWiFS

Future of Ocean Color:

June 1998 (approved)	NASA MODIS

5. Water Vapor, Clouds and Rainfall

Satellite sensors can provide information on cloud type, distributions, fractional coverage, ice content, optical depth and other cloud properties for studying both radiative and energy budgets. The International Cloud Climatology Project (ISCCP) is an excellent long term source of many of these cloud properties. In addition, the availability of high resolution data from the NOAA AVHRR, DMSP OLS, and multiple geostationary platforms including GOES 9 over the east Pacific provide potential high spatial and temporal resolution cloud information over the entire region of interest.

Passive microwave observations can provide information on both liquid and ice content within clouds. A number of techniques have been developed to estimate precipitation from the SSM/I, which has been demonstrated to provide superior estimates of instantaneous rainfall rates over ocean regions than techniques employing satellite infrared and/or visible images. Over 10 years of data is currently available from SSM/I, and 19 years of precipitation estimates based on MSU are available from Spencer (1993).

The successful launch of the first spaceborne precipitation radar on board the Tropical Rainfall Measuring Mission (TRMM) in November of 1997 should provide an excellent opportunity for improving our understanding on the distributions and characteristics of tropical rainfall. This will be especially valuable over the eastern Pacific where current climatological rainfall estimates differ significantly between microwave, infrared, and visible retrieval techniques.

Atmospheric water vapor is a key component of the Earth's radiation budget. Water vapor is the most significant greenhouse gas and causes the largest positive feedback in model simulations of climate change induced by anthropogenic greenhouse gases. Satellite observations of water vapor at various levels throughout the atmosphere are available from the high resolution infrared sounder (HIRS) on board the NOAA polar-orbiting satellite series from 1979 through the present. In addition, microwave-based observations sensitive to tropospheric water vapor are available from the SSM/T2 sounder on board the DMSP satellite series starting in 1991. The limited availability of reliable radiosonde observations, especially over the east Pacific and in the upper troposphere makes satellite-based monitoring critical for understanding both radiative and moisture balances in this region.

a. The AVHRR infrared radiometer discussed above also measures cloud properties.
b. The SSM/I passive microwave radiometer discussed above also measures total columnar water vapor, integrated cloud liquid water, and rain rate.
c. The Tropical Rainfall Mapping Mission (TRMM) research satellite jointly under development by NASA and the Japanese space agency (NASDA) will be launched in late 1997 into a low-inclination orbit for obtaining accurate tropical rainfall measurements during its planned 3-year mission. Preliminary plans for a follow-on precipitation research mission called ATMOS-A1 are underway, but the continuation of the high accuracy TRMM data set and its extension to latitudes outside of the tropics are not presently assured.
d. There are also several atmospheric sounding instruments onboard the NOAA operational satellites that provide profiles of temperature and water vapor, as well as cloud distributions.

6. Atmospheric Temperature

Atmospheric temperature information from the NOAA MSU and DMSP SSM/T sensors has been operational since 1979. Spencer and Christy (1990, 1993) have used data from MSU for monitoring global temperatures going back to 1979. Both the MSU and SSM/T instruments are on board operational satellites providing the capability for long-term atmospheric temperature monitoring continuing through the proposed EPIC period of study.

B. Future U.S. Operational Satellites

Since 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 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. The mission of NPOESS is to provide a convergence of the NOAA, NASA and DMSP operational satellite programs into a single program to acquire, receive and disseminate global and regional environmental satellite data. Where appropriate, one of the goals of NPOESS is to transition technology from the NASA research satellite program to an operational status. NPOESS-1 is expected to launch in 2009, followed by NPOESS-2 in 2010. The plan is to maintain two NPOESS satellites in orbit at all times.

Much of the instrument compliment on NPOESS will consist of the present instruments for operational weather forecasting. Many of these sensors also provide data that are useful for climate studies such as EPIC. There are some instruments, however, that are very important for climate studies but have a less direct impact on weather forecasting. Examples include satellite altimetry and ocean color measurements.

The NPOESS program is presently under review by the National Research Council Committee on Earth Studies. The outcome of the NPOESS development process will not be implemented until after EPIC field activities. However, NPOESS is likely to play a crucial role in the success or failure of satellite data acquisition and analysis efforts in the post-EPIC period when the results of EPIC research are applied to improve precipitation forecasts over North America.

SSM/I (Special Sensor Microwave/ Imager) — This instrument is currently operating on 3 different satellites. A nearly continuous records exists since it initially became operational in July of 1987, providing a 10+ year record. The stability of this instrument makes it ideal for many climatological applications. Data from this instrument is also used for the retrieval of total column integrated water vapor, rainfall, cloud liquid water content, cloud ice content, and various land surface retrievals including moisture content and snow extent.

SSM/T (Special Sensor Microwave/ Temperature sounder) — Provides temperature profile information. This instrument has been operating on board the DMSP series since 1979.

SSM/T2 (Special Sensor Microwave/ Moisture sounder) — Moisture profiler operating on the DMSP series since 1991. There are currently two of these instruments in operation. This instrument provides coarse vertical resolution moisture information all the way up into the upper troposphere. It is less sensitive to the presence of clouds than infrared moisture sounders and is sensitive to changes in moisture at very high levels where radiosondes are of limited or questionable use.

SSM/IS — The next generation sensor which will replace the SSM/I. It is currently scheduled for launch in 2003.

TOVS (TIROS Operational Vertical Sounder) — Long-term observations of water vapor and temperature at various levels are available from 1979 through the present from the HIRS and MSU instruments.

AMSU (Advanced Microwave Sounding Unit) — Scheduled for launch in 1998. This instrument will provide passive microwave observations very similar to the DMSP SSM/I, SSM/T, and SSM/T2 sensors, but at significantly higher spatial resolutions. The AMSU channels will provide information on temperature and moisture profiles, rainfall and cloud liquid water amounts, and surface properties.

GOES 9 (West) — Provides high spatial and temporal resolution imagery over the east Pacific. The imager is useful for studies of various cloud types including both stratus and convective clouds, sea surface temperature retrievals, and upper tropospheric water vapor. Data from the sounder also provides vertical water vapor and temperature information. The high temporal sampling can be used to investigate diurnal variability over large regions.

ISCCP — Long-term cloud observations from the International Cloud Climatology Project provide 3 hourly observations of clouds and related parameters back to July 1983.

TRMM (Tropical Rainfall Measuring Mission) - This satellite was successfully launched in November of 1997 and is currently undergoing a shakedown period prior to the data becoming available to the science community. In addition to carrying the first ever spaceborne precipitation radar, it has visible, infrared, and passive microwave sensors providing high spatial resolution coverage of the tropics. In combination with existing satellites used for estimating rainfall in the tropics this will no doubt be very valuable for validating and improving existing retrieval techniques from other satellite sources as well as providing detailed information on vertical cloud structure during the life of its mission. This is especially important over the eastern Pacific where EPIC is focusing its efforts since current satellite based precipitation estimates from infrared, visible, and passive microwave instruments show dramatic differences. Also on board is the clouds and Earth's radiant energy system (CERES) instrument, which is a follow on to ERBE.

APPENDIX III: Remarks on Instrumentation and Platforms

A. New technology

Several new technological developments that address the issue of in situ observations in remote regions may greatly add to the eastern tropical Pacific air-sea interaction studies. The new instrumentation systems include:

1. Aerosonde. This RPV would give radio-sonde quality profiles at locations specified by the user. It has a long duration and would be more cost effective than conventional research aircraft. It may be able to access areas not possible with conventional aircraft.
2. Glider. Prototype gliders are now being tested and are expected to be available for use by the end of 1999. They are expected to have horizontal ranges as large as 10,000km while profiling vertically roughly 2000 km in total. They are designed to profile temperature and salinity from the ocean surface to as deep as 2 km while maintaining a fixed geographic location. The per profile cost, including the cost of vehicle construction, is expected to be comparable to the purchase price of an XBT probe alone. This oceanic profiler would make profiles in the ocean over long periods of time, communicating as it surfaces via the soon-to-be operational Iridium world-wide cellular phone network.
3. Aerobot. This robotic balloon system provides a possible platform for measurement of tropospheric radiation, water vapor and clouds. Aerobots use new technology involving reversible fluids to achieve altitude control capability. An aerobot cycling over a predetermined range in the boundary layer would give soundings following the mean boundary layer wind trajectory.

B. In situ sensor requirements

Specific measurement items that need thorough examination and care in how they are addressed in the field efforts are:

1. Sea and air temperatures: Accurate near surface ocean temperatures and air temperatures isolated from solar radiation are required on buoys and ships. For research aircraft, infra-red surface temperature measurements need to be refined for higher accuracy and stability.
2. Humidity: Accurate, stable humidity measurements are required for the measurement of air-mass thermodynamic properties from both buoys and research aircraft.
3. Sondes: While the GPS-derived winds on the new generation of atmospheric sondes appear to be a great improvement, the accuracies of the thermodynamic measurements, in particular boundary-layer humidity, needs improvement over those in TOGA COARE.
4. In-cloud temperature: Continued improvement of the measurement of in-cloud temperature from research aircraft is required to study convection processes.
5. Radiometers: Measurement of shortwave and infra-red radiation on ocean buoys is required.
6. Barometric pressure: The accuracy of present pressure sensors on buoys precludes measuring pressure gradients. Long-term accuracies of +/- 0.1 hPa are sought.

7. Rainfall: This remains an elusive measurement; the results of the PACS R/V Brown cruise should help sort out the best and worst sensors. Rainfall is important in ocean surface layer mixing as well as a part of atmospheric convection.

C. Other instrumentation/platform concerns:

1. Satellite scatterometers: Scatterometers with capabilities equal to, or greater than NSCAT, would be valuable for enhanced monitoring of surface wind and wind stress over the eastern Pacific during EPIC.

2. Volunteer ships: The VOS, suitably instrumented, and perhaps complemented with additional instrumentation (ceiliometers), are viewed as an integral part of an observing program in the remote eastern tropical Pacific area.

3. Buoys: Another IMET-type buoy at 18°S, 85°W would be valuable for studies of the stratus clouds during EPIC.

4. Atmospheric soundings: Soundings at fixed locations are labor intensive and expensive. The PACS SONET network has provided useful monitoring of the atmospheric circulation in the PACS area, but additional high quality soundings from island and coastal stations would be valuable to the EPIC program.

5. Research Aircraft: The eastern tropical Pacific area is remote and choice of operating base and flight plans will have to be made with care to maximize research time.

APPENDIX IV: Data Management

The following describes the ongoing PACS data management activities at UCAR's Joint Office for Science Support (JOSS). These are consistent with the EPIC planning efforts. Additional detail will be developed as the EPIC field studies begin.

Data Management Plan.

UCAR's Joint Office for Science Support is tasked with developing and maintaining a comprehensive and accurate data archive to meet the scientific goals of PACS. The plan should follow a strategy to assure that data from pilot and process studies, major field experiments, and the long-term PACS data archive are organized in a comprehensive archive structure. It should define data management activities within PACS that are consistent and complementary with broader-range science programs; and establish guidelines for data collection, sharing and archival within the PACS research community. In addition, JOSS is beginning to meet the broad data requirements based on questionnaire response; to fully exploit the WWW connections as additional data sources are identified; and continuing data collection over the larger PACS General Study area.

Data Management Strategy.

The PACS data management strategy should complement other programs of similar size and scope; as well as support wider ranging international activities such as CLIVAR. Any PACS data archive should easily link to existing data centers like NOAA / National Climatic Data Center (NCDC). This activity is currently underway and JOSS will continue its advisory role. Preparation of a complete data management plan will be based on the results of the PACS data requirements questionnaire.

Questionnaire.

JOSS has developed and distributed a data requirements questionnaire to the general PACS scientific community. The responses will be used to determine long-term data collection activities that are needed in support of PACS science goals. Prior to the distribution of the questionnaire, the PACS DMWG has provided guidelines for datasets of interest. The questionnaire was disseminated via electronic mail and the World Wide Web. JOSS will collate the results and prepare a report for the PACS DMWG and SSC.

CODIAC

Central to the JOSS data management strategy is the on-line, interactive, catalog, archival and distribution system, CODIAC. The system offers scientists a means to identify datasets of interest, the facilities to view associated metadata and the ability to automatically search and obtain data from geographically-dispersed data centers via Internet file transfer or separate media (magnetic tapes, CD-ROM, diskettes, etc.). The CODIAC inventory contains a searchable grid of datasets by time, location, station number or instrument type. Data requests are made possible through World Wide Web browse software, and is capable to download files via file transfer protocol (FTP). Investigators may take advantage of on-line catalog and browse tools to select a subset of the data for ordering; these include plots of individual data parameters or Gif image products. Access to other data sources, such as the NOAA/Pacific Marine Environmental Lab (PMEL)

TOGA-TAO buoy and COADS data archive and the NOAA/National Severe Storms Lab (NSSL) CODIAC are reachable through JOSS with no requirement to duplicate datasets.

Datasets Collected at JOSS

WWW Data Links: JOSS has developed and implemented a PACS data management page on the WWW incorporating the PACS data questionnaire, as well as distributed data links to existing data sources and related tropical meteorological / oceanographic information. JOSS has provided access to this Web page through the PACS Home Page at the Joint Institute for Study of the Atmosphere and Ocean (JISAO), University of Washington.

Satellite Data: One of the costliest datasets for researchers to obtain is satellite imagery purchased from various archives. JOSS presently has the capability to receive and archive GOES satellite imagery, in real time. JOSS has collected geostationary satellite (GOES-8 & 9) imagery over the PACS domain (30°N–30°S, 30°W–150°W, Figure A.IV-1. These geostationary imagery files are archived in McIDAS Area format. Data from polar-orbiting satellites (NOAA series, AVHRR data) are available from NOAA's National Geophysical Data Center and the NOAA/NESDIS Satellite Active Archive. JOSS has the capability to ingest high resolution, infrared satellite data over a subset of the PACS domain. The domain of data collection is identical to the 1997 Pilot Study Area on Figure A.IV-1. This data archive is accessible through the JOSS data management system (CODIAC).

In-Situ Data: Current operational sounding, surface and ship data from the PACS region are transmitted over the Global Telecommunications System (GTS) and archived at NCAR's Data Support Section (NCAR/DSS) and NOAA’s National Climatic Data Center (NCDC). JOSS will archive WMO-coded upper-air messages, surface synoptic data and other reports of opportunity (ships) that appear in the General Study area.

Numerical Models: Global model grid point data from NOAA/NCEP Northern Hemisphere and Global Analyses datasets and the European Centre for Medium-range Weather Forecasting (ECMWF) Advanced Operational Dataset are archived at NCAR's DSS. These data are available at 1.5°/2.5° resolution, in polar stereographic coordinates, in the PACS General Study domain. The fields archived at NCAR/DSS are a subset of the full data output of the models. JOSS provides a link to this archive or could make the datasets accessible through CODIAC.

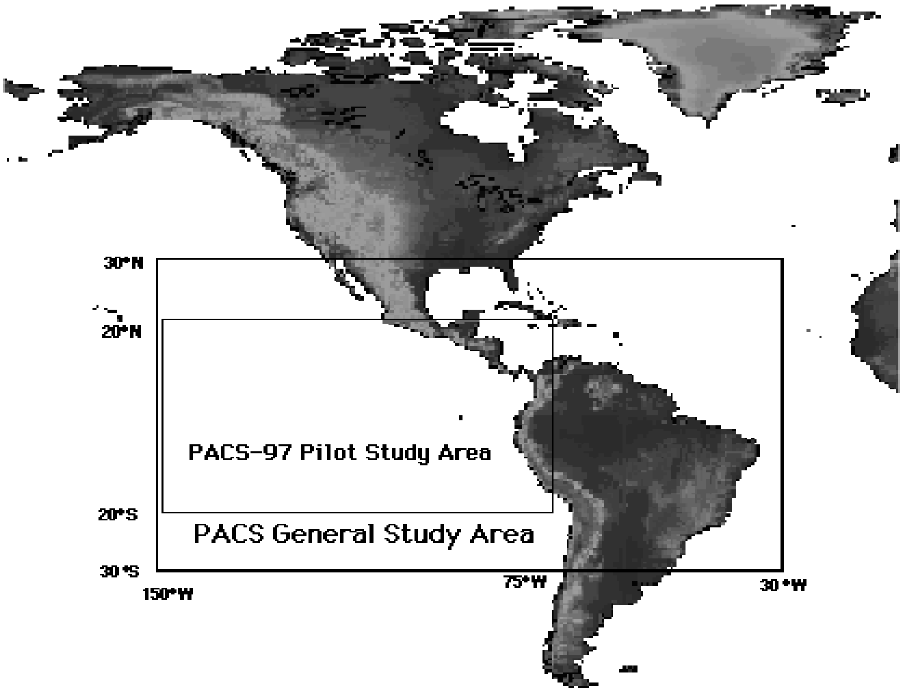


Figure A.IV-1. Domain of the general study and pilot study areas for PACS.

Other PACS General Study Area Existing Data Archives

National archives within Latin American countries in the PACS domain may provide valuable datasets of interest to PACS investigators. It is unknown at this time how widespread the use of the Internet is within the Pan American community; however, JOSS will continue to explore data sources and provide links through a PACS Data Management Web page to various data centers.

Table A.IV-1 provides a summary of the datasets and likely sources of such data to meet the long-term PACS needs. The initial data collection effort began in FY 97 includes datasets starred (*) in Table A.IV-1. JOSS will store or provide access to all these datasets on the CODIAC data management system. This system will also be used in the long term to support PACS. Links to additional national and international data centers will be added as PACS needs dictate.

Special Datasets

An important part of the PACS data management strategy is to include in the archive any special research data such as those described in Table A.IV-2, e.g. a) higher resolution satellite data over the Pilot Study domain (Fig A.IV-1) and b) soundings collected as part of pilot field observations and process studies programs. These data are collected from research platforms or special observations within operational networks. JOSS is providing the quality control processing for research soundings launched during the cruise of the R/V Brown in the 1997 Pilot Study. JOSS will also reprocess data from the PACS-SONET 97 research network into a common format to be available though CODIAC. Links will be added to other special dataset archive.

Additional JOSS support possible during EPIC field phase

Project Logistics: JOSS has the capability to provide full administrative support for any field project activities. JOSS staff can handle shipping needs, interact with customs officials, secure permits and leases. JOSS can also assist in organizing planning meetings and workshops.

Field Operations Plan and Implementation: JOSS can advise or prepare an Operations Plan detailing all pertinent activities that will be necessary to mount a successful field campaign. JOSS has the in-house expertise to create an Operations Center, to provide operational support such as aircraft coordination, network installation and support, communications links, etc.

Field Phase Data Management-Special Research Data Questionnaire: JOSS could develop and distribute a special data requirement questionnaire to PIs participating in the EPIC field project. JOSS would collate the results and prepare a report for the PACS Data Management Working Group and the Scientific Steering Committee. Based on results of this second questionnaire, JOSS would collect or provide links to the appropriate datasets.

Field Phase Data Management- Field Catalo:. During the field phase, JOSS can provide limited on-line data catalog capabilities. The catalog is implemented using a WWW browser interface. The field catalog functions to permit data entry (metadata on collection strategies, field summary notes, sample operational data, etc.) and data browsing (listings, plots) during the experiment. Daily summaries of operations and data-gathering activities would be available to all participants via Internet. If required, it would be possible to create a subset of imagery and products that could be e-mailed to a location where they could be picked up by shipboard scientists.

Special Datasets

JOSS could prepare special releases of selected data to be issued as CD-ROMs, if requested. These media are useful for datasets that are too large for general network dissemination or for possible distribution to international participants who do not have ready access to the Internet.

It is important to state that JOSS believes there is no need to have all PACS datasets in one central archive. The distributed archive concept is reasonable given the ease of movement on the network using the WWW. In fact, it is desirable that P.I.s be primarily responsible for the collection, processing and archival of specialized datasets for which they are most familiar.

Table A.IV-1 — Proposed PACS General Datasets.

Data Type	Data Source
Satellite	
GOES Visible *	JOSS
GOES IR *	JOSS
Water Vapor *	JOSS
Polar Orbiter	NGDC
Derived Products	TBD
GTS data	
Rawinsonde *	JOSS
Surface *	JOSS
Ship reports*	JOSS/NODC/ NCDC
Special Datasets (research / operational)	
High resolution rawinsondes	JOSS/Intl Center
High resolution surface	JOSS/Intl Center
Precipitation	JOSS/Intl Center
Profilers	JOSS
Research radars	P.I.
TOGA-TAO	PMEL
COADS	PMEL
Buoys	TBD
Numerical Models	
NCEP / MRF	NCAR/DSS
ECMWF	NCAR/DSS
Research mesoscale models	P.I./ JISAO
Special PACS runs of operational models	JOSS/NIC
NCEP Re-analysis	NCAR/DSS
Field Programs	
PACS pilot or process studies	JOSS

* Recommended preliminary datasets collected by JOSS beginning in FY-97.

Table A.IV-2 — PACS-97 Pilot Studies Datasets

Satellite Data	Buoy and Moorings Data
H GOES 8/9 (Visible, Infrared, 6.7µ water vapor)	H TOGA/TAO Array
H NOAA AVHRR (SST, etc.)	WHOI IMET
DMSP SSM/I	TIWE
TRMM (2 cm radar, passive microwave)	Drifters
	ATLAS Moorings
	ADCP Moorings
Upper-Air Data	Ship Data
50 and 400 MHz Profiler (AEMN)	Doppler Radar (R/V Brown)
915 MHz Profiler (R/V Brown)	Raingages (R/V Brown)
H NCAR GPS Rawinsondes (R/V Brown)	Meteorological/Oceanographic Measurements (R/V Brown)
H Operational Rawinsondes	Navigation Data (R/V Brown)
Tethersondes	H COADS and other ship observations
H Supplemental Pilot Balloons	
Model Output	Other Land Surface Data
H NCEP Operational Fields	H Operational Meteorological Observations (including rainfall)
H NCEP Reanalysis	
H ECMWF Operational or Supplemental Fields	GPCP data for the Pilot Study domain

APPENDIX V: Draft detailed implementation plan

The following platforms would be needed for the intensive field observations:

Research aircraft — The main advantage of aircraft is mobility, and they provide the only practical means of in-situ measurement of the atmospheric vertical structure and cloud systems, especially in the boundary layer, with high resolution and extended spatial coverage. Logistical and cost constraints with aircraft force a focus on a limited region. The preferred one would be a meridional line at 95°W, where there is long-term monitoring of surface meteorology by TAO buoys from 8°N to 8°S and where the access to bases for the aircraft is feasible (Figure 3.4). Candidate aircraft for the intensive field observations and their instrumentation are listed in Table A V.1.

A candidate flight pattern for WP-3D aircraft is illustrated in Figure 3.5. The aircraft would fly a meridional section extending across the CTIC at 95°W. Its outbound leg would be in the subcloud layer and inbound leg in the mid or upper troposphere. The outbound leg would focus on measurement of the atmospheric boundary layer, while GPS dropsondes would be deployed during the inbound leg to measure the dynamic and thermodynamic structures of the troposphere. The WP-3D Doppler radar would be used in the dual Doppler mode to derive mesoscale flows of a target convective system. Airborne expendable

Table A V.1 Candidate aircraft and instrumentation for intensive field observations in the CTIC.

Aircraft	Instrumentation
NOAA WP-3D	Turbulence probes, temperature and humidity sensors, Radiometers, Drop-sondes, Cloud microphysics probes, Doppler radar, oceanic profilers
NCAR C-130	Turbulence probes, temperature and humidity sensors, Radiometers, Drop-sondes, Cloud microphysics probes, Cloud radar, Lidar, oceanic profilers
NOAA Gulfstream IV	Dropsondes

oceanographic profilers (e.g., AXCP, AXCTD) could be launched during the outbound leg to provide high-resolution snapshots of upper ocean dynamic and thermodynamic structures. This flight pattern and the north-south ship transect (see discussion below) are complementary to each other and their observations could be used to address similar scientific questions. Aircraft sampling is unique in the spatial coverage achieved in a short time period. Measurement of the vertical cross-section of the oceanic mixed layer, atmospheric boundary layer, and the troposphere across from the cold tongue through the ITCZ provided by aircraft is nearly instantaneous and synchronized. Such measurements can be planned prior to, during, and after major atmospheric synoptic disturbances or mesoscale systems in the ITCZ and thus monitor the large-scale effects of these ITCZ perturbations and their interactions with the atmospheric and oceanic environment. Information from these measurements would be useful for numerical modeling, especially coupled modeling.

Another flight pattern would be a number of vertically staggered legs from possibly the lowest altitude to 800–700 mb in a more confined region. This flight pattern would provide measurement of detailed vertical structures of turbulence and radiation fluxes and dynamic and thermodynamic profiles from the boundary layer into the free troposphere at a chosen location.

Research vessel — A well instrumented research vessel is desired for its capability of continuous sampling. Ship-board meteorological instruments would include turbulence probes, radiometers, rain gauges, wind profilers, GPS sondes, lidar, cloud and precipitation radars, and other surface meteorological sensors. A suitable ship with these instruments on board would be the *R/V Ron Brown*.

Two candidate ship modes of operation are discussed here. A ship could be stationed at a fixed location to collect continuous time series of atmospheric and oceanic vertical structure. A preferred location would be underneath the aircraft track and near the center of the ITCZ (Figures 3.4 and 3.5). Observations from this type of ship operation would be used to address issues particularly pertinent to the ITCZ, for example, interactions of the atmospheric boundary layer (ABL) with convective systems, the variability of the ABL between deep convective and cloud-free situations, accumulative effects of the high-frequency (e.g., diurnal, mesoscale, and synoptic-scale) variability on the ocean, the distribution and structures of different types of precipitating clouds and their fractional contribution to the total rainfall, and the local conditions that may help determine the characteristics of deep convection.

A ship could also make north-south transects at the same longitude as the aircraft track making high resolution vertical cross-sections of the atmosphere and ocean across the CTIC. Such measurements would be valuable in building our understanding of the transitions of the atmosphere and the ocean from the cold tongue through the ITCZ. For example, the verification of the relative roles of surface fluxes, entrainment at the top of the ABL, and radiation in the ABL energy budget from one regime to the other would be examined. So, also, would the evolution of the low-level southerly jet from the cold tongue into the ITCZ. Variation in the interactions between the ABL and clouds and of the effects of clouds on the ocean from the trade-cumulus regime to the deep convective regime would be examined.

Moored buoys — Moored buoys, such as upgraded TAO or IMET buoys, provide continuous measurement of surface fluxes of latent and sensible heat and radiation, rain rate, SST, and other surface meteorological conditions. Continuous subsurface measurement from buoys would provide the necessary information to correct the measurements with the airborne oceanographic profilers for aliasing of tidal motions.

Satellite remote sensing — A number of satellite remote sensing products, e.g., high resolution GOES and AVHRR imageries, TRMM observations of precipitation, latent heating profiles, and cloud microphysical structure, and others (see section 3.3.1) provide continuous measurement in time and space of many atmospheric variables. Satellite observations are useful as guiding information for in-field decision making for aircraft flight missions. Satellite observations would also put point or line measurements by aircraft and ships into large-scale perspective.

Upstream land-based upper-air soundings — Enhancement of the sounding network in Mexico and Central America would provide information of the atmospheric flows into the field observational domain.

Elements of the observational program intending to continuously measure oceanic structure over two full annual cycles must rely on unmanned platforms to be cost-effective.

The TAO buoys, sufficiently enhanced to measure fluxes of heat, moisture, and momentum to high precision, and IMET buoys are expected to provide observations of oceanic forcing. Satellite observations, particularly scatterometry, will be crucial in resolving these fields spatially. Drifters and VOS ships will be useful in providing checks on satellite observations and gauge the effectiveness of mapping schemes.

EPIC can significantly advance understanding of the processes that effect seasonal and interannual changes in upper ocean structure, particularly sea surface temperature, by observing the imbalances that cause them. The individual elements (surface buoyancy flux, advection, and mixing) need to be observed concurrently and over a range of locations that encompasses the warm pool and the cold tongue. A candidate plan to carry out such studies is given in Figure 3.6. Arrays of fixed elements are best for resolving the time and space variability that can be expected to effect seasonal and interannual changes in the region. Two arrays are suggested, one where upwelling is expected to be prominent and another where it is not. The fixed array elements build heavily upon the TAO moorings. Ship-based studies are expected to complement observations from unmanned platforms.

Upwelling is important in the cold tongue region and previous observations have successfully measured its intensity at a single location (typically a region centered on the equator) using an array of acoustic Doppler current profilers (ADCPs) to infer vertical motion from the divergence of horizontal currents. As the model flow pattern in Figure 2.3 suggests, vertical motion varies from upward in the center of the cold tongue to downward just north of the equator. It is confined largely to the thermocline, and above, and is closely linked to meridional flows. To observe this structure in the ocean, we propose an array consisting of several upward-looking ADCPs moored near 110°W forming adjacent equilateral triangles roughly 200 km on a side. The triangle centers are at latitudes from 3°S to 3°N. Estimation of advection due to upwelling requires observation of temperature and salinity profiles which can be carried out moored to “virtually moored” instrumentation (discussed below). With the cost of ADCPs having dropped substantially, the vertical motion array (in green) has become more cost effective than in the recent past.

Away from even very close to the equator, the geostrophic constraint is very strong, hence potential vorticity conservation on a beta-plane allows the geostrophic flow field to be inferred exclusively from density observations. The beta spiral method has been attempted using hydrographic surveys separated in time, from which the results are less than ideal because of temporal aliasing. Instead of basing its application on surveys, a coherent array of temperature and salinity profilers at fixed locations can be used to detect density gradients filtered temporally to remove noise from tides, internal waves, and eddies. Such an array, also using a sequence of triangles between elements, is depicted along 95°W from the dynamic height ridge between the South Equatorial Current and the North Equatorial Countercurrent to the coast of Central America.

This array builds upon the TAO array and its extension to cover the ITCZ's seasonal range of positions. The adjacent triangular regions can be used to estimate absolute geostrophic flows from which horizontal advection can be estimated. The beta-spiral method also calculates vertical motion forced by the divergence of geostrophic flow on a beta-plane. To the extent that Ekman currents (not just transport) causes upper ocean flow to be not strictly geostrophic, direct current measurements are also necessary, and could be made at fewer locations than in the upwelling array (i.e., at the centers of some of the red triangles in Figure 3.6; those along 95°W). The time series of temperature and salinity profiles called for in this array can be carried out using "virtually moored" glider vehicles (see section 3.5.A.2). Now under development, these offer the promise of near-real time observation of profiles at fixed locations from low-cost high-endurance autonomous underwater vehicles controlled via satellite communication. The ITCZ array discussed here will use gliders to observe temperature and salinity profiles and their evolution to diagnose the role of three dimensional advection (mainly meridional) in causing seasonal changes in upper ocean structure.

Surface fluxes would be observed from upgraded TAO and IMET moorings. In the ocean, direct observations of turbulent microscale fluxes within the upper ocean requires ship-based observations. Regrettably, these are too expensive to carry out continuously at multiple locations. However, microstructure observations are important in demonstrating the depth-time structure of upper ocean mixing. The distribution of mixing in the water column determines an important element of the upper ocean buoyancy budget to explain local rates of change that are not accounted for by advection. Mixing observations may take place along transects in small scale surveys or at fixed locations.

Surface moorings deployed at select locations will, as mentioned above, capture the surface forcing at select locations. When instrumented completely, they provide time series of all components of the air-sea fluxes of heat, freshwater, and momentum. With care, they can be very accurate and provide the means to calibrate and validate flux fields from models, remote sensing, and other in situ observations. Acoustic rain gauges will provide area-averaged precipitation to complement point gauges on the buoys.

The surface moorings will also be instrumented to measure upper ocean currents, salinities, temperatures, and bio-optical properties. In isolation, such surface moorings provide the means to examine the role of local atmospheric forcing in determining the evolution of SST and the extent to which one-dimensional physics governs the upper ocean. For example, process-oriented questions, such as whether the formation of a "barrier layer" or strong halocline in the ITCZ plays a role in controlling SST there and whether phytoplankton blooms play a role in increasing solar heating near the sea surface in the upwelling regions can be addressed with well-instrumented surface moorings. In addition, surface moorings provide, with high vertical and temporal resolution, upper ocean time series and coincident surface forcing that can be used to benchmark the performance of ocean and coupled models. Such moorings are easily maintained on station for 6 to 9 months per setting, allowing them to be used to examine upper ocean physics and surface forcing on seasonal and interannual time scales. Placed in diverse locations within the EPIC region, they will capture the spatial differences in the air-sea fluxes and upper ocean variability. For example, the air-sea forcing and upper ocean response could be documented and contrasted under the ITCZ, in the cold tongue, and in the stratus deck region. Deployed, as shown in Figure 3.6, in conjunction with other observational elements they can be used to develop upper ocean heat, salinity, and momentum budgets that close. Closure of such budgets and agreement between observed surface fluxes and the surface fluxes calculated as a residual from heat, salinity, and momentum equations provide the means to quantify the relative roles of the various processes at work in the upper ocean.

Large scale hydrographic transects from shore to shore are useful in describing overall mass, heat, and freshwater budgets over a portion of an ocean basin. For EPIC, transects from Central to South America crossing both the warm pool and the cold tongue in different seasons will allow calculation of large scale flows with which those measured by the fixed element arrays can be corroborated. These measurements could conveniently be made concurrently with shipboard atmospheric flux measurements. The shallow pycnocline in this region means that SEASOAR CTD surveys coupled with shipboard ADCP measurements along these transects would resolve most if not all, of the significant ocean currents necessary to estimate the advection component of the heat budget. In addition, these underway high-resolution surveys would nicely complement the shipboard atmospheric measurements by providing concurrent detailed information on the mixed layer temperature, salinity, and current structure.