with 5–10 km horizontal resolution to be made in 17 days. Sections would be subject to noise from internal tides and waves; this might be reduced by temporal filtering of records from the slowly moving vehicles or perhaps by using glider pairs to allow geostrophic shears to be calculated between simultaneous profiles. Sections might also be subject to aliasing by coastally trapped waves that are energetic in the 8–11 day band (Cornejo-Rodriguez and Enfield, 1987), but this could be reduced using filtering that exploits the nonuniform sampling intervals associated with alternating sampling directions, and coherent filtering using altimetric records and data from a few moored current meters to define space-time patterns of variability.

9. Process Experiments

A fundamental characteristic of the ocean-atmosphere climate system is its nonlinearity. So the interannual and decadal variability that is the focus of PBECS cannot be understood and predicted (Lorenz, 1969) without an understanding of higher frequency processes. It is impractical to monitor the ocean on a scale adequate to resolve all of the processes that ultimately affect climate. It is, therefore, necessary to perform focused experiments to examine these processes and build parameterizations for inclusion in models, including assimilating models. We propose a sequence of process experiments as an important adjunct to PBECS.

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

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

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

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

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

The process experiments, discussed in more detail below, are strongly linked by their importance to the meridional cell and, thus, to climate. The overarching goals are to improve parameterizations for use in models and to aid the design of the observational system. We anticipate that small groups of scientists will form to develop and carry out these experiments during the 15-year PBECS time frame. In the following, we simply highlight scientific objectives of importance to climate. Details of implementation are left to the scientists who will one day address the objectives.

9.1 Diapycnal fluxes in the daily cycle below the equatorial mixed layer

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

Owing to its recognized importance, near-surface mixing has been studied intensively on the equator during several process-oriented programs: TROPIC HEAT, TOGA/COARE, and TIWE. All of these have found surprisingly different average mixing levels, as illustrated by the mean profiles of diapycnal diffusivity, K_ρ, in Fig. 9.1. These differences result from changes in the intensity of a daily cycle of mixing in the stratified water below the surface layer (Gregg *et al.*, 1985; Moum and Caldwell, 1985). Figure 9.2 shows several cycles of the deep daily K_ρ cycle during TIWE, the Tropical Instability Waves Experiment. For tens of meters below the surface layer K_ρ varied by factors of 10–100, peaking during the night. By comparison, at most open-ocean sites, convective mixing extends only a few meters below the surface layer. The different behavior on the equator is a consequence of the high mean shear and low mean Richardson number below the surface layer on the equator in the central and western Pacific. Variations in the easterly winds and

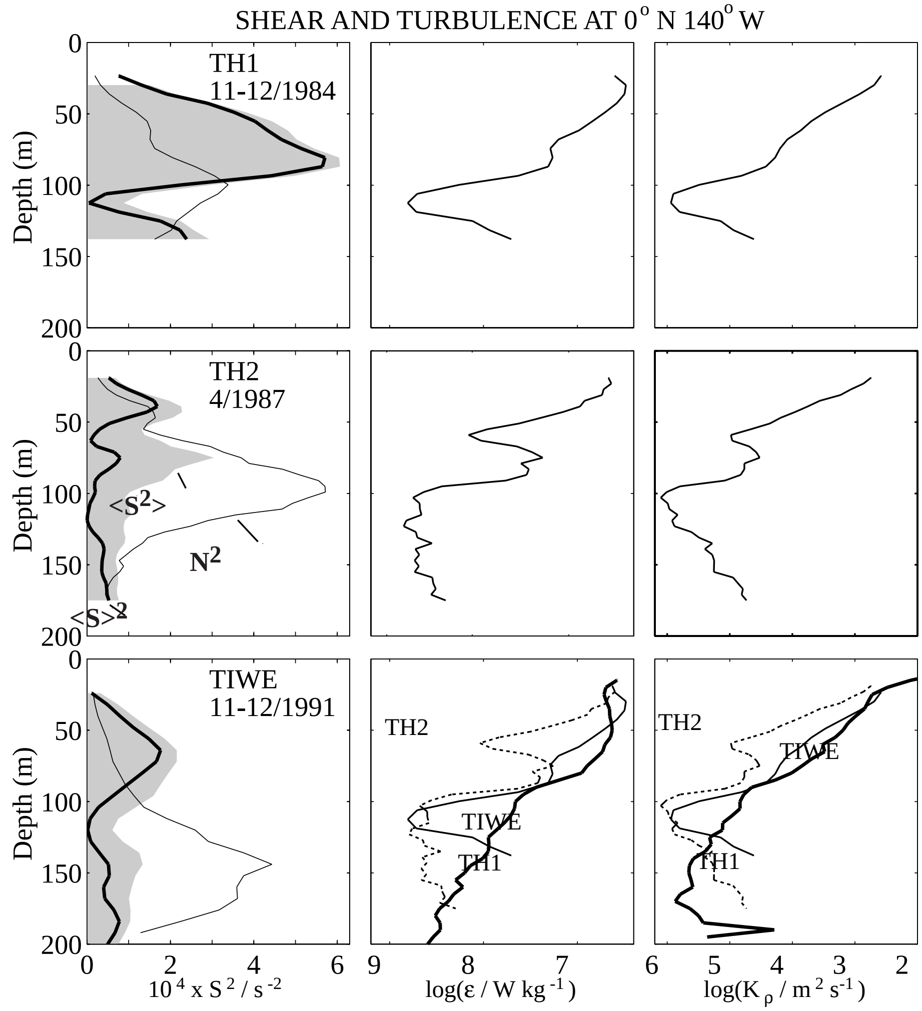

Figure 9.1: Average profiles of stratification, shear, turbulent dissipation, and K_ρ on the equator at 140°W during TROPIC HEAT I (Nov–Dec 1984), TROPIC HEAT II (Apr 1987), and TIWE (Nov–Dec 1991) from Gregg (1998). Panels on the left show stratification N^2, square of the mean shear $< S >^2$, and shear variance $< S^2 >$).

the intensity and depth of the undercurrent modulate the magnitude of the deep cycle and hence the mean diapycnal fluxes of momentum and heat into the surface layer (Lien *et al.*, 1995).

A daily cycle of finescale shear variance and small-scale internal variability accompanies the mixing cycle. One line of studies attributes the turbulence to breaking of the internal waves. Two mechanisms have been explored for the generation of internal waves beneath a convecting surface layer. One is the oscillation of the mixed layer base by convective plumes impinging on it. The other is the response of the stratified shear flow of the undercurrent sweeping across the base of the surface layer roughened by convective plumes. In both cases, the internal waves become dynamically unstable and break while propagating downward through a mean shear flow having a gradient Richardson number of about $\frac{1}{4}$. Another line of studies (e.g., Clayson and Kantha, 1999), concludes that the turbulence is generated directly at the base of the mixed layer and extends downward into a profile already close to instability owing to the high mean shear. According to

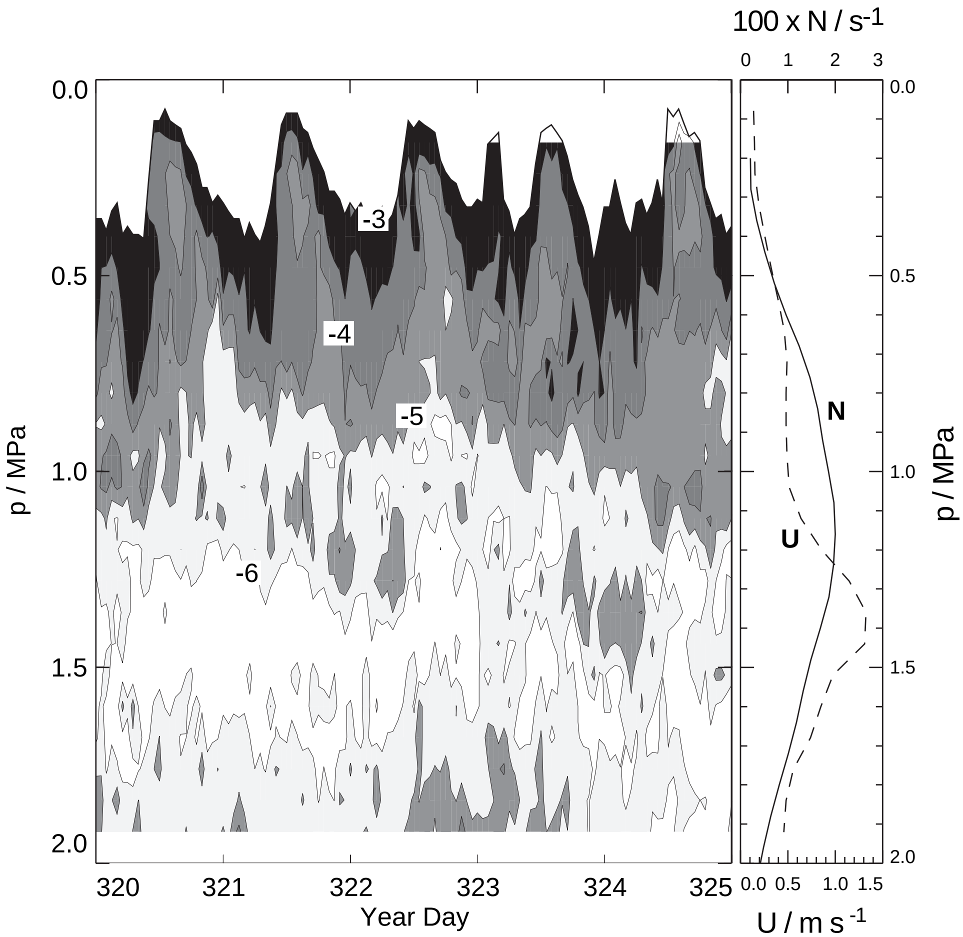

Figure 9.2: Shaded contours of $\log_{10} K_\rho$ begin at the base of the surface layer in the left panel, and the mean profiles of eastward current U, and stratification N are shown to the right for 5 days during TIWE (Gregg, 1998). The diapycnal diffusivity waxes and wanes with a daily cycle lagging the deepening and shoaling of the surface layer.

this scenario, the internal waves are produced by the stratified turbulence and are a result, rather than a cause, of the mixing.

Three conclusions are evident: (1) diapycnal fluxes produced by stratified turbulence below the equatorial surface layer must be parameterized for use in climate models; (2) no satisfactory parameterization exists and even the mechanisms responsible are not agreed upon. Moreover, it may not be possible to parameterize the mixing adequately with variables now in climate models. (3) Further piecemeal work by individual investigators, whether cruises or models, is unlikely to converge on accepted answers soon enough for climate modeling.

Developing satisfactory methods for including deep-cycle fluxes into climate models probably requires oversight from a CLIVAR working group on models and process experiments. Such a working group could be charged with developing coordinated numerical studies, process experiments, and monitoring upon which to base flux representations. This would put necessary focus into the exploration of ocean mixing studies.

9.2 Understanding and parameterizing diapycnal mixing at low latitude

Diapycnal mixing refers to transfers across mean density surfaces. Because the mean slopes of isopycnals are usually very small (10^{-5}–10^{-4}), diapycnal fluxes can be considered vertical but must be distinguished from the vertical components of lateral currents and mixing along isopycnals. These lateral motions are responsible for the large vertical eddy coefficients, $K_Z \sim 10^{-4}$ m^2/s, estimated from budgets (e.g., Munk, 1966), but their horizontal scales are much too large to alter water masses or dissipate kinetic energy. As representations of lateral currents and mixing become more realistic in numerical models, obtaining accurate parameterizations of true diapycnal fluxes is essential for predicting climate variability.

Three processes are known to produce diapycnal fluxes in the upper kilometer of the open ocean: breaking internal waves, salt fingers, and thermohaline intrusions. Of these processes, breaking internal waves are the most common and the best understood. They generate microstructure, allowing their diapycnal fluxes to be estimated from observed variances of temperature and velocity microscale gradients

$$K_T = k_T \frac{\langle |\nabla \theta'|^2 \rangle}{\langle \nabla \theta \rangle^2} \tag{3}$$

(Osborn and Cox, 1972) and $K_\rho \leq 0.2\ \varepsilon/\mathrm{N}^2$ (Osborn, 1974), whereas ε is the turbulent kinetic energy dissipation. Application to the large-scale, low-frequency general circulation is ad hoc (Davis, 1994a, 1994b), but its utility is demonstrated by the factor-of-two agreement with the rate of thickening of a tracer cloud during the North Atlantic Tracer Release Experiment (NATRE) (Ledwell *et al.*, 1993; Toole *et al.*, 1994; Sherman and Davis, 1995).

Microstructure cannot be measured over large areas, but the Garrett and Munk (1972) internal wave spectrum provides a reference linking diapycnal eddy coefficient to statistics of the internal wave field. Gregg and Sanford (1980) found that $K_\rho \sim 7 \times 10^{-6}$ m^2/s, with no N-dependence, when internal waves are at their background state. Henyey *et al.* (1986) constructed a simple analytical model for estimating K_ρ when internal waves differ from background. Gregg (1989) observed levels at mid-latitudes within a factor of two of these predictions, and Polzin *et al.* (1995) improved the agreement by using strain to estimate the average frequency of the waves. These agreements are good enough to make the problem of estimating K_ρ at mid-latitude one of determining the space and time structure of the internal wave field. Consequently, such an effort should be an important adjunct to PBECS.

How K_ρ from breaking internal waves behaves at low latitudes is not well understood. Henyey *et al.* (1986) give the dependence as $f \cosh^{-1}(N/f)$ with f the Coriolis frequency. As seen in Fig. 9.3, the sparse available data are consistent with this dependence, but there are large and unexplained differences between sites at different longitudes. Alford *et al.* (1999) obtained a time series showing varying K_ρ with the 4.5-day inertial period at 6.5°S in the Banda Sea. This variability is consistent with the observed near-inertial modulation of the Froude number, $(S/N)^2$. If this is a general condition at low latitude, then the inertial period establishes the length of sampling required to measure K_ρ, greatly complicating determination of the latitudinal dependence. Owing to the importance of low latitudes in modulating climate, process experiments to parameterize mixing rates there are given the highest priority. The first step is to determine if K_ρ is modulated at the inertial period in the open ocean, as it is in the enclosed Banda Sea. Then sampling strategies can be developed to adequately test Henyey *et al.*'s latitudinal dependence, and to develop alternative parameterizations if necessary.

Salt fingering is possible over wide areas, particularly equatorward of 25°, but there are no observations showing how often they occur or what diapycnal fluxes they produce. If K_ρ from breaking internal waves does vanish toward the equator, salt fingering may be the major agent of

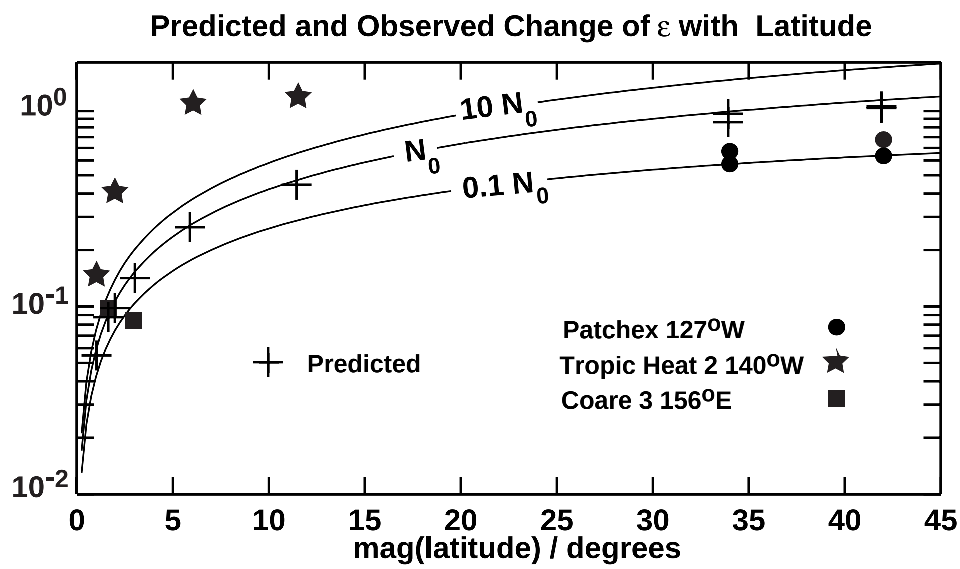

Figure 9.3: The predicted f-dependence of kinetic energy dissipation ε. Varying with stratification and latitude, the term is shown by three solid curves for a 100-fold range of N values. The crosses mark predictions for the particular N and f values where observations have been made, and the symbols show the corresponding observations after correction for the other terms in the Polzin *et al.* (1995) formula.

diapycnal transport at low latitudes. Comparison of microstructure levels with K_ρ from a tracer release should be included in at least one program measuring low-latitude microstructure and internal waves. Significantly faster thickening of the tracer would indicate that salt fingers are important and their fluxes should be included in models.

Thermohaline intrusions, particularly salt-stabilized temperature inversions, are common near fronts and are found to some degree nearly everywhere. They are often observed sloping across isopycnals and often contain signatures of double diffusion, but neither their generation nor their evolution is understood. Owing to the large magnitudes of thermohaline intrusions in equatorial fronts and apparently low levels of background mixing, intrusions may dominate diapycnal fluxes at low latitudes, even though they do not always contain strong microstructure. We cannot be confident of flux parameterizations until the contribution of intrusions are evaluated, and such an experiment should be one of the PBECS process studies.

9.3 Generation of subducted temperature-salinity anomalies

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

The main focus of a process experiment on the downward branch of the meridional cell is to determine how temperature-salinity anomalies are created and injected into the geostrophic circulation. While it is clear that these anomalies are due to atmospheric forcing, the mixed layer is an energetic region in which the anomalies are stirred and mixed before they pass into the deeper geostrophic ocean. For example, horizontal gradients of temperature and salinity in the mixed layer tend to compensate in their effect on density (Rudnick and Ferrari, 1999). That is, fronts in the mixed layer tend to be warm and salty on one side and cold and fresh on the other such that density fronts are minimized. These observational results suggest that horizontal diffusion in the mixed layer is an increasing function of density gradients, in agreement with the theoretical results of Young (1994). A process experiment should observe the establishment of T-S anomalies starting from the initial atmospheric forcing, as by rainstorm, to its eventually more compensated state. It has been known for some time that properties set in the winter mixed layer are transported downward along surfaces of constant density (Iselin, 1939), and that the annual cycle of mixed-layer depth is important (Stommel, 1979). Tracking specific anomalies from the mixed layer would be an essential objective of a process experiment. T-S anomalies on an isopycnal may be conveniently described using the variable called "spice" or "spiciness" (Munk, 1981), which quantifies the component of temperature and salinity that has no effect on density. Spice variability is observed to be largest in the mixed layer, and to decay with increasing depth (Ferrari and Rudnick, 1999). In view of the weakness of vertical mixing in the thermocline (Gregg, 1989), this decrease in spice has been attributed to salt fingers (Schmitt, 1999), although horizontal mixing may also be important (Ledwell *et al.*, 1998). An objective is to observe this decay in spice and determine the responsible mechanism. In summary, the objectives of a process experiment on the establishment of T-S anomalies are to observe and quantify: (a) initiation of anomalies due to atmospheric forcing; (b) evolution of anomalies through stirring and mixing in the mixed layer; (c) propagation of anomalies from the mixed layer to thermocline; and (d) decay of anomalies in the thermocline.

The observational capabilities already exist to address these objectives. It is possible to measure air-sea fluxes, horizontal and vertical structure of the mixed layer and thermocline, and turbulent mixing. The challenge of this experiment is that it is truly three-dimensional: both vertical and horizontal processes are crucial. The experiment is based on well-established theory, and theory is required in the context of this experiment to develop parameterizations for use in numerical models. Finally, the experiment will benefit greatly from the existence of PBECS monitoring. After anomalies have been tracked down into the geostrophic circulation, they can be handed off to Argo floats to follow their long-term propagation.

9.4 Processes of subtropical-tropical exchange

After they are subducted, it is unclear how anomalies are transported from the subtropics to the tropics. Variable subtropical-to-tropical exchange has been conjectured to induce decadal variation in low-latitude stratification and, in turn, the character of El Niño events, as discussed above. The modification of meridional exchange can be manifested as meridional mass transport anomalies, meridional heat transport anomalies, and/or meridional transport of potential vorticity (PV) anomalies. These are all related in one way or another to variations in air-sea heat, buoyancy, and momentum fluxes. A process experiment is envisioned within the large-scale PBECS observing system to explore the physics of the time-varying subtropical meridional overturning cell.

The experiment would observe the evolution of a PV anomaly as it moves south in the low latitude central North Pacific to, and through, the thermocline ridge marking the boundary between the NEC and NECC at about 10°N. The specific objective would be to tag a PV anomaly and measure the rates at which the anomaly is dispersed and dissipated as it translates equatorward. The long-range goal of the study is improved understanding of how off-equator PV anomalies influence low-latitude sea-surface temperature. Of particular interest is how mixing influences the water passing through the PV barrier driven by upwelling at the ITCZ. Quantification of mixing within the upper Pacific Ocean's subtropical-tropical meridional overturning cell is needed to link dynamically the large-scale circulation observations of PBECS to the dynamics of low-latitude stratification change, SST variations, and decadal ENSO variability.

9.5 North Equatorial Current bifurcation study

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

We have little observational or numerical basis for designing the long-term observations of the Pacific low-latitude western boundary currents and their variability. Ocean circulation models do not agree on the mean and variable transport of the Mindanao Current (MC), which is an important factor in the heat and salt budgets of the western Pacific warm pool. Because adequate time-series observations are lacking in the Pacific low-latitude western boundary currents, we cannot tell if any of these models is correct. Not even a complete annual cycle of MC transport has been measured. Fortunately, Japanese and German current time series have been obtained for the New Guinea coastal currents, which give us some guidance for the southern branch of the LLWBC system. A NEC bifurcation study would provide the intensive observations that are required.

9.6 Equatorial upwelling and the emergence of subtropical anomalies

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

This process study would observe, for a limited period of time including at least one complete (non-warm-event) annual cycle, the full range of processes that bring thermocline-level water to the surface, including how water properties are modified in the strong mixing regime above the undercurrent core. One focus is how ocean-atmosphere feedback is triggered by emergence of subducted anomalies, which likely depends on the anomalies themselves. A potential vorticity anomaly can affect the upper heat budget when the associated anomalies of temperature upwell into the upper layer (i.e., mean advection of anomalous temperature), or if the associated horizontal and vertical velocities change the temperature field (i.e., anomalous advection of the mean field) or a combination of both. A spiciness anomaly, on the other hand, does not affect oceanic density and therefore only enters the surface heat budget by changing the temperatures of upwelled water. The process study will require simultaneous observation of winds and surface radiation fields along with vertical profiles of u, v, T, and S at a spatial resolution fine enough to distinguish the effects of horizontal versus vertical advection, mixed layer deepening and entrainment, and heating due to penetrative solar radiation. Ideally estimates of rainfall (probably from satellites referenced to moored rain gauges) would add the ability to confirm the processes deduced from the temperature balance with a salinity budget. Since we have only rather general ideas about the zonal or meridional scales on which upwelling takes place, an array of velocity moorings to measure divergence of the horizontal velocity components (which could also be sampling temperature, salinity, and winds) would likely require on the order of ten sites, in order to be able to take derivatives over a variety of separations and to span the region over which upwelling takes place ($\pm 3°$ latitude). Because much of the Ekman flow occurs in the upper 25 m that is poorly sampled by acoustic current profilers, deployment of point current meters at 10–15 m depth on several TAO picket lines would greatly contribute to our ability to understand the wind-driven divergence that drives upwelling.

If, in the course of the PBECS program, a particular low-frequency subducted thermal anomaly is identified and is predicted to emerge in the equatorial upwelling regions, a study that goes beyond the standard PBECS observations should be mounted to examine how it emerges. This would provide an observational basis to test the ideas and hypothesis about the coupled response to emergent anomalies.

9.7 Vertical structure of horizontal currents

Determination of ocean circulation within PBECS will depend largely on an essentially geostrophic methodology using temperature and salinity observations under the constraints of hydrodynamic models. The upper ocean, as demonstrated by shipborne ADCP observations (Chereskin and Roemmich, 1991; Wijffels *et al.*, 1994), however, is not in geostrophic balance. The ageostrophic circulation extends well below the temperature mixed layer. Models used to describe this upper-ocean circulation parameterize mixing processes that have been well observed in the planetary boundary layer, or mixed layer (Large *et al.*, 1994). Estimates of the vertical diffusivity in the mixed layer during wind mixing conditions are 0.01–0.1 m^2/s. The cross-isopycnal diffusivity 300 m below, in the center of the main thermocline, is $1\text{–}3 \times 10^{-5}$ m^2/s, three orders of magnitude smaller. Existing models of upper-ocean mixing do not adequately parameterize the transition of vertical diffusivity from the geostrophic thermocline circulation to the ageostrophic surface layer.

This is because observations of the forcing of the three-dimensional structure of the upper ocean currents, together with the baroclinic density structure, have not been made in any mixed-layer experiment.

A complete horizontal-momentum, heat, and salt budget experiment of the upper ocean would provide the data set needed to unravel the mixing process below the mixed layer. In such an experiment the pressure gradients and Coriolis forces could be separated and the vertical convergence of turbulent momentum fluxes would be isolated. This experiment is now possible because of autonomous techniques for measuring temperature and salinity, and ways of profiling ocean currents with individual moored instruments or moored acoustic profilers. The uncertainties of in situ air-sea flux estimates have been reduced five fold in the past 10 years so that heat and salt budgets below the mixed layer are now feasible. No longer do we need to measure heat content change to check the surface flux in tropical conditions.

Accurate estimates of motion and fluxes in the upper-ocean are required to achieve the PBECS objectives and this will require improvements of models of upper ocean mixing between the mixed layer and the main thermocline. Connecting satellite altimeter data to Argo subsurface observations also requires understanding the transition of dynamics in this region. The tropical current system south and east of Hawaii has a significant difference between geostrophic currents, which flow to the southeast, and the observed mixed-layer circulation, which is to the north and west. This trade-wind driven system is a prime candidate for study and would be a test bed for the methodology of the PBECS data and models.

10. Integrated Atmospheric Observations

The success of coupled ocean-atmospheric models, as well as the utility of assimilated data sets for research purposes from PBECS, will depend crucially on detailed atmospheric observations with sufficient coverage in both time and space. The existing atmospheric observing system, especially over the extratropical Pacific, has large gaps in coverage. PBECS, in conjunction with other observational efforts, could substantially improve this situation through the optimization of emerging observing and data assimilation systems.

As discussed in Section 2, accurate estimates of the fluxes of momentum (surface wind stress) heat, and the input of fresh water are the cardinal requirements for driving ocean general circulation models (OGCMs). The boundary forcing of an atmospheric GCM (AGCM) is, at least in principle, somewhat simpler, and can be achieved by specifying the SST and the spectrum of incoming solar radiation at the top of the atmosphere. The latter field can be quite accurately calculated. SST is relatively well-observed, compared to the fluxes and precipitation (Section 4), although the sensitivity of the atmosphere to the diurnal cycle and other high frequency fluctuations in SST can not be discounted, particularly in the tropics (e.g. Weller and Anderson, 1996; Shinoda *et al.*, 1998; Woolnough *et al.*, 2000). Thus the boundary forcing of AGCMs might appear to be well-specified compared to the requirements of OGCMs. However, in practice, even the best AGCMs are still severely hampered, since even the best models are not capable of producing the correct ocean-to-atmosphere flux and precipitation fields, even given perfect boundary forcing. Improvements in AGCM climate simulations are therefore focused on improving model physics, such as parameterization of convection and radiation.

Historically, the development of OGCMs for climate studies has been hampered more severely than that of AGCMs by a lack of accurate boundary forcing data, particularly wind stress (Section 3.3). While substantial improvements in the surface wind stress fields have been realized using satellite scatterometers (Section 4.1), these observations are by no means continuous in time or