A Process Study for Equatorial Vertical Exchange: Pacific Upwelling and Mixing Physics (PUMP)

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Introduction

PUMP is a process study planned to observe the complex of mechanisms that connect the thermocline to the surface in the equatorial Pacific cold tongue. These processes allow the interaction of ocean dynamics and property transports with the atmosphere, controlling much of the coupled climate of the Pacific. In addition to heat and momentum transport discussed below, an ability to correctly model the vertical structure of the ocean response to varying winds would foster accurate simulation of upper ocean biological productivity and its connection to CO2 outgassing by the ocean. The equatorial Pacific is the largest oceanic source of CO2, and the variability of its CO2 flux is of the same magnitude as the total global flux.

In both simple and GCM ENSO models, the subsurface memory, carried in thermocline depth and communicated to the surface by upwelling, is the dominant source of inerannual oscillations. In coupled GCMs, the vertical diffusivity is the principal factor controlling the amplitude of ENSO oscillations, with low diffusivity producing a sharper thermocline and more intense El Ninos. These indicate that modeling of ENSO is highly sensitive to how the thermocline and surface communicate.

The inability of coupled GCMs to adequately simulate cold tongue SST is a principal barrier to progress. Even the most modern models consistently show the cold tongue extending too far west (Figure 1), leading to a double ITCZ, and in addition to a poor representation of the annual march.

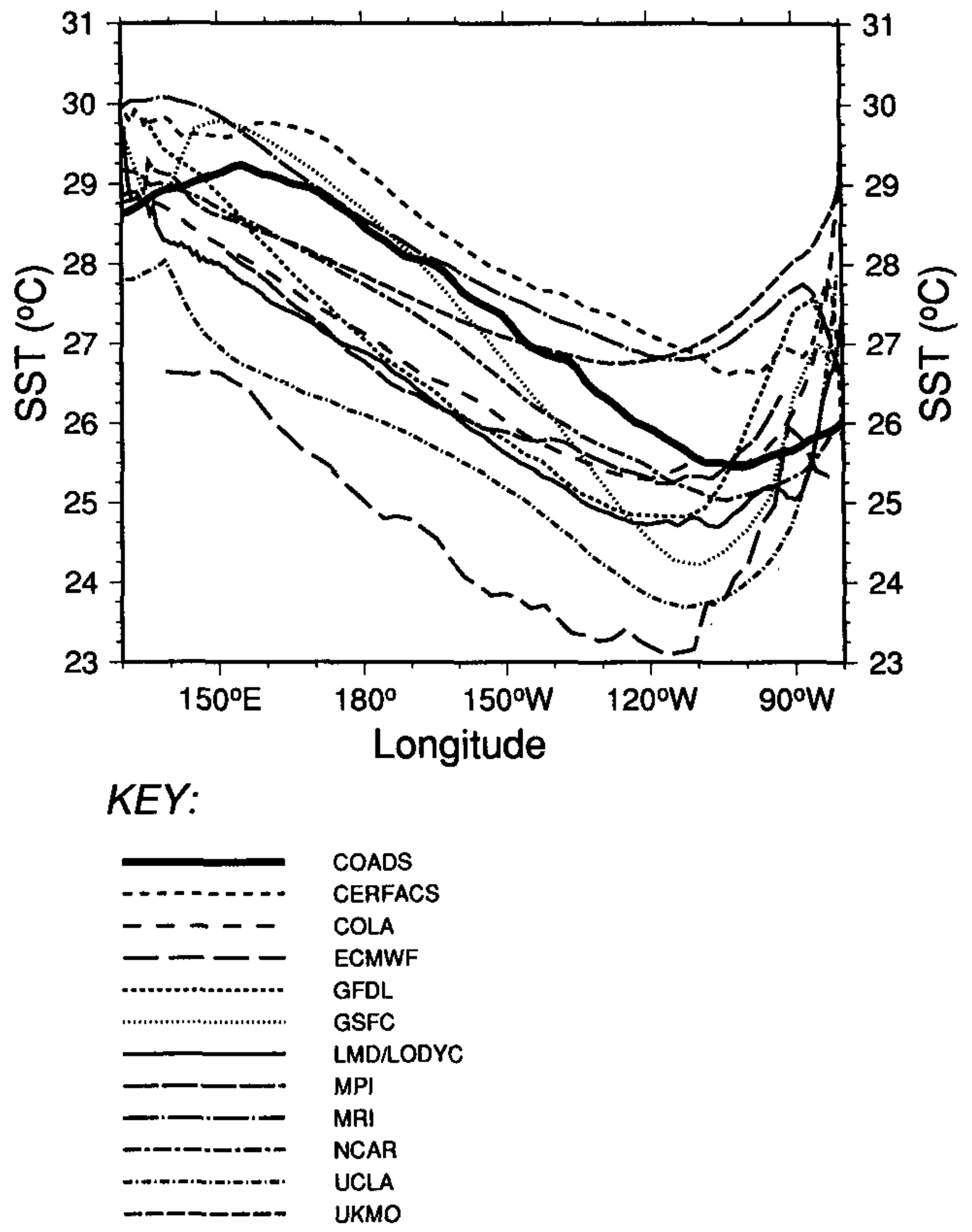


FIG. 1. Annual mean SST along the equator averaged between 2°S and 2°N.

Figure 1 (Mechoso et al 1995). Mean SST simulated by 11 CGCMs.

The premises of PUMP are: 1) we are coming to the point when models can exploit realistic mixing, and 2) observations to date have only measured aspects of the cold tongue system (divergence, mixing profiles) in isolation, which has not yet provided useful guidance to models. What is necessary is to place the turbulence observations in their full context, including the three-dimensional circulation, allowing diagnosis of the complete set of processes for a limited period of time, and thereby sparking development of model parameterizations for vertical exchanges. PUMP intends to describe the transition of the surface boundary layer from the Ekman-geostrophic regime poleward of 5° latitude to the divergent equatorial regime sufficiently well to serve as a challenge to models.

PUMP can be seen as a continuation of TOGA, much of whose success modeling interannual variability consisted of simulating wind-forced equatorial waves displacing a simplified thermocline and thereby modulating SST through crudely parameterized upper ocean processes. That made a lot of progress, but the harder problems of the realistically-stratified ocean remain ahead. These harder problems must be tackled to improve our forecasts of interannual variability.

Processes targeted by PUMP

Figure 2.

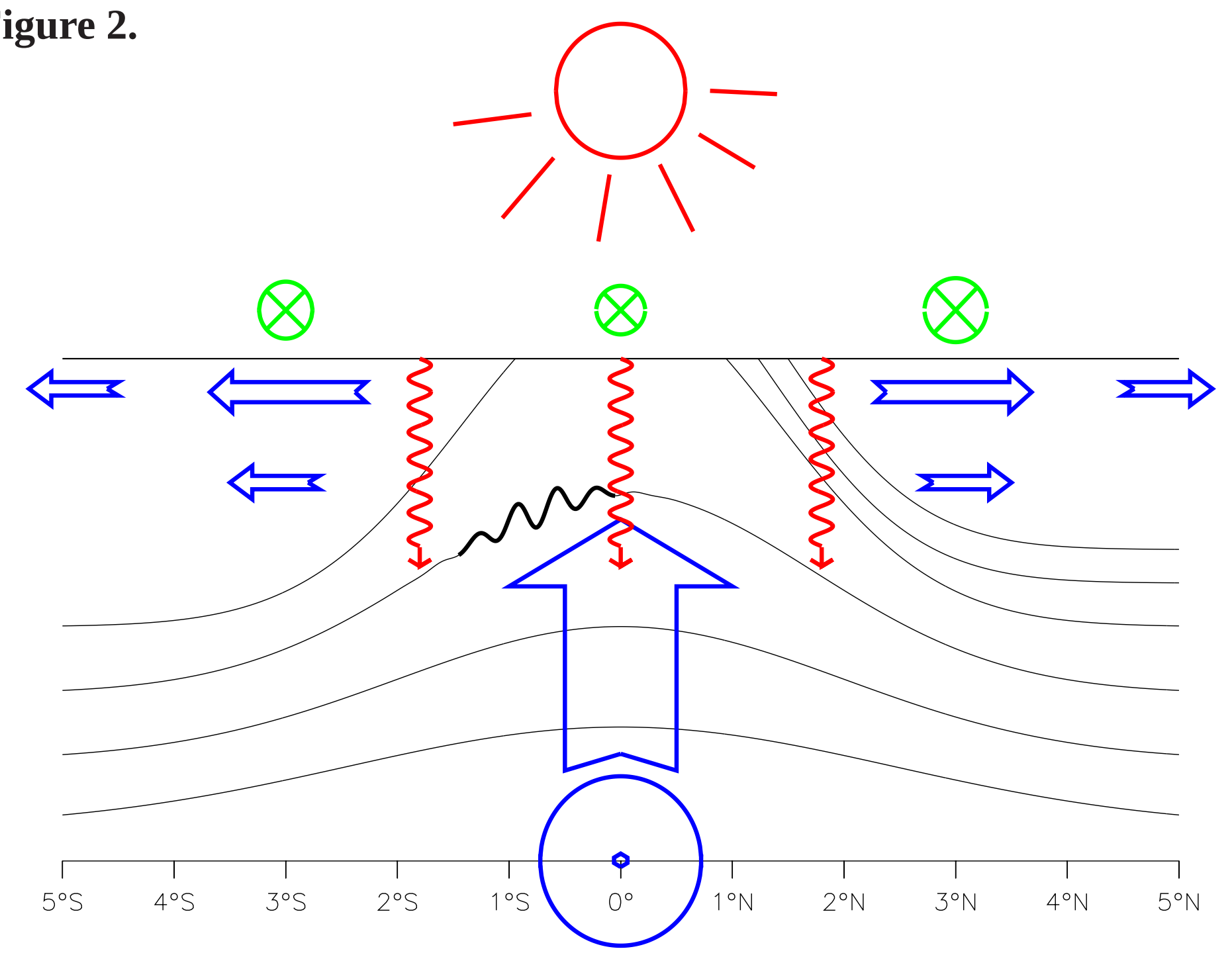


Figure 2 suggests the complexity of processes targeted by PUMP. The balance that maintains the equatorial thermal structure (isotherms in black) is that upwelling (large blue arrow) from the equatorial undercurrent (blue arrowhead), driven by near-surface divergence (horizontal blue arrows) is balanced by heating from above (downward red arrows) and turbulent mixing (suggested by the wiggles on the shallow isotherm). It is now impossible to be quantitative about any of these processes except in integrals over very large areas. Correctly modeling equatorial circulation and SST variability requires the ability to accurately represent all of these.

We do not know:

1. What is the meridional scale of the upwelling? Is it broad and slow, or thin and filamentary? How does it spin up or down in reponse to changes in the zonal wind? How deep does it reach into the stratified layer? The structure of the diverging surface layer is almost completely unknown, but the details of the hard-to-measure near-surface velocities determine the width and thickness of the upwelling. With even the best models using a typically 10m grid spacing, it is hard to have confidence in their simulations of these small scales (see Circulation section).

2. What is the spatial structure of the mixing? Is it closely trapped to the equator (where all the measurements have been made) or does it occur more regionally? While it is clear that mixing varies by orders of magnitude over the course of the ENSO and annual cycles (see Mixing section), we do not know what factors cause these variations and thus cannot infer what mixing will be during any particular situation.

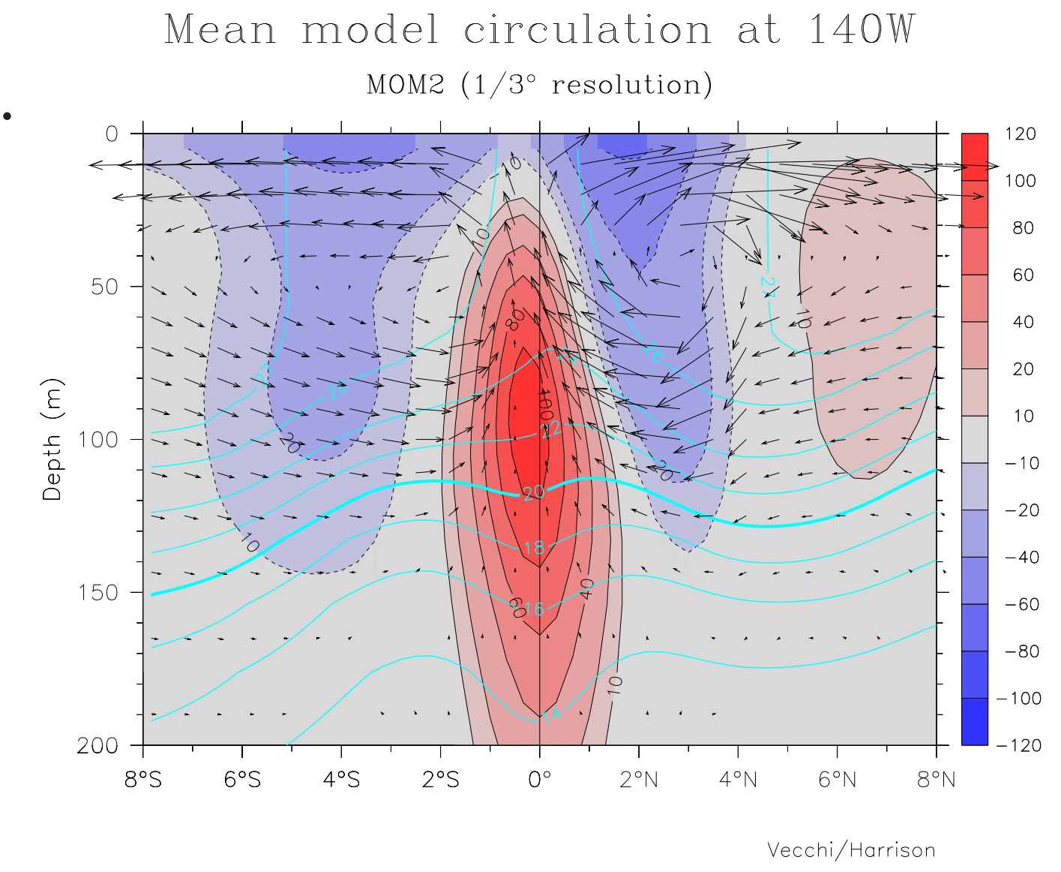
3. Heat flux estimates are perhaps the largest source of error, before the ocean models ever receive them. Given that, the penetration of radiation into the ocean is not well understood. In particular, the role of biology in controlling the penetration depth appears to be complex and allows the possibility of feedbacks.

4. Mixing across the front (shown as the closely packed isotherms near 1°N) due to tropical instability waves must be large, but the mechanisms that produce this mixing in detail remain obscure. Is it essentially a downgradient heat flux, or do small-scale frontal dynamics play an important role?

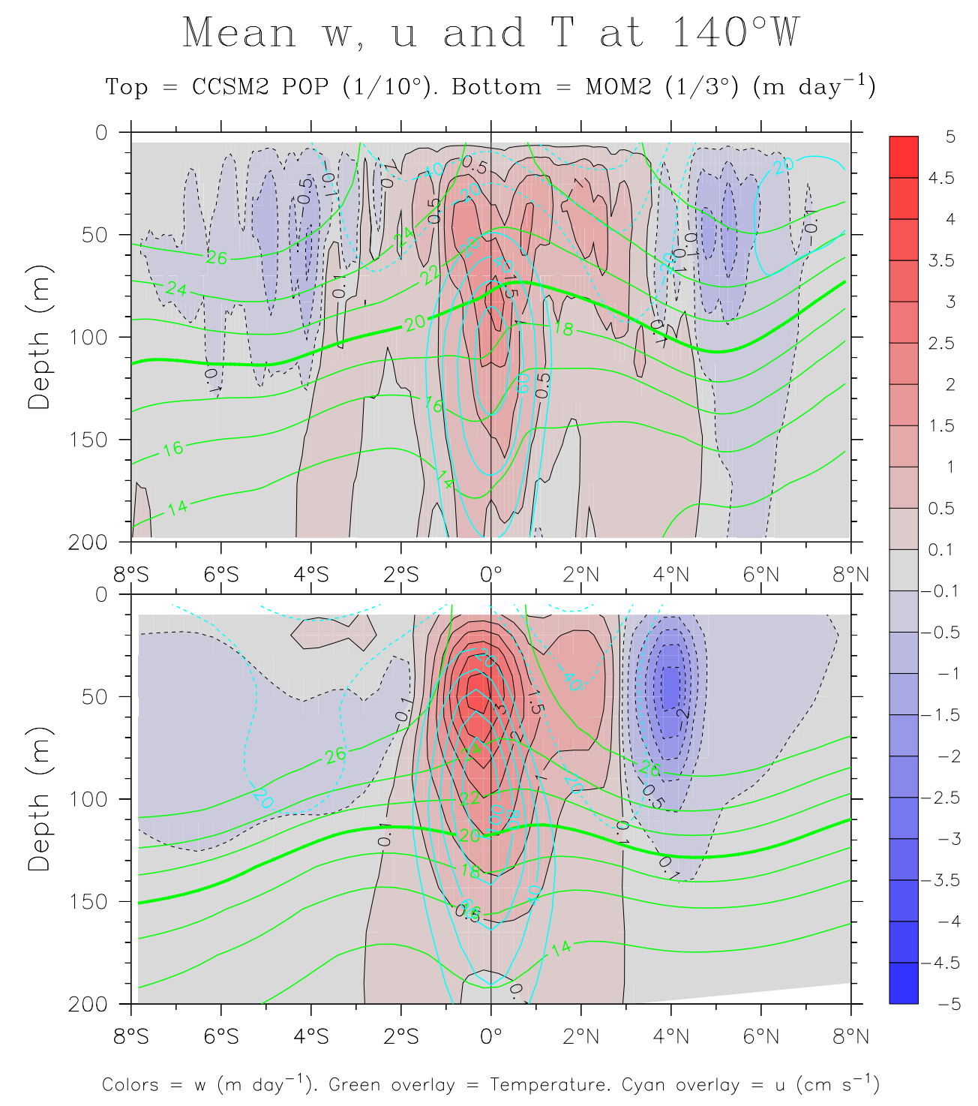
5. Satellite scatterometer wind fields have shown that SST variations feed back on the atmospheric planetary boundary layer, producing distinct wind regimes as a function of SST (suggested by the smaller green wind vector over the cooler equatorial water). Forecast models must account for these interactions, which couple SST and the PBL. Since the wind variations also modify the latent heat fluxes, this coupling involves all the factors of the region.

How well do state-of-the-art ocean models represent the meridional circulation in the tropical Pacific?

Figure 3.



Two state of the art models reproduce a picture of the meridional circulation of the central tropical Pacific that agrees in broad terms with what is known or inferred from observations. Other OGCMs generally agree as well. The Equatorial Undercurrent (EUC) occurs in the thermocline, with the westward South Equatorial Current (SEC) draped over it (Figure 3). Upper thermocline isotherms bulge toward the surface as a signature of upwelling, with colder SST at the equator. Upwelling velocities reach a maximum of 2-3 m/day, with a meridional scale of about 200km that does not seem to be dependant on the horizontal resolution. Downwelling is found a few degrees from the equator.



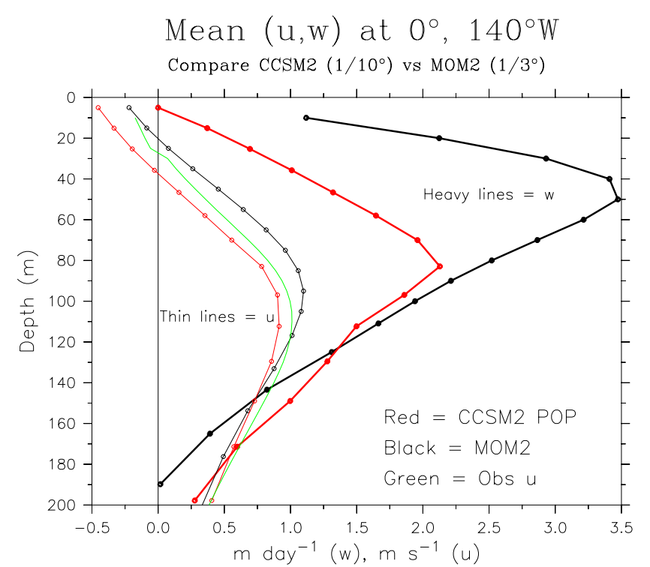


Figure 5

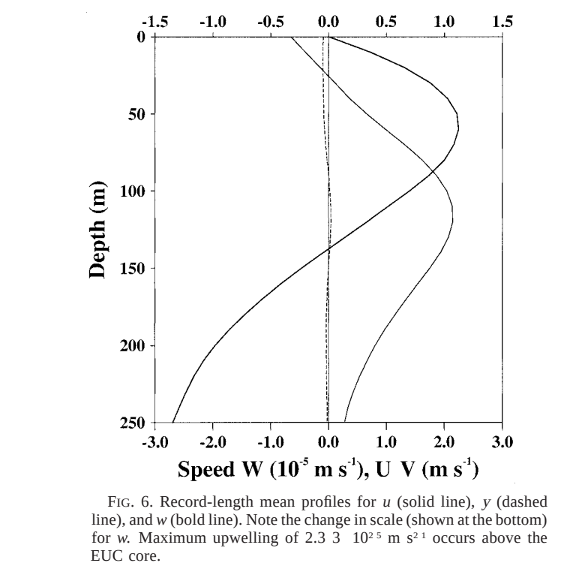


FIG. 6. Record-length mean profiles for *u* (solid line), *y* (dashed line), and *w* (bold line). Note the change in scale (shown at the bottom) for *w*. Maximum upwelling of 2.3 3 10²⁵ m s²¹ occurs above the EUC core.

Figure 4 (Model runs by Bryan [CCSM2] and Vecchi [MOM2])

Figure 6 (Weisberg and Qiao 2000)

Both models produce very similar profiles of zonal current that agree with TAO observations (Figure 5). This is not surprising as the TAO data is a common target for modelers. The fact that for two decades many models have been able to achieve reasonable profiles of mean u(z) at the equator suggests that this is not a stringent test.

However, beyond the broad-brush, the meridional circulation in these models differs substantially. Note that the CCSM2 model has its maximum upwelling right at the core of the EUC, whereas MOM2 has it 40-50m above the core (Figure 4), in agreement with observations (Figure 6). Clearly modeling the complex upwelling/mixing environment above the EUC core is not well understood and implemented even in these modern models.

Figure 7
(Johnson et al. 2001)

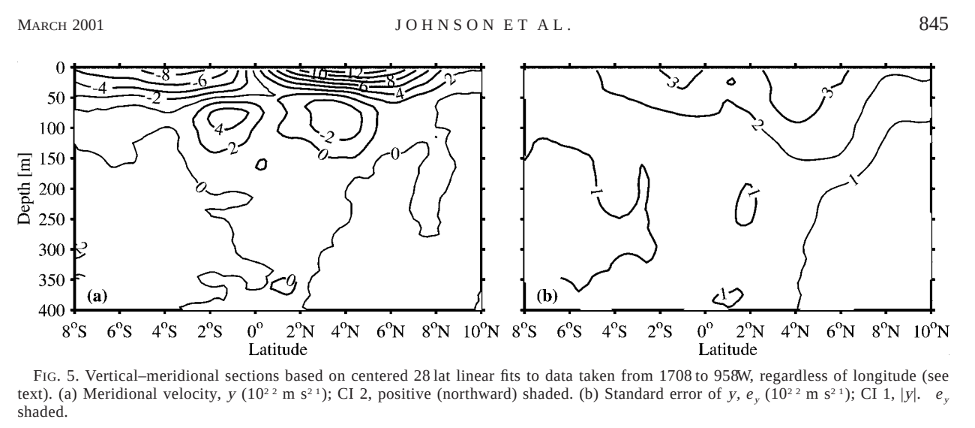


FIG. 5. Vertical–meridional sections based on centered 28 lat linear fits to data taken from 1708 to 958W, regardless of longitude (see text). (a) Meridional velocity, *y* (10²² m s²¹); CI 2, positive (northward) shaded. (b) Standard error of *y*, e_y (10²² m s²¹); CI 1, |*y*|. e_y shaded.

Because moored velocity observations have only been made right at the equator, the best observational representation we currently have of the meridional circulation is based on repeated cruises made in the course of servicing the TAO array (Figure 7). Because of the aliasing due to tropical instability waves, the meridional velocity can only be seen above the noise by averaging over all longitudes from 95°W to 170°W, and over more than 10 years of sampling. These data also show maximum upwelling of 1-2 m/day at about 60m depth. But this is an insufficient portrait because the shipboard ADCP only samples below about 20-25m depth. As can be seen from Figure 7, most of the divergent limb of the circulation occurs above the sampling depth, and the near-surface velocity is only estimated by extrapolating to the surface.

Observations of mixing:

Microstructure observations shown the high-shear, stratified region above the EUC core to be the site of intense mixing, which could be inferred from the need to maintain the heat balance in the face of the meters/day background upwelling (e.g. Figure 3). Profiles of the eddy diffusivity K_ρ show consistently high values in the upper 75m (Figure 8). A major contributor to this mixing is "deep-cycle turbulence" in which the mixed layer deepens each night, and convection extends further below (Figure 9). Two primary hypotheses have been advanced for the diurnal turbulence. Internal waves may be generated through pumping of the mixed layer base, or due to sheared horizontal flow along the distorted base. In either case, it is thought that the internal waves propagate downward into the stratified layer (nearly unstable because of the strong shear) and break.

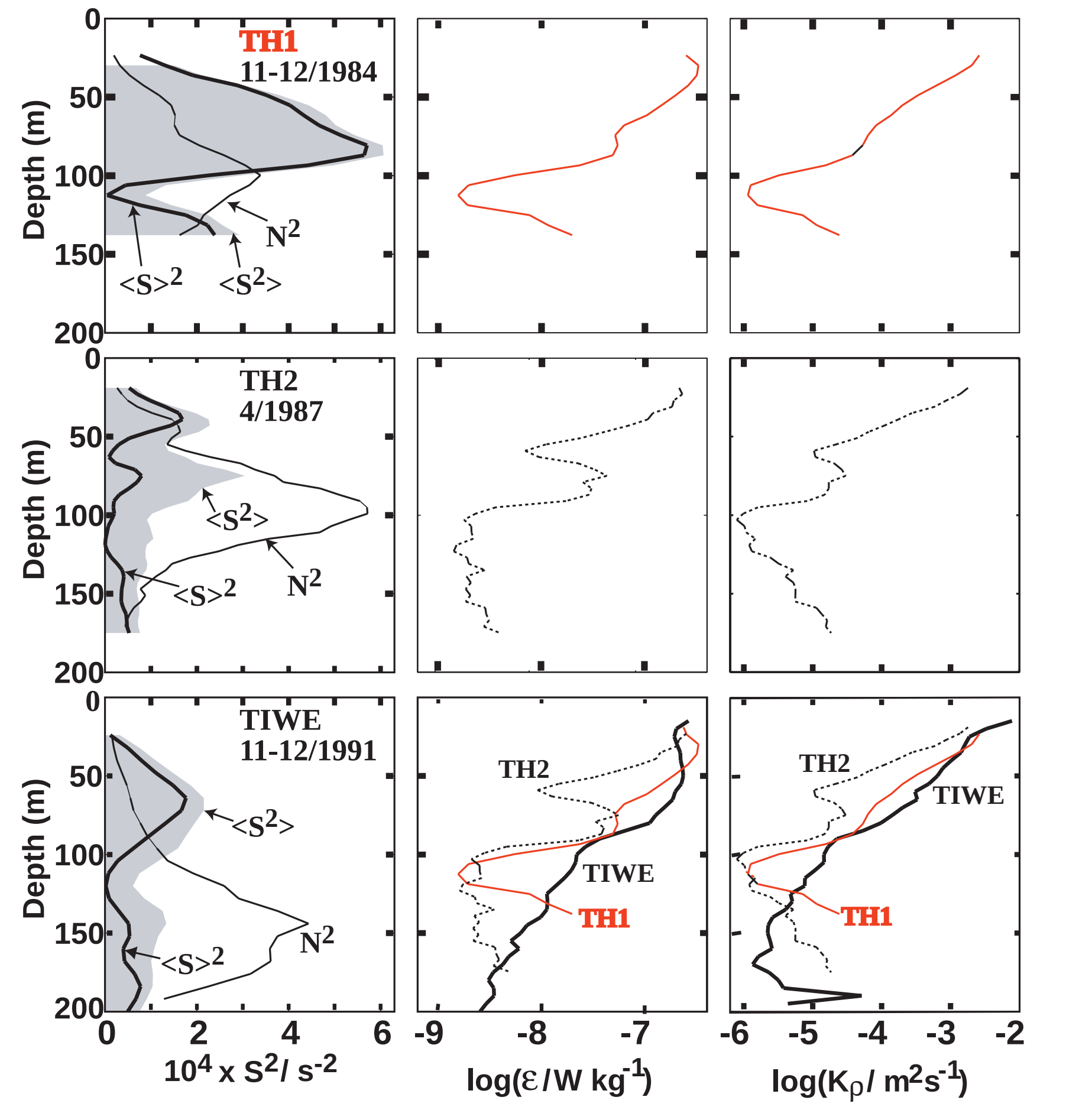


Figure 8 (Gregg 1998). Shear and turbulence observed during three microstructure experiments at 0°, 140°W.

Despite the obvious need for an observationally-tested parameterization of mixing for the OGCMs, the turbulence observations have not been as useful as might have been hoped because of the apparently strong regime dependence of mixing. Three intensive experiments have been conducted at 0°, 140°W in different phases of the ENSO and annual cycles, and produced three quite distinct profiles of K_ρ (Figure 8, right panels). Although theories can be spun about the relation between the changing large-scale environment and the mixing profiles, there are only a small number of realizations. It would be impractical to undertake enough of these intensive surveys to decipher the relation between background and mixing from such experiments alone. Unlike previous experiments, the strategy of PUMP will be to embed the microstructure measurements within a full meso- and large-scale context, allowing diagnosis of the complete set of processes for a limited period of time.

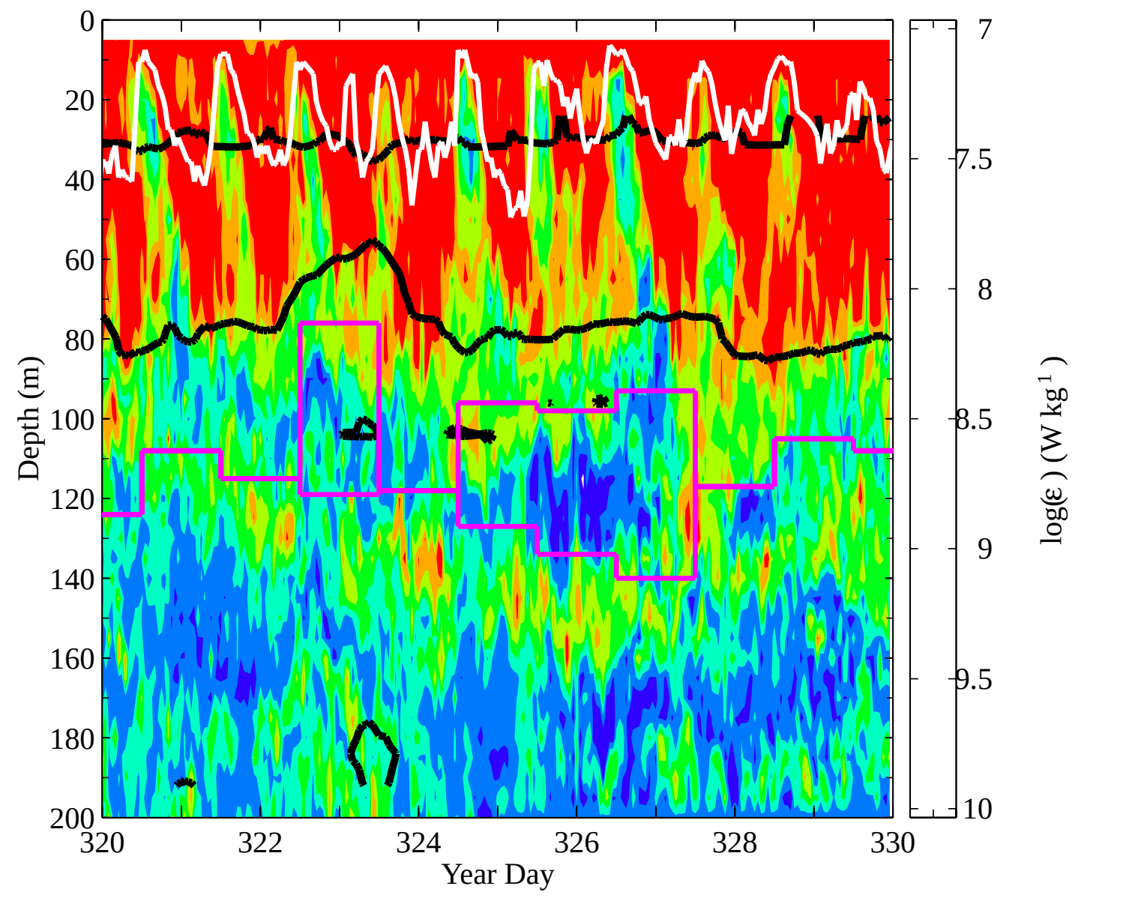


Figure 9 (Lien et al. 2002). Color shows the log of turbulent KE dissipation rate ε observed during TIWE. The white curve shows the base of the mixed layer. The black lines delineate where Ri is less than 1/2. The magenta stair shows the EUC core.

Conclusion

Previous work over two decades has made a variety of important measurements at the equator in the central Pacific, including velocity profiles, a few estimates of w based on divergence, and three month-long mixing surveys. However, because equatorial SST variability is a convolution of surface fluxes, mixing and upwelling in a complex and time-dependent meridional circulation, these careful observations have not yielded an understanding of the mechanisms of vertical exchange that can be distilled into improved model parameterizations. Further, existing observations have not been able to provide a description of the meridional circulation that would let us evaluate the realism of the these structures in modern OGCMs, whose development has focused primarily on the equatorial zonal currents. Nor does theory explain how the “Ekman depth” should change as the equator is approached. To progress from this unsatisfactory situation, PUMP will observe the transition from the Ekman/geostrophic regime at ±5° latitude to the equator, and produce a quantitative model and observational diagnosis of the meridional circulation for a period of one year. In this task, the surface flux, turbulence and velocity measurements are complementary checks on one another, and will serve as a testable challenge for the models.

Since we will not be able to monitor upwelling or vertical exchanges continuously in the way that Argo, TAO and altimetry let us monitor the gyre circulations, the ultimate goal of the process study is to provide the observations and interpretation that will let models accurately represent vertical exchanges near the equator. There are two elements to improving models: first, to improve the parameterizations through more precise diagnosis of the situation at and near the equator, and second, to learn how to use sparse sustained observations assimilated into models to infer and diagnose upwelling events.

The proposed observations will require a substantial combined effort of several institutions deploying multiple moored and ship-based instrumentation, but the techniques are relatively well understood. The modeling project is more precarious because mixing must be parameterized, not derived from physical principles, and because a parameterization must function correctly over a wide range of conditions, regions and regimes. The recent organization of a CLIVAR “Climate Process Team” on tropical upper ocean mixing shows the commitment of influential members of this community to solve this problem, and their belief that it is tractable now.

The benefit of PUMP will be, first and foremost, an improvement in our ability to forecast interannual variability originating in the tropical Pacific, especially ENSO. ENSO is the largest source of climate variability in most parts of the world, and the past two years have shown that we are a long way from being able to make accurate forecasts even a few months ahead in many situations. Nothing the climate community could do would be of more benefit to more people than to advance this aspect of climate prediction.

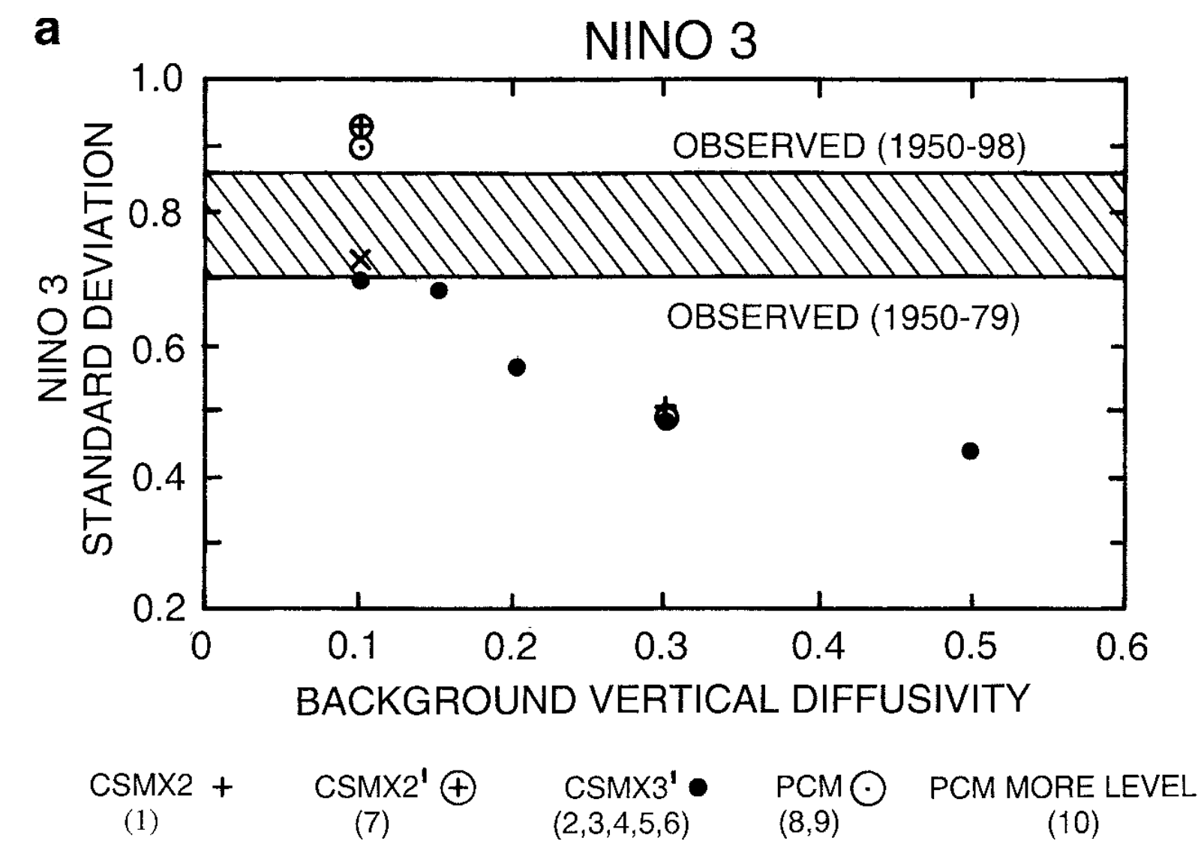


Figure 10 (Meehl et al. 2001). Ocean model background diffusivity versus Nino3 amplitude.

Diagnosis of the ocean and atmosphere factors that control ENSO amplitude in modern coupled models (which is typically too weak) showed that “The dominant influence on El Nino amplitude is the magnitude of the ocean model background diffusivity.” The effect was primarily due to a realistically sharper equatorial thermocline. This strongly argues that improvement in ENSO representation (and presumably forecasting) will come from perfecting the modeling of the processes targeted by PUMP: the complex of mechanisms that connect the thermocline to the surface in the equatorial Pacific cold tongue.