Mixed Layer Modelling in the Western Equatorial Pacific Ocean

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1. Introduction

Designing a numerical model for the mixed layer of the Western Equatorial Pacific presents difficult issues for representing the various processes associated with the regional maintenance of the SST. One clearly has to include the effects of buoyancy forcing (due to the strong evaporation-precipitation contrasts) on the equatorial mixed layer property budgets as well as the vigorous 3-dimensional circulation. Some studies have also suggested that the heretofore neglected effect of the earth's horizontal component of rotation (i.e., the traditional approximation) should also be included (Garwood et al., 1985). The unique nature of the mixed layer in this region demands that the model be able to distinguish the following: the interface between the South Equatorial Current and the Equatorial Undercurrent, the interface between the turbulent mixed layer and the thermocline, and the interface between a fossil isothermal layer and a fresh water cap that appears to be embedded in the layer above the thermocline. The model must be able to incorporate the property exchanges that take place amongst these very different physical regimes. The choice of turbulent mixing parameterization (i.e., how the model numerically "couples" these distinct regions) thus becomes the central issue. A successful model would be required to explain why the surface waters of the region hover around 28°-30°C with little variability and why the region is a "pool", i.e., lacking large horizontal variability (Figure 1). Equally as important is the vertical structure and the explanation of the isohaline-isothermal subsystem (Figure 2) and its effects on entrainment of cold subthermocline waters.

This paper briefly reviews the issues mentioned above, as well as the added complexity of the short time scale wind forcing and the western boundary currents, that one must contend with in designing a mixed layer model of the region. I will argue that although the problem seems to require a "kitchen sink" GCM, it would be dangerous to rely on only such a modelling effort. We have to define testable hypotheses that are more amenable to a process oriented modelling approach. In fact we already have a hypothesis of the maintenance of the fresh water cap in an isothermal layer that provides a test for the model. This is the idea of Lukas and Lindstrom (1987) that will be mentioned later. There is also a need for very simple kinematical models that address fundamental issues like how much of the pressure head is representable in terms of only the evaporation-precipitation flux. Models that simply advect temperature and salinity as passive tracers are also quite useful and could be quickly developed. Finally, one-dimensional mixed layer models would be useful in helping to sort out the complex vertical structure of salinity and temperature.

2. Modelling Considerations

There are a number of considerations in designing the mixed layer model that are unique to the warm pool domain. In this section I briefly outline what I consider to be the most important of these.

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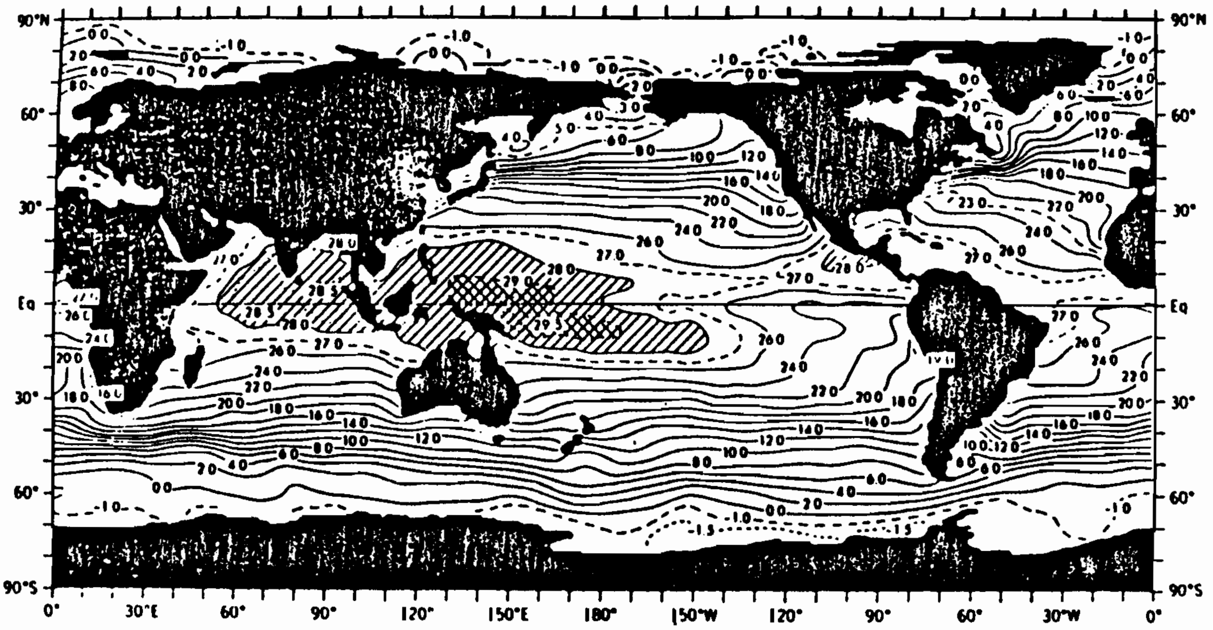

Fig. 1 The 28°C surface isotherm approximately bounds the warm water pool of the western Pacific and eastern Indian oceans. The warmest part, temperatures greater than 29°C, lies between 140°E and 170°E, north of New Guinea. Adapted from Levitus, 1982.

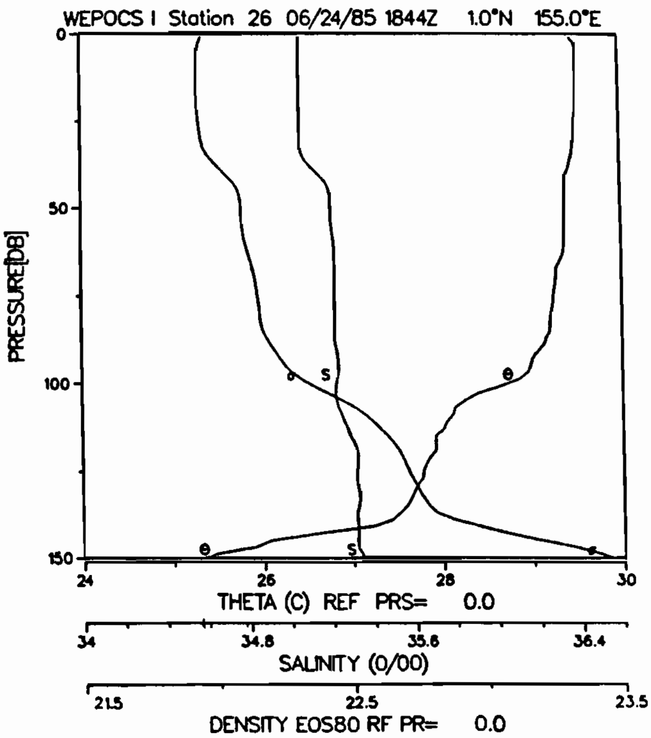

FIG.2. Profiles of temperature (θ, °C), salinity (S, ‰) and density at 1°S-155°E from the WEPOCS experiment. The temperature and salinity are plotted on scales such that equal abscissa variations will result in similar variations of density. The upper ocean is clearly not mixed and shows an overlaying structure of stable layers resulting from varitions in the salinity and temperature structure. 80% of the WEPOCS stations in the western Pacific possessed similar structural complexity. (Lukas, personal communication).

2.1 Salinity Effects

Salinity effects have traditionally been "turned off" or at most used as passive tracers in most numerical experiments of the equatorial circulation. If resolving the fresh water cap and determiniing its influence on the SST is an important goal of the Coupled Ocean-Atmosphere Response Experiment (COARE), then one must include a dynamically active salinity component in the modelling effort.

It appears that salinity effects are most important in influencing the entrainment of cold water from below the thermocline and not in directly forcing currents. From scaling the relative importance of wind and buoyancy forcing, one finds that the buoyantly forced currents are an order of magnitude smaller than the wind forced currents (Rothstein, 1984). However, salinity is hypothesized to play an important role in DIRECTLY determining the regional SST (Lukas and Lindstrom, 1987). In a one-dimensional model, Miller (1976) found that the vertical salinity profile is crucial in the evolution of the mixed layer depth, determining whether the mixed layer warms or cools under a given surface forcing. This can be understood as follows. The mixed layer efficiently cools through entrainment of thermocline water into the upper layer. The fresh water cap can provide a "barrier" between surface forcing and entrainment cooling (Figure 2), effectively insulating the waters of the thermocline from wind effects. With the additional stability provided by the barrier layer, a given wind would find it more difficult to entrain cold thermocline waters than in the absence of the barrier layer. Entrainment cooling, therefore, is only effective when the winds are strong enough to erode the barrier layer. Turbulent mixing parameterizations unique to the Western Equatorial Pacific are required.

2.2 Wind Forcing

We've just finished arguing for the relative unimportance of entrainment cooling except for strong wind forcing. The COARE region, of course, happens to be a region of strong wind forcing, albeit on relatively short time scales. Although southeast trades prevail over the warm pool, sudden bursts of westerly winds exert more stress. The trades are light and are interrupted by the westerly bursts between November and May. These wind events usually last only a few days; however, some have been observed to persist for a few weeks with amplitudes sometimes reaching 15 m/sec (Figure 3). These are "downwelling" winds which can precondition the isothermal layer for the "upwelling" trades. Since the location of the cold water source is important for SST prediction, how a model handles detrainment due to these wind bursts appears to be a crucial issue.

2.3 Detrainment

For large heating rates or downwelling, the mixed layer depth becomes large and surface layer turbulence cannot be sustained over the entire layer depth. The interface between turbulent and non-turbulent fluid retreats, leaving behind a fossil turbulent layer ABOVE the main thermocline. This fossil (detrained) mixed layer water needs to be accounted for in the model and there are a number of possibilities. Mixing the detrained water back into the (isohaline) mixed layer would correspond to a view of the ENTIRE layer above the thermocline (isohaline and isothermal layers) as the mixed layer, clearly at odds with COARE hypotheses. Mixing the fossil layer into thermocline waters would be more consistent with the view of the isohaline layer as the mixed layer but this choice would eliminate the possibility of resolving the isohaline-isothermal substructure. It seems appropriate that this fossil layer should retain its own character, i.e., it should not be mixed into the isohaline layer nor should it be mixed down into thermocline water.

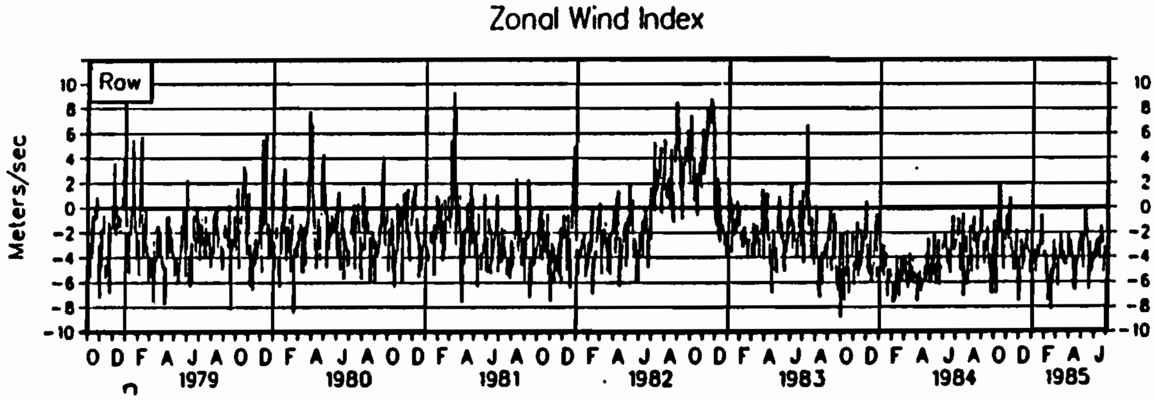

Fig. 3 Composite zonal winds measured on islands near 170°E (kindly supplied by R. Lukas). At the eastern end of the warm pool, the dominant winds are easterly trades. Nevertheless, a very strong, sustained westerly burst in late 1982 was associated with the intense 1982-1983 El Niño.

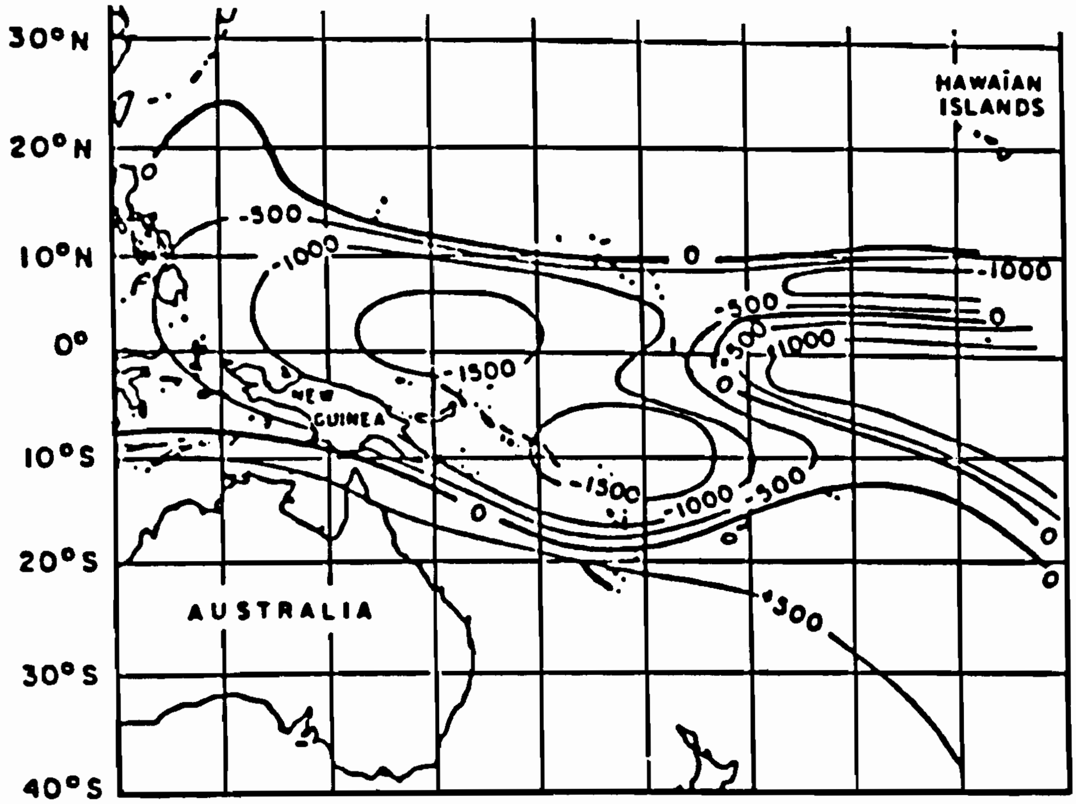

Fig. 4 Evaporation-Precipitation balance expressed in millimetres per year in the Western Pacific. (from WEARE et al, 1981a)

We conclude that a successful mixed layer model must be able to account for these short time scale wind events and accurately represent the (NON?)mixing that goes with detrainment. We again see that issues related to turbulent mixing are the central ones in these models.

2.4 Mixing Parameterizations

Entraiment and detrainment are critical processes for the model to develop realistic SST gradients. In fact, THE essential physics of SST evolution and mixed layer modelling in the western equatorial Pacific could arguably be the influence of the fresh water cap on entrainment cooling. In the central Pacific, the TROPIC HEAT experiment has shown us that the mixed layer is about 40-50 meters deep, with a pronounced diurnal cycle of mixing due to surface nighttime cooling and convective overturning (Gregg et al., 1985). However, in the COARE region, the stratification is almost always stable due to the excess precipitation (Figure 4). How, then, does one parameterize the mixing? This is perhaps the crucial question for all of oceanography these days. The laws that ultimately govern the coupling between the various layers of a mixed layer model are poorly known. We can proceed on an ad hoc basis, trying different schemes (simple switches for entrainment-detrainment, Richardson number mixing, explicit Kraus-Turner turbulent mixing schemes, etc.), but this phase of the modelling will have to be closely linked with the microstructure observational component of COARE. I feel this is one of the central issues for the experiment.

2.5 Other Considerations

There are a number of other items that one must contend with in the proper design of a model to treat the mixed layer of the COARE region. In this section I briefly review these issues.

2.5.1 Surface buoyancy forcing

In an active thermodynamic model like the one that is being designed for COARE, one has to be able to locate a realistic surface buoyancy forcing. This takes the form of both heat and fresh water flux at the surface. The algorithms presently used in calculating the various contributions to the total surface heat flux should be checked against COARE observations. In the early stages of the modelling effort, it would be useful to force the model with various idealizations of the real forcing. For example, it would be interesting to look for the response to a mean E-P pattern (Figure 4) in a decoupled experiment, i.e., don't allow for the readjustment of heat and salinity by the dynamics (a passive tracer experiment). After gaining confidence in the physics of the model (testing the various paremeterization schemes), attempts can be made to activate salt and heat and force the model more realistically, ultimately atttempting a coupling to a moist atmospheric mixed layer model. The atmospheric model must be able to obtain intense, small scale convection such as the model of Lau and Peng (1987).

2.5.2 Western boundary effects

The "boundary" of the western equatorial Pacific is not well defined, yet theoretical and modelling studies have recently placed particular emphasis on the reflection of equatorially trapped Kelvin waves as the mechanism by which a growing, coupled air-sea instability in the central and eastern equatorial Pacific is shut down (Schopp & Suarez, 1988). In fact, a COARE hypothesis is that the upwelling Kelvin wave necessary to shut off the growing coupled air-sea instability is primarily influenced (generated?) by air-sea

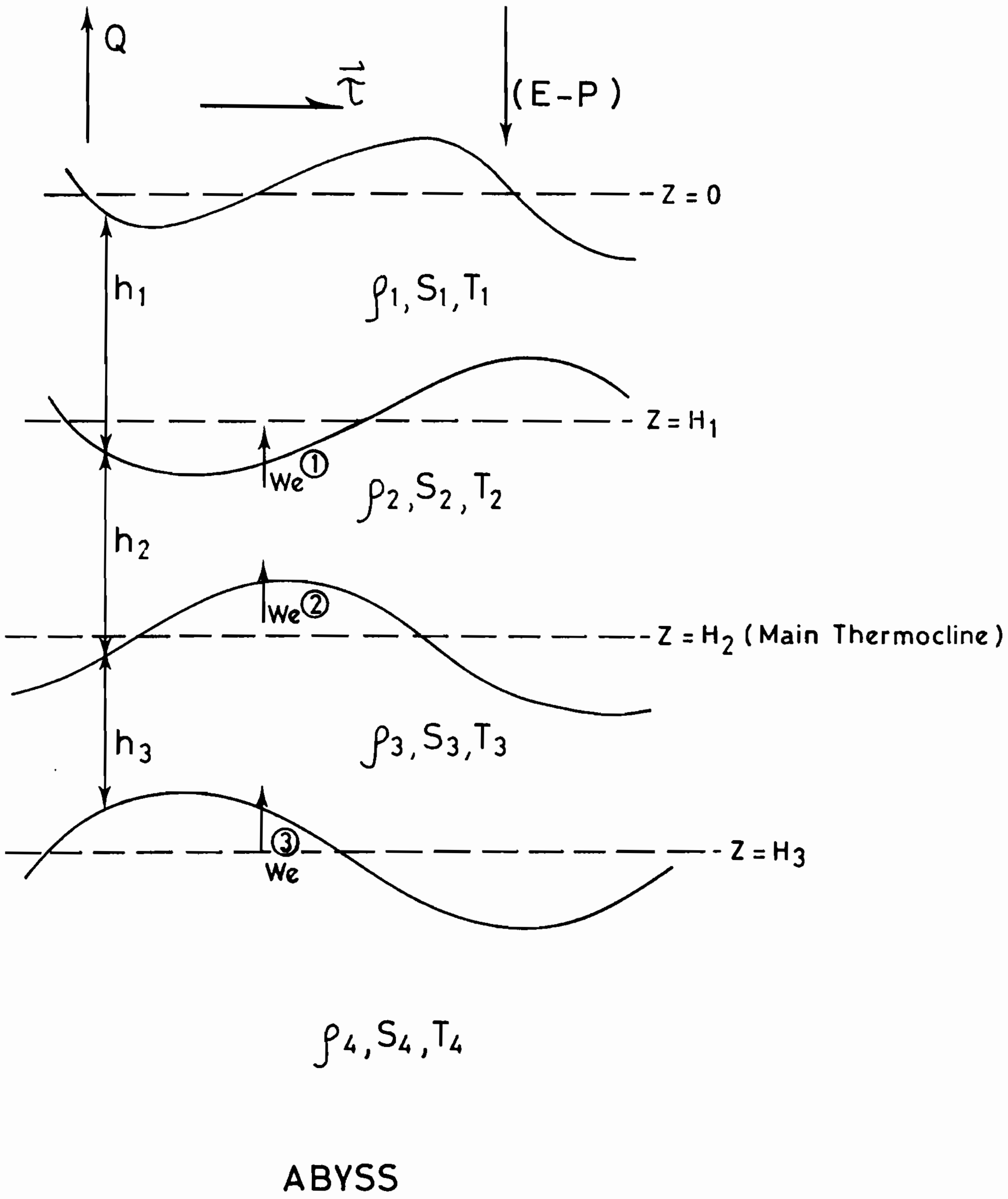

Fig. 5 Schematic of the 3-1/2 layer model.

interactions in the warm pool region (wind burst forcing of Kelvin waves). It becomes important to sort out the relative role played by all potential sources of Kelvin waves. Furthermore, the western boundary acts as a conduit of information from higher latitudes, i.e., the circulation associated with the western boundary can also play an important role in the maintenance of the warm pool. All these issues need to be resolved properly in a mixed layer model. Due to the geometrical complexity of the Indonesian archipelago, realistic simulations must await finely resolved GCMs. However, simpler models with closed sloping boundaries and artificial dampers would prove useful.

2.5.3 The traditional approximation

Garwood et al. (1985) argue for the importance of the "traditionally" neglected horizontal component of the earth's rotation vector in affecting the depth of the mixed layer on the equator. The interaction between the planetary rotation and zonal wind stress increases the turbulent kinetic energy and is hypothesized to be the reason for the deep isothermal mixed layer of the western equatorial Pacific. Their model does not include a salt budget. These are interesting questions and the inclusion of these additional terms in the model does not seem to require a tremendous amount of numerical effort, i.e., no new time scales are introduced into the system.

3. The Subduction Hypothesis: Model Testing

As a first stringent test of any model that includes salinity, I would think that the recreation of the isothermal-isohaline substructure would be an essential requirement. There is a testable hypothesis for maintaining this structure; the subduction hypothesis of Lukas and Lindstrom (1987). Put simply, the maintenance of the isothermal (and saltier) layer below the fresh water cap is thought to be due to zonal advection from the east in the Souh Equatorial Current. Due to excess evaporation in the central equatorial Pacific, the water advected in this way is denser than the warm pool waters and upon encounter with the warm pool the possibility exists that the denser waters would subduct. The meridional circulation may also play a role. The elements of the model that I am building include all of the physics that can adequately test this hypothesis. The proposed model follows.

4. The Model

To design a model short of a GCM we must make decisions to cut corners somewhere. I propose to limit the number of degrees of freedom in the vertical to three active layers overlying a motionless abyss. This is just sufficient to resolve the distinct regimes reviewed in the introduction. The model is designed with the hypothesis that horizontal advection is important. Again the important parametrizations appear as coupling between the layers (the entrainment-detrainment process) and must be chosen with care. Figure 5 is a schematic representation of the 3.5 layer model forced by a wind stress and surface heat and fresh water fluxes. The equations governing the dynamics and thermodynamics in each active layer are:

<u>Layer 1</u>

$$(h_1\bar{v}_1)_t + \nabla \bullet (\bar{v}_1 h_1 \bar{v}_1) + \beta y \bar{k} x h_1 \bar{v}_1 + h_1 \overline{\nabla p_1} = \bar{\tau} + We^1 \bar{V}_2 + \nu_h \nabla^2 (h_1 \bar{v}_1) - {}_m h_1 \bar{v}_1 - {}_z h_1 \bar{v}_1$$

$$(h_1)_t + \nabla \bullet (h_1 \bar{v}_1) = We^1 + K_h \nabla^2 h_1 - {}_z(h_1 - H_1)$$

$$(T_1)_t + \overline{V}_1 \cdot \nabla T_1 = Q/h_1 - We^1(T_1\text{-}T_2)/h_1 + K_h\nabla^2 T_1$$

$$(S_1)_t + \overline{V}_1 \cdot \nabla S_1 = (E\text{-}P)/h_1 - We^1(S_1\text{-}S_2)/h_1 + K_s\nabla^2 S_1$$

Layer 2

$$(h_2\overline{v}_2)_t + \nabla \cdot (\overline{v}_2 h_2 \overline{v}_2) + \beta y\overline{k}x h_2\overline{v}_2 + h_2\overline{\nabla p_2} = We^2\overline{V}_3 - We^1 V_2 + \nu_h\nabla^2(h_2\overline{v}_2) - {}_m h_2\overline{v}_2 - {}_z h_2\overline{v}_2$$

$$(h_2)_t + \nabla \cdot (h_2\overline{v}_2) = We^2 - We^1 + K_h\nabla^2 h_2 - {}_z(h_2\text{-}H_2)$$

$$(T_2)_t + \overline{V}_2 \cdot \nabla T_2 = Qd/h_2 + We^1(T_1\text{-}T_2)/h_1 - We^2(T_2\text{-}T_3)/h_2 + K_h\nabla^2 T_2$$

$$(S_2)_t + \overline{V}_2 \cdot \nabla S_2 = Sd/h_2 + We^1(S_1\text{-}S_2)/h_1 - We^2(S_2\text{-}S_3)/h_2 + K_h\nabla^2 S_2$$

Layer 3

$$(h_3\overline{v}_3)_t + \nabla \cdot (\overline{v}_3 h_3 \overline{v}_3) + \beta y\overline{k}x h_3\overline{v}_3 + h_3\overline{\nabla p_3} = -We^2\overline{V}_3 + \nu_h\nabla^2(h_3\overline{v}_3) - {}_m h_3\overline{v}_3 - {}_z h_3\overline{v}_3$$

$$(h_3)_t + \nabla \cdot (h_3\overline{v}_3) = -We^2 + K_h\nabla^2 h_3 - {}_z(h_3\text{-}H_3)$$

$$(T_3)_t + \overline{V}_3 \cdot \nabla T_3 = Qd/h_3 + We^2(T_2\text{-}T_3)/h_2 - We^3(T_3\text{-}T_4)/h_3 + K_h\nabla^2 T_3$$

$$(S_3)_t + \overline{V}_3 \cdot \nabla S_3 = Sd/h_3 + We^2(S_2\text{-}S_3)/h_2 - We^3(S_3\text{-}S_4)/h_3 + K_h\nabla^2 S_3$$

where

$$\overline{\nabla p_1} = g\alpha\nabla\{h_1(T_1\text{-}T_4) + h_2(T_2\text{-}T_4) + h_3(T_3\text{-}T_4)\} - g\alpha\frac{h_1}{2}\nabla T_1$$

$$+ gB\nabla\{h_1(S_1\text{-}S_4) + h_2(S_2\text{-}S_4) + h_3(S_3\text{-}S_4)\} - gB\frac{h_1}{2}\nabla S_1$$

$$\overline{\nabla p_2} = g\alpha(T_2\text{-}T_3\text{-}T_4)\nabla(h_1+h_2+h_3) + g\alpha\frac{h_2}{2}\nabla(T_2\text{-}T_3\text{-}T_4)$$

$$+ gB(S_2\text{-}S_3\text{-}S_4)\nabla(h_1+h_2+h_3) + gB\frac{h_2}{2}\nabla(S_2\text{-}S_3\text{-}S_4)$$

Surface heat flux (Haney, 1971):

$$Q = (H_1/t_h)\,(T_0 - T_1)$$

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$\overline{V}_1 = \overline{V}_2 = \overline{V}_3 = 0$ (No slip); $T_{1n} = 0$(No flux); $h_{1n} = h_{2n} = h_{3n} = 0$ (mass conserved) and Qd and Sd represent diabatic exchanges of heat and salt.

The model will be tested this fall and results reported shortly thereafter.

5. Conclusions

I have briefly presented the important issues and proposed a model for studying the mixed layer physics of the COARE region. Space has not allowed me to discuss simpler, one-dimensional models which I feel are necessary in the modelling hierarchy. At this time I do not feel that GCMs have much to contribute simply because they are not efficiently designed for hypothesis testing. The parameter space that must be explored for this problem is simply too large for efficient use of a GCM.

An important numerical issue which I have not mentioned is the treatment of surfacing layers. Clearly the isohaline layer is not a feature of the entire equatorial basin and would seemingly surface to the east. Historically the surfacing of layers has been dealt with in several ways. In most two-layer models the interface is kept from surfacing by positioning it far below the sea surface. O'Brien et al. (1977), however, uses turbulent entrainment of water to keep the interface submerged. Bleck and Boudra (1981) propose a quasi-isopycnic vertical coordinate. These various methods will be investigated for specific application to the COARE mixed layer model.

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