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12.3 THE GROWTH OF THE OCEANIC BOUNDARY LAYER DURING THE COARE INTENSIVE OBSERVATIONAL PERIOD: LARGE EDDY SIMULATION RESULTS

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1. INTRODUCTION

A principal goal of the Tropical Ocean Global Atmosphere (TOGA) Coupled Ocean-Atmosphere Response Experiment (COARE) is to gain an understanding of the processes that control mixing in the upper 100 m of the western tropical Pacific warm pool. The warm pool is an important heat reservoir for the global ocean and is responsible for many of the observed climatic changes associated with El Nino/ Southern Oscillation (ENSO) events. This water mass is highly sensitive to mixed-layer processes that are controlled by surface heat, salinity, and momentum fluxes. During most of the year, these fluxes are dominated by solar heating and occasional squalls that freshen the top of the mixed layer and force shallow mixing of about 10-20 m. From November to April, the usual weather pattern is frequently altered by westerly wind bursts that are forced by tropical cyclones and intraseasonal oscillations (McPhaden et al. 1988). These wind bursts generate a strong eastward surface current and can force mixing as deep as 100 m over a period of days (Moum and Caldwell 1994). Observations from the intensive observation period (IOP) in COARE indicate that mixed-layer deepening is accompanied by strong turbulence dissipation at the mixed layer base (Figure 1). Shown in Figure 1 is a short westerly wind burst that occurred during the first leg of TOGA-COARE, and lasted about 4-5 days. During this period, the maximum winds were about 10 m s^{-1}, and the resulting eastward surface flow was about 0.5 m s^{-1}. The strength of this event was somewhat weaker than a typical westerly wind burst, but the mixed-layer structure and growth are similar to the more vigorous wind bursts discussed in McPhaden et al. (1988) and Moum and Caldwell (1994).

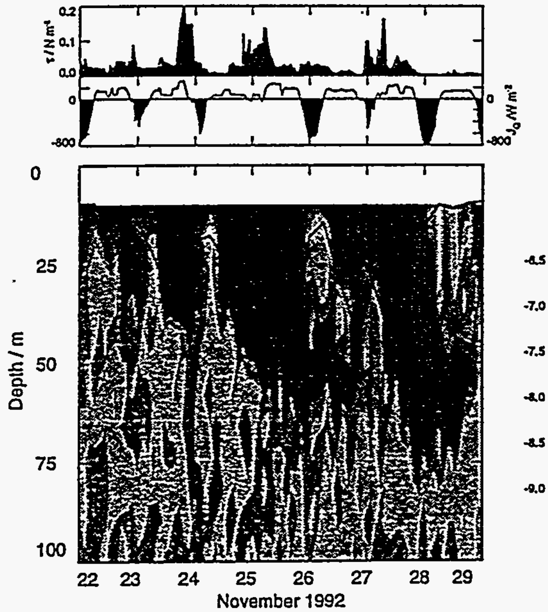

Figure 1. A wind event observed during November 22-28, 1992. Shown are 2-h averages of wind stress, τ, and surface net heat flux (top two panels), and 8-m averaged epsilon (W kg^{-1}) (bottom). The thick solid line denotes the depth at which the layer density exceeds the surface density by 0.01 kg m^{-3}.

By the end of the wind event, turbulent mixing penetrated to a depth of about 75 m. The largest turbu-

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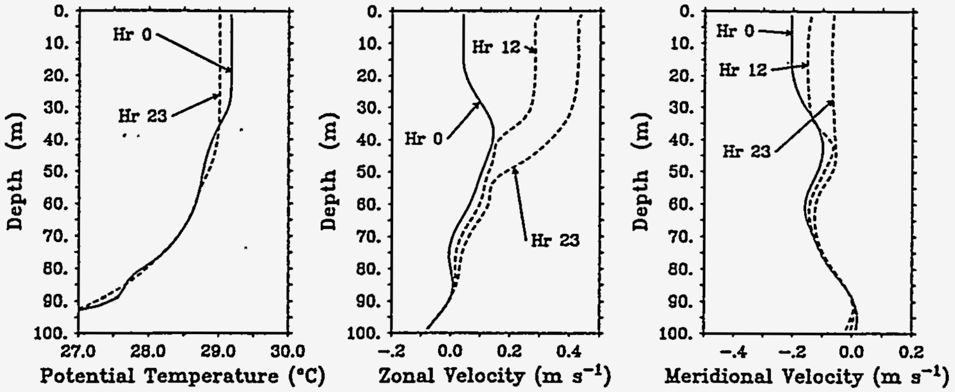

Figure 1. Initial conditions of potential temperature, zonal velocity, and meridional velocity taken from Day 329 of the first leg of the COARE-IOP. Also shown are the mean currents from the model at Hours 8 and 23.

lence dissipation rate (ε) occurred when the warm pool was forced by both strong winds and convective cooling (Figure 1). A shallow layer of high ε appeared in the stratified pycnocline, just below the mixed-layer base (dark solid line in the last panel in Figure 1). Pycnocline mixing continued in a layer of high shear near 75 m on November 28, although winds were weak and the mixed layer was as shallow as 10 m.

In this paper, we examine turbulence processes forced by an idealized westerly wind burst event using a large eddy simulation (LES) model modified to account for surface-wave effects. Our results show that the mixed layer deepens in response to increased shear production of turbulence at the mixed-layer base, as postulated from microstructure measurements by Moum and Caldwell (1994). In addition, we examine the role internal waves could have in enhancing entrainment rates at the mixed-layer base.

2. MODEL AND INITIAL CONDITIONS

The LES model used in this study is based on the non-hydrostatic, Boussinesq equations of Deardorff (1980) modified to include a parameterization of surface wave effects and a radiative boundary condition at the model bottom. A complete description of the model is presented in Denbo and Skyllingstad (1994) and Skyllingstad and Denbo (1994) along with validation experiment results.

Initial conditions for the model were taken from daily average temperature and horizontal current profiles from November 24, 1992 (Figure 2). The domain size was set to 320 m by 320 m in the horizontal and 100 m in the vertical with a 2.5-m grid spacing. The Coriolis force was set constant using a latitude of 2° S, representing the IOP location. A constant westerly wind stress of 0.15 $\mathrm{Nm^{-2}}$ and a surface heat loss of 160 $\mathrm{Wm^{-2}}$ were applied throughout the 24-h simulation period. An eastward propagating, monochromatic surface-wave field was assumed with a wavelength of 40 m and a wave height of 1.5 m for the surface-wave parameterization. These idealized conditions represent the average forcing during a typical westerly wind event, but actual wind stress, heating, and wave fields vary significantly, which may be important in forcing mixed-layer turbulence. Also, actual wind bursts are accompanied by heavy precipitation, which can have a significant effect on the surface buoyancy flux.

3. RESULTS

The time evolution of the simulated mean temperature and velocity profiles are presented in Figure 2. These profiles are consistent with observations showing a strong response in the mixed-layer current structure as the wind stress accelerates the surface flow. The resulting mixed-layer velocity profile is rather uniform, with a strong shear zone at the top of the thermocline. Also, the effects of the earth's rotation are evident, with a slow transfer of momentum between the zonal and meridional currents. The inertial oscillation produced in the model has a period of about 14 days, which is similar to the observed current behavior (Moum and Caldwell 1994).

The combination of surface cooling and wind-wave forcing produces a mixed-layer circulation pattern that is strongly aligned with the mean current direction. This is shown in Figure 3 as linear downwelling regions that extend across the model domain in the zonal direction. This pattern is consistent with sheared convective flows as demonstrated by Moeng and Sullivan (1994), and with Langmuir circulation results presented in Skyllingstad and Denbo (1994). A cross section of vertical velocity and potential temperature (Figure 4) at zonal distance = 200 m shows that the turbulent eddies increase in size as a function of depth, eventually scal-

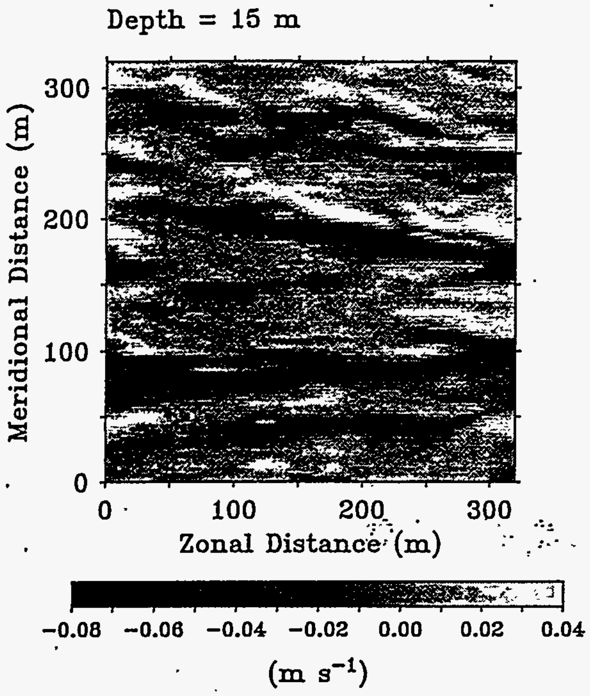

Figure 2. Vertical velocity at 15 m depth at Hour 23

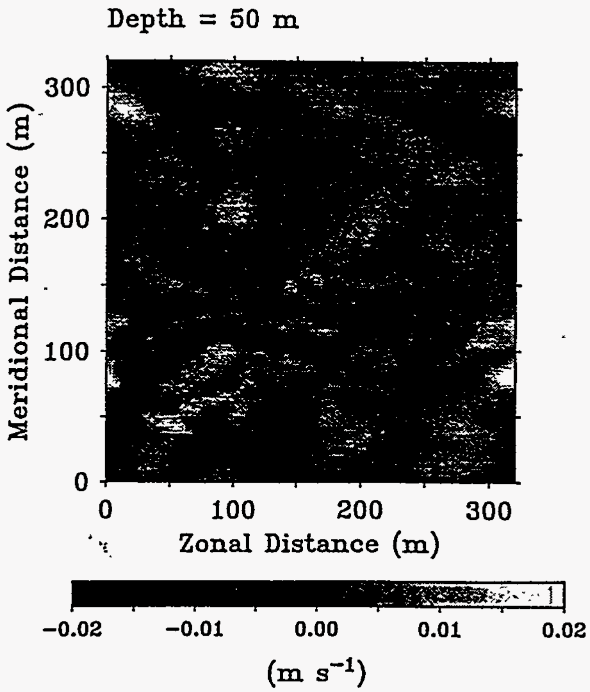

Figure 3. Vertical velocity at 50 m depth at Hour 23

ing to roughly the mixed-layer depth. At the base of the mixed layer, internal waves are evident, as shown by the vertical motion and horizontal variability in the potential temperature at the top of the thermocline between 30 and 50 m depth. Internal waves are most pronounced in the high shear region at the base of the mixed layer (see Figure 2). A plot of the vertical velocity at 50 m (Figure 5) shows an alternating pattern, particularly near the southern boundary, that is associated with internal waves that are aligned perpendicular to the flow direction at this depth (roughly eastward currents). This is in contrast to the eddy vertical motion in the mixed-layer interior, which is aligned parallel to the mean flow direction (Figure 3).

The importance of the strong shear and internal waves at the mixed-layer base can be analyzed using the turbulent kinetic energy (TKE) budget equation,

$$\frac{\partial E}{\partial t} = -\left[\overline{uw}\frac{\partial U}{\partial z} + \overline{vw}\frac{\partial V}{\partial z}\right] + \frac{g\overline{w\rho'}}{\rho_o} - \left[\frac{\partial \overline{wE}}{\partial z} + \frac{\partial \overline{wp}/\rho_o}{\partial z}\right] + \varepsilon \tag{1}$$

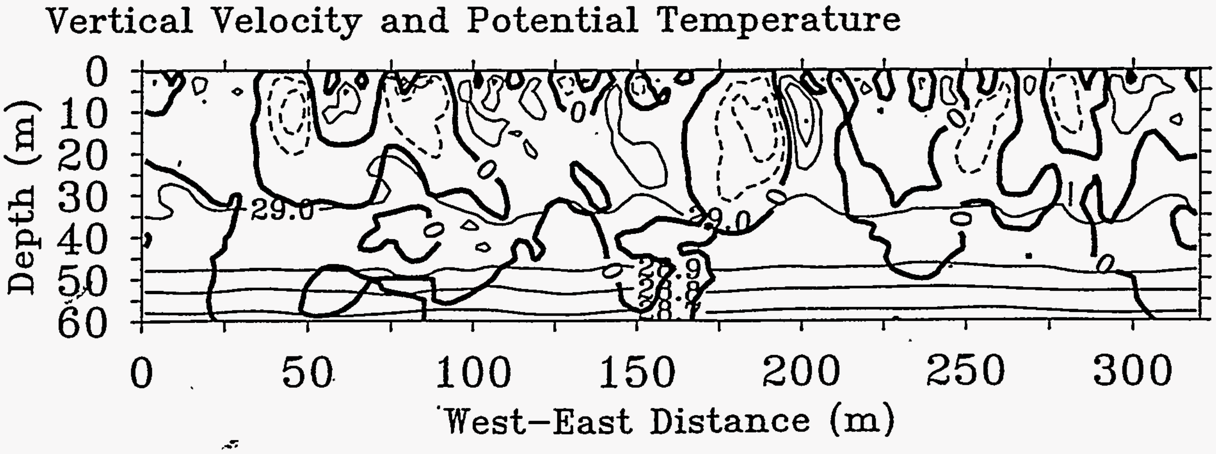

Figure 1. Vertical velocity and potential temperature at zonal distance 200 m, Hour 23

where $E = \left(\overline{u^2 + v^2 + w^2}\right)/2$ is the resolved turbulent kinetic energy, u, v, and w are perturbation velocities in the zonal, meridional, and vertical directions, x, y, and z, respectively, U and V are horizontally averaged zonal and meridional velocities, g is gravity, ρ' is the perturbation density, ρ_0 is the horizontally averaged density, and p is the pressure and surface wave forcing. The terms in the TKE budget equation are, respectively, the shear production term, buoyant production term, turbulent transport term, and the dissipation. If the turbulence is in relatively steady state, ε can be estimated by calculating each of the TKE budget terms and solving for ε as a residual, as shown in Figure 6. This plot is consistent with observations from the COARE IOP showing strong turbulence dissipation rates near the surface, a relative minimum in dissipation rate at the center of the mixed layer, and a secondary maximum at the mixed-layer base. The surface maximum is produced primarily by the shear and transport terms, whereas the smaller peak at the mixed-layer base is dominated by the shear production term. Our results are similar to those of Moeng and Sullivan (1994), which also show a secondary peak in the TKE dissipation rate near the mixed-layer bottom (top in the atmosphere). In the oceanic case, however, the thermocline stratification is considerably weaker and allows for stronger mixing by shear instability, causing relative higher dissipation rates.

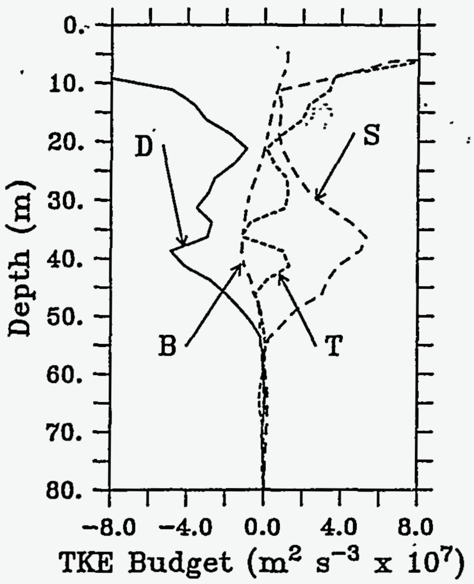

Figure 4. Turbulent kinetic energy budget terms for shear production (S), buoyancy (B), transport (T), and dissipation (D) at Hour 23

4. CONCLUSIONS

The behavior of the mixed layer in the tropical western Pacific warm pool was examined using an oceanic LES model. We found that wind-forced currents create a strong shear layer at the mixed-layer base, which leads to gravity wave instabilities and increased turbulent kinetic energy. The results are consistent with observations showing a pronounced increase in mixing at the mixed-layer base during westerly wind burst events.

5. ACKNOWLEDGMENTS

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