Modulation of equatorial turbulence by a tropical instability wave

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[1] Strong modulation of turbulent mixing by a westward-propagating tropical instability wave (TIW) was observed in the stratified shear layer between the equatorial undercurrent (EUC) and the surface mixed layer during October and November 2008 at 0°N 140°W. The unique deep diurnal-cycle mixing in the stratified layer beneath the equatorial cold tongue was observed where nighttime turbulent mixing was a factor of 10 greater than during daytime. The turbulent kinetic energy dissipation rate, $\varepsilon$, was $O(10^{-6})$ W kg$^{-1}$, and the turbulent heat flux was $\sim -500$ W m$^{-2}$, at least 5–10 times greater than observed previously in the central equatorial Pacific. Turbulence mixing varied significantly during the four distinct phases of the meridional flow associated with the TIW. Observations during the northward-to-southward transition recorded the largest values of reduced shear squared, the thickest nighttime surface mixed layer, the deepest penetration of the deep-cycle turbulence, and the largest turbulent heat flux and largest integrated $\varepsilon$ in the deep-cycle layer (DCL). During steady southward flow, the depth of the bases of the nighttime surface mixed layer and of the DCL were the shallowest. A 50-m-thick layer of strong turbulence was observed immediately above the EUC core during the northward-to-southward and steady southward phases. Here, the average $\varepsilon$ exceeded 10$^{-6}$ W kg$^{-1}$, the eddy diffusivity exceeded 10$^{-3}$ m$^{2}$ s$^{-1}$, and the turbulent heat flux was $\sim -500$ W m$^{-2}$. To parameterize mixing in the central equatorial Pacific accurately, numerical models must simulate the enhancement of mixing associated with TIWs and also the variability of mixing in different TIW phases.


1. Introduction

[2] In the central and eastern Pacific, the equatorial cold tongue has an important dynamic influence on atmosphere–ocean interactions, mediating the thermal structure and the evolution of the oceanic surface mixed layer. The heat balance of the surface mixed layer in the equatorial cold tongue, based on long-term mooring observations, is primarily between the cooling by the turbulent heat flux at the base of the surface mixed layer ($\sim -100$ W m$^{-2}$) and the warming by the net surface heating and the meridional advective heat flux ($\sim \pm 50$ W m$^{-2}$ each) [Wang and McPhaden, 1999, 2001]. This estimate of turbulent heat flux, as the residual in the heat budget analysis, is close to that observed in previous microstructure experiments conducted at 0°N 140°W in Tropic Heat 1 (TH1, 1984) [Gregg et al., 1985; Moum and Caldwell, 1985]. Tropic Heat 2 (TH2, 1987) [Peters et al., 1991], and the Tropical Instability Wave Experiment (TIWE, 1991) [Lien et al., 1995].

[3] TH1 measurements revealed the unique deep-cycle turbulence at 0°N 140°W; turbulence and internal wave activity were enhanced at night, extending below the surface mixed layer into a stratified shear layer where the large-scale mean Richardson number ($Ri = N^2/\overline{\theta}^2$, where $N^2$ is the squared buoyancy frequency and $\overline{\theta}^2$ the squared vertical shear of mean horizontal currents) barely exceeded its critical value of 0.25 [Gregg et al., 1985; Moum and Caldwell, 1985; Moum et al., 1989]. Deep-cycle turbulence properties and their relation to internal waves have been investigated extensively since TH1 [Wijesekera and Dillon, 1991; Moum et al., 1992; Lien et al., 1996; Mack and Hebert, 1999]. Nighttime turbulent kinetic energy dissipation rate in the deep-cycle layer (DCL) exceeded the daytime value by more than a factor of 10 [Moum et al., 1992, 2011] and isotherm displacements and shear variances at nighttime were several times daytime levels [McPhaden and Peters, 1992; Peters et al., 1994].

[4] The dynamics of deep-cycle turbulence, including its generation and interaction with internal waves, has been studied theoretically and numerically [Boyd et al., 1993;
Skyllingstad and Denbo, 1994; Sutherland, 1996; Mack and Hebert, 1997; Sun et al., 1998; Wang et al., 1998; Wang and Müller, 2002], but a first-order understanding remains inconclusive. One hypothesis suggests that shear instability is responsible for the enhanced nighttime internal waves and turbulent mixing in the DCL. Internal waves generated at the base of the surface mixed layer can transport momentum below the surface mixed layer, add small-scale shear into the already near-critical shear layer associated with the Equatorial Undercurrent (EUC), and trigger shear instability [Moum and Caldwell, 1985; Gregg et al., 1985]. Internal waves generated by the shear instability may enhance the background mean shear and again lead to new shear instability. Others argue that internal waves are not needed to generate deep-cycle turbulence and that turbulence in the entrainment layer, immediately below the base of the surface mixed layer, transports momentum into the strong mean shear zone leading to shear instability and thereby deep-cycle turbulence [Clayson and Kantha, 1999]. In the first scenario, internal waves trigger the shear instability, whereas in the second internal waves result from the shear instability. Both are plausible mechanisms. Perhaps a combination of these processes is responsible for the deep-cycle turbulence and it is difficult to identify each process. Previous measurements did not capture how internal waves and shear instabilities evolve in the DCL, and therefore the cause of the shear instability remains unresolved.

5 The intensity of deep-cycle turbulence may be modulated by large-scale tropical oceanic processes. Tropical instability waves (TIWs) are prominent in the central and eastern equatorial Pacific, propagating westward at 0.3–0.5 m s⁻¹ with periods of 15–40 days and wavelengths of ~700–1600 km [Lyman et al., 2007]. Usually strong in boreal fall and winter, TIWs are absent during El Niño years.

6 The TIWE of 1991 was designed to study the effects of TIWs on equatorial turbulence mixing, but because of an unexpected El Niño, tropical instability waves were absent in the fall of 1991 when extensive profiling microstructure measurements were made [Lien et al., 1995]. Subsequent measurements with a Lagrangian float on the equator near 125°W revealed, for the first time, strong modulation of equatorial turbulence by a TIW [Lien et al., 2008]. The strongest turbulence occurred at the leading edge of the TIW trough, with an eddy diffusivity of $K_o \sim 10^{-2}$ m² s⁻¹ and a turbulent heat flux of $J_q \sim 1000$ W m⁻² at the base of the surface mixed layer. The turbulence at 2° south of the TIW trough observed by the Lagrangian float decreased by nearly 2–3 decades from its equatorial values, $K_o \sim 10^{-4}$ m² s⁻¹ and $J_q \sim 10$ W m⁻². During the 2008 Equatorial Internal Wave Experiment (EQUIX), a large-amplitude TIW propagated through 0°N 140°W, enhancing turbulence levels nearly tenfold [Moum et al., 2009] and contributing a cooling of the sea surface at the rate of 2°C/month. Moum et al. [2009] report a significant correlation between sea surface cooling and TIW energy from the long-term TAO mooring record at 0°N 140°W, suggesting that mixing may always be enhanced during the passage of TIWs. Numerical models have also indicated that TIWs can modulate entrainment heat fluxes into the surface mixed layer [Menkes et al., 2006; Dutrieux et al., 2008].

7 Here, we extend the analysis of Moum et al. [2009] to examine the variability of turbulence as a function of TIW phase using a combination of shipboard microstructure measurements and high-frequency moored observations. EQUIX is described in section 2. Background oceanic and atmospheric conditions are presented in section 3. In section 4, we present observations of turbulence, internal waves, deep-cycle properties, and their modulation by a TIW. Section 5 summarizes the modulation of equatorial turbulence bulk properties during different TIW phases. In section 6, we discuss relationships among internal wave amplitudes, shear instability, and turbulence mixing and compare turbulence mixing observed during EQUIX with observations from three earlier microstructure experiments (TH1, TH2, and TIWE). A summary is presented in section 7.

2. Experiment and Measurements

[8] EQUIX was conducted at 0°N 140°W near NOAA’s Tropical Atmosphere-Ocean (TAO) mooring at that site to study internal waves, shear instability, and turbulent mixing under the equatorial cold tongue. EQUIX included two observational components (Figure 1): (1) an upper-ocean surface-buoy mooring (23 October 2008–3 March 2009) and (2) shipboard microstructure profiling from R/V Wecoma (23 October–8 November 2008).

2.1. Mooring

[9] The EQUIX mooring was deployed in two periods: (1) 23 October 2008–8 November 2008 (the intensive observational period, IOP) and (2) 11 November 2008–3 March 2009 (the extensive observational period, EOP). During the IOP (coincident with shipboard observations), the mooring was equipped with 20 Seabird SBE37 pumped CTD sensors, 10 χ pods, and four ADCPs (Table 1). Here, we focus on the data collected during the IOP only.

[10] After the R/V Wecoma arrived at the mooring station, several shipboard CTD casts were made between the surface and 150-m depth to identify the diurnal variation of the surface mixed layer, which provided guidance for the sensor depths on the mooring. One CTD sensor was mounted on the bridle of the mooring, immediately below the sea surface, and 19 CTD sensors were mounted across the base of the nighttime surface mixed layer and into the DCL with roughly 1-m vertical separation between 20 and 55 m depth. Ten CTD sensors had pressure sensors and these measurements, together with measured sensor spacing, were used to assign depths to all of the sensors on the mooring. Ten χ pods were mounted below the surface mixed layer between 24.5 m and 91 m depth. Data from χ pod instruments are presented elsewhere [Perlin and Moum, 2012] and not discussed here.

[11] Four ADCPs were deployed on the mooring. Two 1200-kHz ADCPs were mounted back-to-back at 45 m depth in master/slave mode, synchronized in time to measure flow in the depth ranges 25–44 m and 46–65 m. One upward-looking 300-kHz RDI was mounted at 90 m depth to take velocity measurements between 10 and 88 m depth. An upward-looking 75-kHz RDI Long Ranger was mounted at 590 m depth, permitting velocity measurements between 60 and 570 m depth. The velocity data from the 75-kHz ADCP are not used in this analysis.

[12] A 2-Hz sampling rate on the ADCPs allowed resolution of surface waves (3–10 s period); their signature was removed by low-pass filtering. One-minute averages of
ADCP velocity measurements were used for the analysis presented here, unless noted otherwise. These ADCP and CTD data are used to analyze internal wave properties and shear instability (section 6.1).

2.2. Shipboard Microstructure Profiler and ADCP Measurements

The tethered free-fall microstructure profiler, Chameleon, is equipped with airfoil probes and temperature, Figure 1. Schematic of the Equatorial Internal Wave Experiment (EQUIX), (left) Mooring sensor configuration, and (right) microstructure profiler (Chameleon) and shipboard ADCPs onboard R/V Wecoma. Mooring is equipped with 20 SeaBird CTD sensors at ~1-m vertical separation, 10 moored microstructure sensors pods, two back-to-back 1200-kHz ADCPs, one 300-kHz ADCP, and one 75-kHz ADCP. Depths, specifications, and sampling configurations of moored sensors are given in Table 1.

Table 1. Sampling Rates, Deployment Depths, and Sensor Configurations on the EQUIX Mooring

<table>
<thead>
<tr>
<th>Type</th>
<th>Sampling Rate</th>
<th>Depth (m)</th>
<th>Bin Size (m)</th>
<th>Penetration Range (m)</th>
<th>Pulse Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SeaBird CTD: SBE37</td>
<td>7 s</td>
<td>1, 25.5, 26.5, 27.5, 29.5, 30.5, 31.5, 33.5, 34.5, 35.5, 36.5, 37.5, 38.5, 44.3, 45.3, 46.3, 47.3, 49.3, 50.3, 52.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>χ-pod</td>
<td>T = 10 Hz</td>
<td>24.5, 26.5, 28.5, 32.5, 48.3, 51.3, 53.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>dT/dt 120 Hz</td>
<td>62.3, 71.3, 80, 91</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>P = 10 Hz</td>
<td>3-axis accelerations – 120 Hz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Compass – 1 Hz</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upward looking 1200-kHz ADCP</td>
<td>2 Hz</td>
<td>40.5</td>
<td>0.5</td>
<td>15–20</td>
<td>0.5</td>
</tr>
<tr>
<td>Downward looking 1200-kHz ADCP</td>
<td>2 Hz</td>
<td>42.3</td>
<td>0.5</td>
<td>15–20</td>
<td>0.5</td>
</tr>
<tr>
<td>Upward looking 300-kHz ADCP</td>
<td>2 Hz</td>
<td>90</td>
<td>2</td>
<td>90</td>
<td>2</td>
</tr>
<tr>
<td>Upward looking 75-kHz ADCP</td>
<td>2 Hz</td>
<td>590</td>
<td>16</td>
<td>590</td>
<td>16</td>
</tr>
</tbody>
</table>
were computed by integrating turbulence shear variances observed by airfoil shear probes. Measurements of temperature, conductivity, and pressure sensors. Vertical profiles from the sea surface to 200 m were made at 6–8-min intervals during the IOP. Estimates of the turbulent kinetic energy (TKE) dissipation rate \( \varepsilon \) were computed by integrating turbulence shear variances observed by airfoil shear probes. Measurements of temperature, conductivity, and pressure were obtained between the sea surface and 200-m depth. Because of the potential that \( \varepsilon \) could be contaminated by the ship’s wake near the sea surface, the upper 10 m is excluded from this analysis. Details concerning the profiler, its sensors, and the methods to compute \( \varepsilon \) are presented in Moum et al. [1995]. R/V Wecoma was equipped with hull-mounted 300-kHz and 75-kHz ADCPs. To ensure high-quality measurements above the EUC core, a 150-kHz ADCP was mounted over the port side of R/V Wecoma during the IOP. For the following analysis, velocity measurements from the three shipboard ADCPs were combined: 300-kHz ADCP data from 10 m to 120 m depth, 150-kHz ADCP data between 124 and 154 m depth, and 75-kHz ADCP below 154 m depth. In section 6.1 only velocity measurements from mooring ADCPs are used to compute the shear and reduced shear squared.

3. Background Oceanic and Atmospheric Conditions

[14] During EQUIX, a large-amplitude TIW with wavelength 1000 km (as determined from satellite observations of sea surface temperature; Figure 2) was observed propagating westward along the equator at 0.7 m s\(^{-1}\). On 1 November, the trough of the TIW passed the EQUIX experiment site accompanied by a sharp front that passed the site in less than 1 min. After passage of the front, the upper 50 m of the ocean was \( \sim0.7^\circ \)C warmer, \( \sim0.15 \) psu fresher, and \( \sim0.2 \) kg m\(^{-3}\) lighter (Figures 3b and 3c and Figures 4a and 4b).

[15] The observed sudden change of water mass at the equator was due to the southward advection of the warmer and fresher water north of the equator by the TIW. Johnson et al. [2002] and McPhaden et al. [2008] provide detailed descriptions of the meridional structure of temperature and salinity fields in the eastern tropical Pacific. The TIW front separates the colder, saltier, and heavier water on the southern (equator) side from the warmer, fresher, and lighter water on the northern side. The stratification on the equator side of the TIW front is weaker than that on the northern side.

[16] Measurements of surface wind, air pressure, humidity, short- and long-wave radiation, sea surface temperature (SST), and air temperature taken onboard R/V Wecoma were used to compute surface wind stress, air–sea heat flux, and buoyancy flux using bulk formulae [Fairall et al., 1996]. The net surface buoyancy flux, \( J_b \), was dominated by the solar radiation during the day and by the latent heat flux at night. The nighttime buoyancy flux was typically \( 10^{-7} \) W kg\(^{-1}\), fluctuating with the surface wind stress (Figure 3f). The magnitudes of surface wind stress and buoyancy forcing during EQUIX were similar to those during previous microstructure experiments [e.g., Lien et al., 1995].

[17] The average surface wind stress was \( \sim0.1 \) Pa between 24 and 29 October, decreased to \( \sim0.05 \) Pa between 30 October and 6 November, and increased to \( >0.1 \) Pa after 7 November. The zonal wind stress was westward throughout the entire experiment, and was much stronger than the meridional wind stress. The westward wind stress favors generation of westward shear and, thereby, enhances the westward mean shear associated with the EUC. Numerical model simulations of the upper equatorial ocean show that the diurnal cycle of internal wave activity, and thereby the DCL turbulence, exists only during westward wind-forcing [Skyllingstad and Denbo, 1994; Wang and Müller, 2002]. Previous microstructure studies have shown that the DCL turbulence depends not only on the surface wind-forcing, but also other parameters, e.g., surface buoyancy flux, shear, and stratification. Numerical model simulations of the wind-forced upper ocean further

Figure 2. Three-day averaged (centered at 1 November 2008) sea surface temperature from SSMI/TMI (http://www.remss.com). Red line shows the equator and red dot marks the EQUIX experiment site (0°N 140°W). Sporadic black spots in the ocean indicate no valid SST data, mostly due to precipitation. Black contour lines marks the 25.5°C isotherm, as a reference to show the temperature signature associated with the tropical instability wave (TIW). The equatorial cold tongue, the TIW, and the cold upwelling caused by the gap wind centered at \( \sim15^\circ \)N 95°W are evident. TMI data are produced by Remote Sensing Systems and sponsored by the NASA Earth Science MEaSUREs DISCOVER Project.
Figure 3
confirm that the turbulence below the surface mixed layer depends on the shear as well as the wind stress \cite{Clayson and Kantha, 1999; Grant and Belcher, 2011}.

3.1. Definition of TIW Phases

\cite{INOUUE ET AL.: EQUATORIAL TURBULENCE MODULATED BY A TIW} Meridional velocity averaged between 10 and 80 m depth $\bar{V}$ (Figure 3a) is used to characterize distinct phases of the TIW: (1) northward phase (N) before 27 October, $\bar{V} \sim 0.6 \text{ m s}^{-1}$; (2) northward-to-southward transition phase (N→S) between 27 October and 1 November, $\bar{V}$ from $\sim 0.6 \text{ m s}^{-1}$ to $\sim 0.6 \text{ m s}^{-1}$; (3) southward phase (S) during the period 1–7 November; and (4) southward-to-northward transition phase (S→N) after 7 November. One of the primary purposes of this analysis is to characterize variations in turbulence as a function of TIW phase.

3.2. Surface Mixed Layer, EUC Core, DCL, and Upper Core Layer

\cite{INOUUE ET AL.: EQUATORIAL TURBULENCE MODULATED BY A TIW} We define the surface mixed layer depth (MLD) (Figure 3g) as the minimum depth within which the potential density is 0.015 kg m$^{-3}$ heavier than the surface value, the buoyancy frequency squared, $N^2$, exceeds $2 \times 10^{-3} \text{ s}^{-2}$, and the shear squared, $\bar{\epsilon}^2$, exceeds $5 \times 10^{-3} \text{ s}^{-2}$. The nighttime MLD was $\sim 30 \text{ m}$ during N and N→S phases, and was $\sim 20 \text{ m}$ during S and S→N phases. The Monin–Obukhov length scale ($L_{MO} = \frac{\bar{u}^2}{\bar{\epsilon} \bar{\epsilon}}$), where $\bar{u}$ is the surface friction velocity, $\kappa$ von Karman’s constant, and $\bar{\epsilon}$ the surface buoyancy flux) at nighttime was comparable with the MLD, suggesting that surface wind-forcing and convective forcing were equally important within the surface mixed layer. The EUC core is defined as the depth where the vertical shear of the hourly averaged zonal current vanishes (Figure 3g). The DCL is characterized by a daily cycle in turbulence, which includes nighttime intensification, daytime decay and vertical penetration. Here, we identify the base of the DCL through the time derivative of $\bar{\epsilon}$. This definition differs from that used previously and is explained in Appendix A. This new definition distinguishes the DCL from the recently discovered turbulent layer immediately above the EUC core, referred to as the upper core layer (UCL; section 4.2).

\cite{INOUUE ET AL.: EQUATORIAL TURBULENCE MODULATED BY A TIW} The depth of the EUC core remained at $\sim 100 \text{ m}$ throughout the experiment. The base of the DCL varied significantly during the TIW event. During the N→S phase and the S→N phase, the base of the DCL was the deepest, reaching the EUC core at 100 m depth. In the S phase of the TIW, the base of the DCL was the shallowest, sometimes $\leq 50 \text{ m}$ depth. The DCL was the thickest, $\sim 70 \text{ m}$, in the N→S phase and S→N phase, and thinnest, frequently $< 40 \text{ m}$, during the S phase.

3.3. Velocity, Shear, and Stratification

\cite{INOUUE ET AL.: EQUATORIAL TURBULENCE MODULATED BY A TIW} The EUC core speed and depth were not affected significantly by the TIW, though above the EUC core $U$ and $V$ were strongly modulated by the TIW (Figures 4c and 4d). During N and N→S phases, the zonal flow averaged between 10 and 80 m depth was eastward (Figure 3a). During S and S→N phases, the zonal flow was westward between 40 and 50 m depth and eastward between 50 to 80 m depth, with an average flow between 10 and 80 m depth nearly zero. The meridional flow, mostly associated with the TIW, was vertically coherent between 10 and 80 m depth (Figure 4d). Generally, the vertical shear of the zonal current was larger than that of the meridional current (Figures 4e and 4f). The strongest vertical shear was above the EUC core, with typical shear variances of the zonal component ($\bar{\epsilon}_u \frac{\partial U}{\partial z}$) approximately $10^{-3} \text{ s}^{-2}$. During the N phase before 26 October, $\bar{\epsilon}_u \frac{\partial U}{\partial z}$ above the EUC decreased to $\sim 10^{-4} \text{ s}^{-2}$, accompanied by a reduced vertical penetration of the deep-cycle turbulence.

\cite{INOUUE ET AL.: EQUATORIAL TURBULENCE MODULATED BY A TIW} The observed variances of vertical shear had three distinct features in the entrainment layer, below the DCL, and above the EUC core. These features are described as follows.

3.3.1. Vertical Penetration of Strong Shear in the Entrainment Layer

\cite{INOUUE ET AL.: EQUATORIAL TURBULENCE MODULATED BY A TIW} During nighttime, a 10-m-thick layer of $\bar{\epsilon}_u \frac{\partial U}{\partial z}$ developed immediately below the base of the convection surface mixed layer and descended with the deepening surface mixed layer into the weakly stratified and sheared remnant mixed layer [$\text{Brainerd and Gregg, 1993}$] produced the night before (Figures 4e and 5b). After the mixed layer reached its equilibrium depth, the entrainment shear zone merged into the mean shear layer of the EUC. This zone of enhanced shear penetrated into the DCL but not beyond. To our knowledge, this is the first time the vertical penetration of enhanced shear in the entrainment layer has been observed under the equatorial cold tongue. The deepening of the shear layer from the surface had not been observed previously, presumably due to inadequate resolution by earlier velocity measurements in this area.

3.3.2. A Shallow Weak Shear Layer Below the Base of the DCL During the TIW S Phase

\cite{INOUUE ET AL.: EQUATORIAL TURBULENCE MODULATED BY A TIW} During the S phase of the TIW, there was a distinct thin layer, $O(10 \text{ m})$, of weak shear (Figures 4e and 5b) immediately below the base of the DCL. The DCL was thinner and the penetration depth shallower during the S phase. The vertical penetration of strong shear variance below the base of the surface mixed layer stopped immediately above this weak shear layer and did not merge with the mean shear layer associated with the EUC. The dynamics of this weak shear layer are unknown.

Figure 3. (a) Daily low-pass filtered meridional velocity (black shading) and zonal velocity (gray curve) averaged between 10 and 80 m depth, (b) sea surface temperature (thin curve) and temperature averaged between 10 and 80 m depth (thick curve), (c) salinity averaged between 10 and 80 m depth, (d) surface wind stress (including both zonal and meridional components), (e) zonal (thick solid curve) and meridional (thin solid curve) components of surface wind stress, (f) surface buoyancy flux (positive value shaded), (g) the base of the surface mixed layer (upper thin curve), the base of the DCL (thick black curve), the core of the equatorial undercurrent (EUC) (lower thin curve), and the Monin–Obukhov depth (gray shading), (h) the total shear squared (including both the zonal and meridional components) (thick curve) and $4N^2$ (gray shading) averaged within the DCL, and (i) turbulent kinetic energy dissipation rate averaged within the DCL (black) and that average in the upper core layer (gray). Periods of different TIW phases are labeled on the top of Figure 3a. Vertical dashed line in Figure 3b marks the arrival of the temperature front.
Figure 4. Depth-time contour plots of (a) potential temperature, (b) salinity, (c) zonal velocity $U$, (d) meridional velocity $V$, (e) squared vertical shear of $U$, and (f) squared vertical shear of $V$. Thin black curves represent isopycnals in all panels; the thick gray curves represent the base of the surface mixed layer and the EUC core, and the thick white curve represents the base of the DCL in Figure 4e. Periods of different TIW phases are labeled on the top of Figure 4a.
3.3.3. A Strongly Sheared Turbulent Layer Above the EUC Core During the TIW N → S and S Phases

Elevated zonal and meridional shears accompanied by strong turbulence (section 4) were observed between 50 and 100 m depth, immediately above the EUC core during the N → S (28–30 October) and S (1–7 November) phases of the TIW. During the N → S phase and the early part of the S phase, this layer merged with the DCL and became indistinguishable from the deep-cycle turbulence. During the S phase, this layer was dynamically decoupled from the DCL, separated by the aforementioned weak shear layer, and clearly decoupled from direct surface forcing. This “deep” strong turbulent layer has not been observed in previous microstructure experiments, presumably because it is a distinct feature associated with the TIW.

4. Turbulent Mixing

Measurements of the turbulent kinetic energy dissipation rate $\varepsilon$ during EQUIX show strong turbulence within the surface mixed layer, in the stratified DCL at nighttime, and in a 50-m-thick layer immediately above the EUC core, the UCL (Figure 5a). Turbulence properties in these layers are discussed as follows.

4.1. Deep-Cycle Turbulence

The turbulent kinetic energy dissipation rate $\varepsilon$ averaged within the DCL, $\varepsilon_{dcl}$, usually showed a clear nighttime enhancement, increasing from $\sim 10^{-7}$ W kg$^{-1}$ during daytime to $>10^{-6}$ W kg$^{-1}$ at nighttime (Figure 3i). Despite the varying level of day-night variation, the weakest $\varepsilon_{dcl}$ appeared immediately before sunset, and the strongest $\varepsilon_{dcl}$ occurred mostly near midnight. This robust feature has been observed in all previous microstructure measurements of deep-cycle turbulence.

The penetration depth and thickness of the DCL varied significantly with TIW phase (Figure 3g and Figure 5a). There were several large turbulent events with $\varepsilon_{dcl} \sim 10^{-5}$ W kg$^{-1}$ in the N → S and S phases. The maximum nighttime intensity of
 varied between $2 \times 10^{-6}$ and $10^{-5}$ W kg$^{-1}$. Because the DCL was the thickest during the N$\rightarrow$S phase and the thinnest during the S phase, the turbulent kinetic energy dissipation rate integrated within the DCL was the largest during the N$\rightarrow$S phase and the smallest during the S phase.

### 4.2. Upper Core Layer

One of the most unique new features revealed by the EQUIX measurements is the strong turbulence between the base of the DCL and the undercurrent core during the S phase of the TIW (Figure 5a). This turbulent layer was ~50 m thick with an average of $\varepsilon \sim 10^{-6}$ W kg$^{-1}$ (Figure 5i). Apparently, the UCL turbulence was neither forced directly from the surface nor was it coupled dynamically with the deep-cycle turbulence because (1) the average $\varepsilon$ within the UCL, $\varepsilon_{\text{UCL}}$, showed no diurnal variation or nighttime enhancement (unlike the surface force or deep-cycle turbulence) and (2) it was separated from the deep-cycle turbulence by a ~10-m layer of weak turbulence, ~$10^{-5}$ W kg$^{-1}$.

UCL turbulence existed in a layer of strong mean shear and was likely generated by local shear instability, $Ri < 1/4$ (Figure 5d). Why it was formed mostly during the TIW S phase requires further study. Previous microstructure experiments did not take measurements during the TIW S phase nor observe this strongly turbulent layer above the EUC.

The turbulence kinetic energy dissipation rate $\varepsilon$ below the surface mixed layer is significantly correlated with the Richardson number (Figures 5a and 5d). The correlation between $\log_{10}(\varepsilon)$ and $\log_{10}(Ri^{-1})$ is 0.62 with the 95% significance level of 0.02. This significant correlation suggests that shear instability is the primary mechanism of the observed turbulence in the stratified shear layer within the DCL and UCL.

### 5. Summary of TIW Modulation

Currents, vertical shear, temperature, salinity, stratification, shear instability, and turbulence mixing were all strongly modulated by the TIW. Vertical profiles of these properties (Figure 6) and their averages in the DCL (Table 2) in different phases of the TIW are summarized as follows.

N Phase (24–27 October): Zonal current was eastward above the EUC core, ~100 m depth (Figure 6a), and meridional current was northward, decreasing from ~0.75 m s$^{-1}$ at 10 m depth to 0 at the EUC core (Figure 6b). Above the EUC core, temperature was relatively lower than in other TIW phases, salinity modest, density high, and shear and stratification relatively weak (Figure 6c–6g). In the upper 50 m (within the DCL), the inverse gradient Richardson number $Ri^{-1} = \langle \kappa^2 \rangle / \langle N^2 \rangle$ was greater than 4, in favor of shear instability, and $\varepsilon$ was slightly greater than $10^{-6}$ W kg$^{-1}$ at the base of the surface mixed layer, decreasing with depth to $10^{-8}$ W kg$^{-1}$ at the EUC core (Figures 6h and 6i). The eddy diffusivity $K_\rho$ decreased from $2 \times 10^{-2}$ m$^2$ s$^{-1}$ at 20 m depth to $10^{-5}$ m$^2$ s$^{-1}$ at the EUC core. Within the DCL, $K_\rho$ varied between $10^{-3}$ m$^2$ s$^{-1}$ and $10^{-2}$ m$^2$ s$^{-1}$ (Figures 6j–6l). Turbulent heat flux was ~800 W m$^{-2}$ in the upper 50 m and decreased to ~2 W m$^{-2}$ at the EUC core.

N$\rightarrow$S Phase (27 October–1 November): Zonal current in the upper 50 m nearly vanished. The EUC had a maximum speed of 1.4 m s$^{-1}$ and the EUC core was at ~100 m depth. The average meridional current in this transition period nearly vanished. Temperature was higher than during the N phase, salinity was highest, and density was about the same as during the N phase. Above the EUC core, stratification and shear variance were the weakest of all TIW phases, except below 70 m during the N phase. In the upper 90 m, the inverse Richardson number $Ri^{-1}$ was greater than 4, suggesting shear instability, and $\varepsilon$ was relatively uniform at ~$2 \times 10^{-6}$ W kg$^{-1}$ in the upper 100 m, decreasing to ~$2 \times 10^{-4}$ W kg$^{-1}$ at 120 m depth, $K_\rho$ decreased from $2 \times 10^{-2}$ m$^2$ s$^{-1}$ at 20 m depth to $10^{-5}$ m$^2$ s$^{-1}$ at 120 m depth. Within the DCL, $K_\rho$ varied between $10^{-3}$ m$^2$ s$^{-1}$ and $10^{-2}$ m$^2$ s$^{-1}$, as in the N phase. The turbulent heat flux was ~800 W m$^{-2}$ in the upper 90 m and decreased to ~5 W m$^{-2}$ at 120 m depth.

S Phase (1–7 November): Zonal current was westward in the upper 50 m, and meridional current was southward at ~0.6 m s$^{-1}$. Below 50 m depth, meridional flow decreased to 0 at 100 m depth, producing a layer of strong meridional shear. Temperature was similar to that in the N$\rightarrow$S phase, and salinity was lower than in the earlier TIW phases, reducing the density. Shear squared in the upper 100 m was ~3 times that in the N$\rightarrow$S phase, and $N^2$ was ~10 times larger. A weak shear layer at ~50 m depth separated the deep-cycle turbulence from the UCL turbulence, which was centered at 85 m depth. $K_\rho$ decreased from $0.8 \times 10^{-2}$ m$^2$ s$^{-1}$ at 20 m depth to $10^{-3}$ m$^2$ s$^{-1}$ below 50 m depth. The turbulent heat flux was ~400 W m$^{-2}$ above 90 m and decreased to ~5 W m$^{-2}$ below the EUC core. The deep-cycle turbulent heat flux was the weakest during this TIW phase.

S$\rightarrow$N Phase (7–9 November): EQUIX measurements were made over only 2 days of this TIW phase. Zonal current remained westward in the upper 50 m while the meridional current was southward. Temperature in the upper 50 m remained the same as in the S phase. Salinity and density in the upper 50 m continued to decrease from that in previous TIW phases. $Sh^2$ was weaker than in the S phase in the upper 50 m but stronger between 50 and 80 m depth. Stratification between 30 and 100 m depth was stronger than during the S phase. The inverse Richardson number averaged over this TIW phase shows that the entire water column, except near 20 m at the base of the surface mixed layer, was unfavorable to shear instability, although there were shear instabilities and was deep-cycle turbulence below the base of the surface mixed layer at nighttime (Figure 5d). The turbulent kinetic energy dissipation rate was nearly constant, ~$2 \times 10^{-6}$ W kg$^{-1}$ in the upper 70 m, decreasing to ~$4 \times 10^{-6}$ W kg$^{-1}$ at 120 m depth. $K_\rho$ decreased from ~$10^{-2}$ m$^2$ s$^{-1}$ at 20 m depth to ~$10^{-3}$ m$^2$ s$^{-1}$ at 120 m depth. The turbulent heat flux was ~600 W m$^{-2}$ above 60 m, and decreased to ~1 W m$^{-2}$ at 120 m depth.

Observations show that turbulence varied significantly in different TIW phases. During the N$\rightarrow$S Phase, $\varepsilon$ was the largest, the vertical penetration of the deep-cycle turbulence the deepest, and the eddy diffusivity and the turbulent heat flux were the strongest. During S and S$\rightarrow$N phases, $K_\rho$ and the turbulent heat flux in the DCL above ~50 m depth were weaker than during the other two TIW phases.

Numerical model results [Jochum and Murtugudde, 2006] also show strong modulation of turbulent heat flux by TIWs. Model results suggest that the turbulent entrainment...
heat flux into the surface mixed layer was the strongest when the surface mixed layer was the shallowest due to the enhanced shear across the mixed layer. Our observations, however, show that the turbulent heat flux was the weakest when the surface mixed layer was the shallowest, and the turbulent heat flux was the strongest when the surface mixed layer was the deepest. Because the model [Jochum and Murtugudde, 2006] does not include diurnal forcing, it does not simulate deep-cycle turbulence, and therefore the discrepancy between model results and observations is to be expected.

6. Discussion

6.1. Internal Waves and Shear Instability in the DCL From Mooring Observations

[39] Internal wave activity and turbulent mixing are elevated in the DCL at nighttime, implying that they are related


Table 2. Averages of Velocity, Temperature, Salinity, Shear Squared, Buoyancy Frequency Squared, Turbulent Kinetic Energy Dissipation Rate $\epsilon$, Eddy Diffusivity $K_{ij}$, Turbulent Heat Flux $J_q$, and Surface Wind Stress in Different TIW Phases\(^{a}\)

<table>
<thead>
<tr>
<th>N Phase</th>
<th>N→S Phase</th>
<th>S Phase</th>
<th>S→N Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U/m s^{-1}$</td>
<td>0.66</td>
<td>0.40</td>
<td>−0.18</td>
</tr>
<tr>
<td>(0.65, 0.68)</td>
<td>(0.39, 0.41)</td>
<td>(−0.19, −0.17)</td>
<td>(−0.05, 0.00)</td>
</tr>
<tr>
<td>$V/m s^{-1}$</td>
<td>0.65</td>
<td>−0.06</td>
<td>−0.61</td>
</tr>
<tr>
<td>(0.64, 0.65)</td>
<td>(−0.07, −0.05)</td>
<td>(−0.61, −0.60)</td>
<td>(−0.39, −0.37)</td>
</tr>
<tr>
<td>$T^\circ C$</td>
<td>24.11</td>
<td>24.31</td>
<td>24.95</td>
</tr>
<tr>
<td>(24.07, 24.14)</td>
<td>(24.29, 24.33)</td>
<td>(24.64, 24.73)</td>
<td>(23.98, 24.05)</td>
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<tr>
<td>$S/PSU$</td>
<td>35.31</td>
<td>35.41</td>
<td>35.41</td>
</tr>
<tr>
<td>(35.31, 35.31)</td>
<td>(35.41, 35.41)</td>
<td>(35.12, 35.13)</td>
<td>(34.97, 34.98)</td>
</tr>
<tr>
<td>$10^4 \times \sigma_h^2/m^{-2}$</td>
<td>2.94</td>
<td>3.42</td>
<td>3.73</td>
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<tr>
<td>(2.86, 3.03)</td>
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<td>(3.64, 3.80)</td>
<td>(6.50, 7.10)</td>
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<tr>
<td>$10^4 \times 4N^2/m^{-2}$</td>
<td>3.26</td>
<td>3.20</td>
<td>4.35</td>
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<td>(3.13, 3.38)</td>
<td>(3.11, 3.29)</td>
<td>(4.25, 4.44)</td>
<td>(8.02, 8.77)</td>
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<td>1.86</td>
<td>1.82</td>
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<td>(1.25, 1.43)</td>
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<td>(1.71, 1.93)</td>
<td>(1.44, 1.70)</td>
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<tr>
<td>$10^3 \times K_{ij}/m^3 s^{-1}$</td>
<td>6.93</td>
<td>8.78</td>
<td>5.36</td>
</tr>
<tr>
<td>(6.32, 7.47)</td>
<td>(8.35, 9.16)</td>
<td>(4.88, 5.78)</td>
<td>(3.37, 4.34)</td>
</tr>
<tr>
<td>$-J_q/W m^{-2}$</td>
<td>474.41</td>
<td>556.77</td>
<td>359.62</td>
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<td>(439.04, 505.57)</td>
<td>(532.76, 580.18)</td>
<td>(337.16, 380.46)</td>
<td>(364.10, 430.60)</td>
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<td>$MLD/m$</td>
<td>16.39</td>
<td>16.93</td>
<td>16.95</td>
</tr>
<tr>
<td>(15.28, 17.79)</td>
<td>(15.58, 18.22)</td>
<td>(9.31, 10.30)</td>
<td>(14.79, 18.06)</td>
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<td>$DCL base/m$</td>
<td>68.69</td>
<td>85.80</td>
<td>55.45</td>
</tr>
<tr>
<td>(65.34, 71.93)</td>
<td>(84.78, 87.01)</td>
<td>(54.42, 56.44)</td>
<td>(76.79, 81.03)</td>
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<tr>
<td>$DCL thickness/m$</td>
<td>52.10</td>
<td>68.87</td>
<td>45.64</td>
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<td>$\tau_{r/pa}$</td>
<td>−0.110</td>
<td>−0.079</td>
<td>−0.059</td>
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<tr>
<td>(−0.117, −0.104)</td>
<td>(−0.082, −0.076)</td>
<td>(−0.062, −0.056)</td>
<td>(−0.121, −0.112)</td>
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<tr>
<td>$\tau_{p/pa}$</td>
<td>0.059</td>
<td>0.035</td>
<td>0.035</td>
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<tr>
<td>(0.024, 0.035)</td>
<td>(0.016, 0.022)</td>
<td>(0.033, 0.038)</td>
<td>(0.051, 0.060)</td>
</tr>
</tbody>
</table>

\(^{a}\)Averages are taken between the bases of the mixed layer and deep-cycle layer. Values within parentheses represent 95% confidence intervals obtained from the bootstrapping method. The surface mixed layer depth (MLD), and deep-cycle layer (DCL) depth and thickness are also shown.

dynamically [e.g., Moum et al., 1992; McPhaden and Peters, 1992; Lien et al., 1996]. A particularly large shear instability was reported by Hebert et al. [1992]. Because instability events generally have a time scale of the buoyancy period, $O(10)$ min, in this environment, it is difficult to capture instability events with microstructure profiler measurements. Using data from $\gamma$ pods on the TAO mooring at $0^\circ$, $140^\circ$W, Moum et al. [2011] clearly linked the properties of narrowband, near-N waves with those of shear instabilities and with intensification of mixing within the DCL. Smyth et al. [2011] report that the instabilities must be near-N because 1) the dominant frequency of an ensemble of instabilities scales with $Sh$, and 2) $Sh$ and $N$ are closely related where $Re = O(1)$. The closely spaced sensors on the EQUIX mooring permit a closer look at the properties of shear instabilities during passage of a TIW. Temperature, salinity, pressure, and velocity were measured with high vertical and temporal resolution on the EQUIX mooring using twenty CTDs between 20 and 55 m depth and three ADCPs in the upper 100 m. Though mooring sensors are ideal to record instability events, only a few large instability events were observed, probably due to the limited depth coverage of sensors on the mooring.

One instability event was recorded by mooring sensors near midnight on 27 October (Figure 7). Vertically coherent waves appeared around 22:00 local time, with peak-to-peak amplitude ~5 m and period ~20 min, grew to more than 10 m before midnight, and broke after midnight with a density inversion greater than 10 m in the stratified layer. A microstructure profiler ~3 m north of the mooring site recorded a turbulence kinetic energy dissipation rate greater than $10^{-6}$ W kg$^{-1}$ at nearly the same depth and time. Though the dynamics of internal waves, instabilities, and turbulence mixing are beyond the scope of this analysis, the relationships among the intensities of these processes, i.e., internal wave amplitude, reduced shear squared, and $\epsilon$ provide additional insight.

Internal wave vertical displacements were computed using mooring CTD measurements as $\eta = (\rho - \bar{\rho})/\bar{\rho}$, where $\rho$ is density sorted to increase monotonically with depth, $\bar{\rho}$ is the closest hourly average of $\rho$, and $\bar{\rho}$ the vertical gradient of the closest density. Hourly averages of $rms$ vertical displacement $\langle \sigma_p \rangle$ and turbulence kinetic energy dissipation rate $\epsilon$ were derived from shipboard microstructure profiling measurements, and reduced shear squared $\langle Sh^2 \rangle - 4N^2$ from mooring measurements (Figure 8). Mooring CTD sensors ran out of power after 5 November and therefore did not record the S→N phase. All variables were averaged between 20 and 55 m and measurements within the surface mixed layer and below the DCL were excluded.

Averages of $\epsilon$ between 20 and 55 m include a major part of the deep-cycle turbulence, and therefore reflect its properties (Figure 8a). $Sh^2$ and $N^2$ fluctuate in unison, with a rapid increase at the transition from N→S phase to S phase (Figure 8c). Reduced shear squared was mostly positive during N and N→S phases, implying favorable shear instability, and was mostly negative during the S phase (Figure 8b). Although $Sh^2$ intensified in the S phase, $N^2$ was enhanced even more, which creates an environment less favorable for shear instability.

During N and N→S phases, the reduced shear squared increased at nighttime, suggesting the presence of shear instability in the nighttime DCL. It is interesting to note that reduced shear squared and $\epsilon$ exhibited similar high
An event of enhanced internal wave activity and turbulence mixing below the nighttime mixed layer: (a) turbulent kinetic energy dissipation rate $\varepsilon$ (color shading) observed by a shipboard microstructure profiler and isopycnal fluctuations (white curves) observed from CTD sensors on the EQUIX mooring 27 and 28 October and (b) expanded view from within the black box shown in Figure 7a. The blue curve indicates the base of the surface mixed layer. CTD data are low-pass filtered at 10 min.

frequency patterns such as the double-burst events of strong turbulence and positive reduced shear squared on 27–28 and 31 October.

In fact, the similar pattern between $\varepsilon$ and reduced shear squared is to be expected for shear instability driven turbulence. Baumert and Peters [2005] report that in high Reynolds number flows the time rate change of $\log(\varepsilon)$ is proportional to the reduced shear squared if the turbulence reaches structural equilibrium with steady enstrophy and shear. However, because turbulence mixing could destroy the shear rapidly, turbulence might not reach structural equilibrium. The predicted relation between the time rate change of $\log(\varepsilon)$ and the reduced shear squared is not observed in our data, either because of the lack of the structural equilibrium state or the insufficient temporal resolution of microstructure measurements.

The rms vertical displacement $\langle \sigma_n \rangle$ generally varied between 0.5 and 2 m. Events of 2–5 m occurred during the N→S phase, then $\langle \sigma_n \rangle$ decreased to < 1 m after 4 November (Figure 8d). Two large events of $\langle \sigma_n \rangle$ = 5 m on 28–29 October correspond well with the large $\varepsilon$ derived from microstructure profiling. The rms vertical displacement was the weakest after 4 November, corresponding to the highest stratification in the S phase.

6.2. Comparison With Previous Microstructure Observations at 0°N 140°W

Four microstructure experiments (TH1, TH2, TIWE, and EQUIX) have been conducted at 0°N 140°W since 1984 (Table 3). Lien et al. [1995] summarized and compared the first three experiments and reported different levels of turbulence in response to surface forcing, background shear and stratification, and effects of equatorial Kelvin waves, the El Niño, and shear waves. The weakest turbulent heat flux in the DCL $\sim$ $-10$ W m$^{-2}$, was observed during TH2 when winds were weak and during the latter part of TIWE when a Kelvin wave depressed the thermocline and the EUC vanished. Large turbulent heat fluxes, $-60 \sim -40$ W m$^{-2}$, were observed during TH1 and the first part of TIW, when the wind was relatively strong and the central equatorial Pacific had neither an El Niño nor La Niña.

Here, we compare vertical profiles of $\varepsilon$, $K_p$, $N^2$, and $S^2$ observed during the four microstructure experiments (Figure 9). Turbulent kinetic energy dissipation rate was most intense, $>10^{-6}$ W kg$^{-1}$ in the upper 90 m, during EQUIX, which was 5–10 times that measured during TH1, 10 times TIWE, and more than 10 times TH2. Below the EUC core, $\varepsilon = 10^{-9} - 10^{-8}$ W kg$^{-1}$, similar during all four experiments. During EQUIX, $K_p$ decreased from $10^{-2}$ m$^2$ s$^{-1}$ at 25 m to $10^{-3}$ m$^2$ s$^{-1}$ at 90 m depth, twice the TH1 and TIWE values, and 10–100 times the TH2 values.

During TH2 the turbulence mixing was relatively weak, likely due to strong background stratification and weak shear variance (Figures 9c and 9d). The weaker shear variance in TIWE compared with TH1 and EQUIX may also explain the weaker observed turbulence.

During EQUIX, $\varepsilon$ was 5–10 times that measured during TH1, although $N^2$ and $S^2$ were nearly identical (Figures 9c and 9d). Both EQUIX and TH1 experiments took place during TIWs (Figure 10). The TH1 experiment in 1984 was conducted during a northward TIW phase, when the meridional current averaged over 10–80 m depth was $\sim 0.5$ m s$^{-1}$. The EQUIX experiment captured nearly the full cycle of a TIW and the meridional current amplitude averaged over 10–80 m depth was 0.6 m s$^{-1}$. The TIW intensity during EQUIX was greater than during TH1. Could the different observation period within TIWs or the slightly stronger TIW amplitude explain the higher turbulence mixing during EQUIX? Further observations and numerical model studies are needed.

7. Summary

Measurements of turbulent mixing and internal waves were made during October and November 2008 at 0°N 140°W using shipboard microstructure profilers and moored sensors. A large-amplitude TIW propagated westward across the experimental site, modulating turbulent mixing, shear variance, stratification, currents, temperature, and salinity. Results from analysis of measurements are summarized as follows.

1. Deep-cycle turbulence: Turbulence mixing rates were 1–2 order of magnitudes greater than previous microstructure observations at the same place. Average turbulent kinetic energy dissipation rates increased from $\sim 10^{-7}$ W kg$^{-1}$ during the day to $10^{-6}$ W kg$^{-1}$ at night. The average turbulent heat flux was $\sim 500$ W m$^{-2}$ and average $K_p$ was $10^{-5} - 10^{-2}$ m$^2$ s$^{-1}$. 

Figure 7. An event of enhanced internal wave activity and turbulence mixing below the nighttime mixed layer: (a) turbulent kinetic energy dissipation rate $\varepsilon$ (color shading) observed by a shipboard microstructure profiler and isopycnal fluctuations (white curves) observed from CTD sensors on the EQUIX mooring 27 and 28 October and (b) expanded view from within the black box shown in Figure 7a. The blue curve indicates the base of the surface mixed layer. CTD data are low-pass filtered at 10 min.
TIW phase modulates flow: The reduced shear squared, surface mixed layer depth, thickness of the DCL, vertical penetration of the deep-cycle turbulence, and the turbulent kinetic energy dissipation rate were largest during the TIW N→S phase. The bases of the surface mixed layer and of the DCL were shallowest during the TIW S phase.

Upper core layer: A strong turbulent layer about 50-m thick was present immediately above the EUC core during the TIW S phase. UCL turbulence was likely triggered by the mean shear associated with the EUC modulated by the TIW. The UCL turbulence was separated from the deep-cycle turbulence by a 10-m layer of weak shear and strong stratification during the S phase, suggesting it is not surface forced. Within the UCL, \( K_r \approx 10^{-3} \text{ m}^2 \text{ s}^{-1} \) and the turbulent heat flux was \( \sim -300 \text{ W m}^{-2} \). The UCL was not observed in previous microstructure experiments, TH1, TH2, and TIWE, likely because EQUIX was the first experiment where microstructure measurements were taken during the TIW S phase.

Vertical penetration of enhanced shear: A 10-m-thick layer of enhanced zonal shear variance was observed immediately below the nighttime convective surface mixed layer. After the surface mixed layer reached its equilibrium depth, this layer of enhanced shear continued descending and merged with the strong zonal shear associated with the EUC. This enhancement of shear variance in the entrainment layer has not been observed by previous microstructure experiments, likely due to inadequate ADCP vertical resolution.

Comparison with previous microstructure measurements: The turbulent kinetic energy dissipation rate \( \varepsilon \), eddy diffusivity \( K_r \), and the turbulent heat flux \( J_q \) were larger during EQUIX than in previous microstructure experiments, TH1, TH2, and TIWE, likely because EQUIX was the first experiment where microstructure measurements were taken during the TIW S phase.

Figure 8. Time series of hourly averages of (a) turbulent kinetic energy dissipation rate \( \varepsilon \), (b) total shear squared \( S_h^2 \) and \( N^2 \), (c) reduced shear squared \( S_h^2 - 4N^2 \), and (d) rms isopycnal displacement \( \langle \sigma_n \rangle \). All variables are averaged vertically within the 20 and 50-m depth range, excluding the surface mixed layer. Figures 8b–8d are produced from mooring data, whereas Figure 8a is from shipboard microstructure data.

Table 3. Comparison of Previous Microstructure Observations at 0° 140°W

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
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<tbody>
<tr>
<td>TIW</td>
<td>strong</td>
<td>weak</td>
<td>strong</td>
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<td>strong</td>
</tr>
<tr>
<td>Kelvin waves</td>
<td>absent</td>
<td>absent</td>
<td>middle crest</td>
<td>absent</td>
<td>strongest</td>
</tr>
<tr>
<td>Deep cycle</td>
<td>strong</td>
<td>weak</td>
<td>strong</td>
<td>weak</td>
<td>weakest</td>
</tr>
<tr>
<td>Heat flux from surface mixed layer</td>
<td>60 W m⁻²</td>
<td>10 W m⁻²</td>
<td>40 W m⁻²</td>
<td>10 W m⁻²</td>
<td>400 W m⁻²</td>
</tr>
</tbody>
</table>

*aThis table is an extension of Table 1 in Lien et al. [1995]. The TIWE experiment is divided into two periods of different phases of an equatorial Kelvin wave.*
in the equatorial Pacific. Weaker turbulence in TH2 and TIWE can be explained by the weaker reduced shear squared. Although $Sh^2$, $N^2$, reduced shear squared, surface wind-forcing, and equatorial conditions were similar in TH1 and EQUIX, the turbulence kinetic energy dissipation rate during EQUIX was 5–10 times larger than in TH1.

Equatorial turbulence varies strongly as a function of TIW phase. To parameterize turbulence mixing accurately in

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Figure 9. Averaged vertical profiles of (a) turbulence kinetic energy dissipation rates, (b) eddy diffusivities, (c) buoyancy frequency squared, (d) total shear squared, and (e) the reduced shear squared observed in four microstructure experiments, TH1 (black), TH2 (cyan), TIWE (purple), and EQUIX (red).

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Figure 10. (a) Daily averaged meridional velocity averaged between 10 and 80 m depth at 0°N 140°W in 1984 (thin curve) and in 2008 (thick curve), (b) depth-time contour plot of meridional velocity in 1984, and (c) depth-time contour plot of meridional velocity in 2008. Periods of TH1 and EQUIX experiments are labeled on the top of Figures 10b and 10c, respectively. These plots are generated using TOGA TAO mooring data before 23 October and EQUIX mooring data after 23 October. Asterisks on the left edges of Figures 10b and 10c mark the depths of current meters on the TOGA TAO mooring.
the equatorial Pacific, numerical models must simulate details of this TIW variability correctly.

Appendix A: Definition of the Deep Cycle Layer

[57] In previous analyses [e.g., Lien et al., 1995], a threshold value of mean gradient Richardson number, \( Ri = N^2/S\theta^2 \), was used to define the base of the DCL. However, the presence of a newly discovered turbulent layer immediately above the EUC core, referred to as the upper core layer (UCL; section 4.2), presents a more complicated situation in this data set and we found that different \( Ri \) criteria were needed to define the base of the DCL (not shown). We have reconsidered the nature of the DCL, which is most fundamentally defined by the daily cycle in \( \varepsilon \) beneath the mixed layer and here use the time derivative of turbulent kinetic dissipation rate, \( \varepsilon/dt \), to define the base of the DCL. First, \( \varepsilon \) was averaged at 6-h intervals to smooth high-frequency fluctuations (Figure A1a) and then \( d\varepsilon/dt \) computed at each depth from this series (Figure A1b). This aided identification of the penetration of daily varying \( \varepsilon \) and we subjectively chose the greatest depth of this penetration from Figure A1b. This provides a single value every day. Further interpolation was performed to derive the series shown in, for example, Figure 3i.

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References


