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# **Geophysical Research Letters**

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#### **Key Points:**

- Subsurface tropical instability waves, with zonal velocity oscillation peaking at 70–90 m, are identified in the eastern equatorial Pacific
- The waves have periods of 5–20 days and amplitudes of 0.1–0.2 m/s and can persist for 3–7 months from July to the following February
- The waves can induce periodically enhanced and reduced shear and hence mixing at ~50 m and above the core of the Equatorial Undercurrent

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#### LIU ET AL.

# The Subsurface Mode Tropical Instability Waves in the Equatorial Pacific Ocean and Their Impacts on Shear and Mixing

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**Abstract** The tropical instability waves (TIWs) in the eastern tropical Pacific have generally been considered as surface-intensified structures resembling the first baroclinic mode. Here, we report on the existence of subsurface-intensified TIWs on the equator. These TIWs are primarily manifested in zonal velocities, inducing maximum velocity oscillations at 70–90 m depth with amplitudes of 0.1–0.2 m/s and periods of 5–20 days. They account for ~20% of the variance at 5- to 30-day periods, with another ~50% being contributed by the surface-intensified TIWs. These waves are most significant during the TIW seasons; they are energized in part by barotropic instabilities and usually last for 3–7 months. Via interacting with the mean flow, they can induce strong out-of-phase shear changes between ~50-m depth and just above the Equatorial Undercurrent core and may lead to complex diapycnal mixing structures. Their horizontal structures, generation mechanism(s), and large-scale impacts remain to be disclosed.

**Plain Language Summary** The eastern equatorial Pacific is an area of intense ocean heat uptake due to the strong equatorial Sun. The fate of this heat depends on turbulent mixing processes in the upper ocean: heat may be returned quickly to the atmosphere or be carried into the deeper ocean and stored for many years, with obvious consequences for climate. The same is true of other important water properties such as  $CO_2$  content. Equatorial turbulence originates largely with vertically sheared currents. One important mechanism for this is tropical instability waves (TIWs), 1,000-km waves that generate and amplify vertical shear (i.e., vertical differences in the horizontal current), which in turn generates the turbulence that mixes heat downward. Previous studies have shown that TIWs concentrated at the ocean surface carry the most energy. Here, we show that TIWs focused below the surface, while less energetic, can carry a disproportionate fraction of the shear, and it is of course that shear that drives turbulence and the resulting fluxes of heat,  $CO_2$  and other properties. We describe the times of the year when these subsurface TIWs are strongest, the periods at which they oscillate, and the depths at which they generate enhanced shear.

# **1. Introduction**

Tropical instability waves (TIWs) are prominent mesoscale features with strong oscillating velocities (>1 m/s) confined in the central and eastern equatorial Pacific Ocean (and also Atlantic Ocean; e.g., Legeckis, 1986). They affect the oceanic energy cascades and induce both lateral and vertical heat transports (e.g., Menkes et al., 2006; Moum et al., 2009). TIWs also affect regional air-sea interactions by inducing rapid changes in latent heat fluxes and thus in the wind field through the resulting sea surface temperature anomalies (e.g., Wei et al., 2018). Therefore, they have attracted intense research efforts over the past several decades. It is increasingly clear that there exist (at least) two modes of TIWs in the eastern equatorial Pacific: One is on the equator and the other is to the north. Around the equator, Halpern et al. (1988) observed waves



in the upper 100–150 m that had a central period of 20 days and were largely antisymmetric about the equator, resembling Yanai waves. North of the equator, Flament et al. (1996) observed a vortex-like structure centering at ~5°N with different propagation speed from the equatorial mode. Subsequent work revealed that those two modes of TIWs have characteristic periods of 10–25 and 28–35 days, respectively (Bryden & Brady, 1989; Flament et al., 1996; Halpern et al., 1988; Kennan & Flament, 2000; Malardé et al., 1987; McPhaden, 1996; Miller et al., 1985; Musman, 1989; Périgaud, 1990; Qiao & Weisberg, 1995). Lyman et al. (2007), using empirical orthogonal function (EOF) analysis and linear models, showed that these TIWs have characteristics similar to a surface-intensified unstable Yanai wave and an unstable first meridional, first baroclinic mode Rossby wave, respectively. More recently, Liu et al. (2019) termed the two modes as the equatorial and vortex modes of TIWs, respectively, and constructed their horizontal structures using reanalysis data.

The TIWs have been shown to substantially impact diapycnal mixing in the upper ocean by generating additional vertical shear. During the TIW event in October–November 2008, Moum et al. (2009) observed stronger diapycnal mixing than the observations that did not encounter TIWs. They attributed the enhanced mixing to the vertical shear induced by the TIW-associated meridional velocity. Holmes and Thomas (2015) found instead that the TIW-associated zonal velocity contributes most of the vertical shear and argued that the meridional gradient of the TIW-associated meridional velocity should amplify the vertical shear of the zonal velocity via vortex stretching. Liu et al. (2019), on the other hand, argued that the westward velocity anomaly, which is associated with the tilted equatorial mode TIWs, induces strong vertical shear via its nonlinear interactions with the mean flow (to be discussed below in section 3.2). The results indicated that any complex vertical structure of the oscillating velocities of the TIWs, particularly from the zonal component, may have significant impacts on the structure of mixing due to the interaction with the mean flow.

At the same time, little attention has been paid to the vertical structures of the TIWs, let alone the modulation of mixing by such structures. (Lyman et al., 2007, is an exception who showed that both the equatorial and vortex modes of TIWs have a first baroclinic mode-like, surface-intensified structure.) Nevertheless, results from some previous studies do indicate the existence of vertically complex, higher mode-like structures. For example, Halpern et al. (1988) and Luther and Johnson (1990) found peaks of variance of anomalous zonal velocity at 10–50 days at ~80-m depth; these were particularly significant at 1°N. Peters et al. (1991) found "shear waves" above the thermocline with a vertical wavelength of ~50 m. Qiao and Weisberg (1995) found enhanced velocity variance and covariance at subsurface layers (~70 m). Moum et al. (2009) and Inoue et al. (2012) reported a weakened shear layer around 50 m and enhanced shear and mixing between 80 m and the eastward Equatorial Undercurrent (EUC) core at ~110 m. (The letter layer was referred to as the turbulent upper core layer; the EUC core denoting the eastward velocity maximum). Liu et al. (2016) found frequent occurrence of shear instability (indicating stronger shear) in and below the center of the EUC core. All of these results suggest complex vertical structures of the TIWs and the resulting mixing.

Our goal, therefore, is to draw attention to the existence of deeper mode TIWs from observations of velocity at 140°W on the equator (Eq 14 0 W hereafter), a hotspot of TIW occurrence. We will show that these waves can induce significantly increased/decreased shear in the upper thermocline and above the EUC core, potentially impacting the vertical structure of diapycnal mixing.

### 2. Data

Hourly averaged temperature and velocity data, daily averaged depth of the 20 °C isotherm, and long-term mean salinity data at Eq 14 0 W are used. These data are collected by the Tropical Atmosphere and Ocean mooring array (McPhaden, 1995) and freely downloaded from http://www.pmel.noaa.gov/tao/data\_deliv. The velocity data have a vertical resolution of 5 m, while the temperature was measured at nonuniform vertical intervals, with an average internal of <10 m above 80m depth and of ~20 m between 80 and 140 m depths. The original hourly salinity data are sparse and hence replaced by their long-time mean (Smyth & Moum, 2013). All the data are carefully interpolated and/or extrapolated into 1-m grids (the interpolation and extrapolation methods are described in detail in Liu et al., 2016). Hourly density profiles are then calculated from these data. The time period for the analysis is 2000–2010.



**Figure 1.** (a, c, and e) Square of 5- to 30-day band passed u' for three TIW seasons (August–February of 2000/2001, 2005/2006, and 2008/2009, respectively). The red and black curves at ~100 m represent 10-day-moving-averaged depths of the 20 °C isotherm (representing the thermocline center) and the EUC core, respectively. (b, d, and f) Mean zonal (blue), meridional (green) velocities (in m/s), squared shear (black), and 4 times squared buoyancy frequency (red) calculated from mean velocity and density profiles respectively (in  $10^{-3} \text{ s}^{-2}$ ). The velocities and density are averaged over corresponding TIW seasons.

### 3. Results

## 3.1. Peaks of Zonal Velocity Anomalies in Subsurface Layers

We first show that the anomalous velocities at the typical period band of TIWs vary significantly with depth and have peaks in *subsurface* layers (Figure 1). The zonal (u) and meridional (v) components of the velocity are first band-pass filtered at 5–30 days at each depth (before band-pass filtering, occasional data gaps were filled with the 11-year mean), and then the square of the resulting zonal velocity anomaly,  $u'^2$ , is calculated. During the 11-year period (2000–2010), subsurface maxima of  $u'^2$  were detected in every TIW season (defined here as a 7-month period beginning 1 August). The signal was strongest during the TIW seasons of 2001/2002, 2005/2006, and 2008/2009. Further analysis will focus on these three examples, which we denote as *Case 1, Case 2*, and *Case 3*, respectively. (A common structure of the subsurface waves over the entire 11-year period will be derived in section 3.3.) The subsurface-intensified feature is distinctly different from the well-recognized surface-intensified, first mode-like TIWs in these three examples.

In order to identify the specific periods and the depth dependence of the waves, we further computed the power spectral density (PSD) of the hourly velocities at each depth for the three example periods. First, the meridional component (Figure 2, left column) shows broad band periods (10–30 days) with a PSD peak at ~16–18 days, and the PSD is surface intensified and gradually decay till the thermocline center (at ~100 m depth). In contrast, the zonal component (Figure 2, right column) does not have a single peak within the broad period band (10–30 days), nor a sole surface-intensified, decaying-with-depth PSD pattern. Instead, it shows several PSD peaks distributed among different depths and periods: peaks at 20–24 days at 50–100 m in *Case 1* (Figure 2a), 14–17 days at 50–80 m in *Case 2* (Figure 2c), and 18–23 days at 30–80 m in



**Figure 2.** PSD (shading) for hourly (a, c, and e) *v* and (b, d, and f) *u* as a function of depth and period. The top, middle, and bottom panels are for the three 7-month-long periods (August to February) denoted in inset. Each of *u* and *v* is normalized by its absolute maximum before calculation.

*Case 3* (Figure 2e). The periodic zonal velocities can be clearly distinguished from the surface-intensified TIWs. We will term these waves as the subsurface mode TIWs (subTIWs) hereafter.

#### 3.2. The Oscillating Velocities and Shears of the SubTIWs

We further explore the characteristics of the three example subTIWs. We first obtain the oscillating velocities (in both components, denoted as u' and v', respectively) by band-pass filtering in their specific period bands (Figures 3a–3c). The waves are now clearly manifested in u'. Their amplitude can reach 0.2 m/s for *Case 1*, 0.1 m/s for *Case 3*, and between 0.1 and 0.2 m/s for *Case 2*, which is all comparable to their meridional counterparts at the same periods. The largest u' occurs at subsurface, around 75, 80, and 60 m depths, respectively. In comparison, v' is surface intensified. The amplitude of u' drops from the subsurface maxima both upward and downward; the upper bounds can be at the sea surface, but mainly upward from ~20–50 m above the subsurface maxima, little decrement in amplitude is seen; whereas the lower bounds are always around 100 m depth, near the EUC core.

All the waves show an evolutionary cycle. The *Case 1* wave first appeared in late July 2000 (not shown), grew until the end of October, then started to decay (Figure 3a), disappearing at the end of February 2001 (not shown). Figure 3a shows its mature state, extending from September to December 2000. The *Case 2* wave emerged in late July 2005 and grew until mid-November before it started to decay and disappeared at the end of January 2006. The *Case 3* wave appeared in September 2008 and grew till the end of November (encompassing the period of Moum et al.'s, 2009, observations of enhanced turbulence). Overall, the growth period lasts for 3–5 months, while decay takes 2–3 months, totally covering the entire TIW season.

From Figures 3a–3c we see that u' and v' are almost always in phase, with positive (negative) u' corresponding to positive (negative) v', resulting in positive covariance, u'v'. This characteristic might be critical for the



**Figure 3.** The (a) 20–24 days, (b) 14–17 days, (c) 18–23 days band passed u' (color shading) and v' (contours), vertical shear of u' (d, f), the resulting changes of shear squared  $\Delta S_u^{'2}$  (g–i), and reduced shear squared  $\Delta S_{ured}^{'2}$  (j–l), for the three cases. In (a)–(c), the contour interval is 0.1 m/s, with solid (dashed) contours for positive (negative) values. The red and black curves at ~100 m show the 20 °C isotherm and the EUC core as in Figure 1.

growth of the waves. Considering that the meridional gradient of the mean zonal flow,  $U_{y}$ , is generally negative at the study site (Johnson et al., 2002), the shear production of wave energy (i.e., barotropic energy conversion rate),  $- \langle u'v' \rangle U_{y}$ , is mostly positive and thus favors the growth of the waves (here *U* stands for the mean zonal flow, and  $\langle \rangle$  denotes time average). From Figures 3a–3c, we see that the amplitude of either u' or v' grows during the interaction period. This suggests that the zonal velocity oscillations could be generated and sustained by barotropic instabilities of the mean flow; note, however, that other sources (e.g., the baroclinic energy conversion) for the growth of the observed subTIWs cannot be ruled out, and the observed wave decay might be due mainly to the seasonal weakening of the EUC in the winter (not shown), which removes the energy source for the instabilities.

One of potential impacts of the subTIWs may be the vertical shear and thus diapycnal mixing they induce. The vertical shears are quite prominent in the upper 120 m and manifest as wave-like pattern (Figures 3d–3f). The magnitude of shear is large above and below the peak of the oscillating velocities, showing shear waves with a vertical half wavelength of about 50 m, an estimated distance between the upper and lower shear peaks, which are at ~60 and ~110 m, respectively, for *Case 1*, ~50 and ~100 m for *Case 2*, and ~70

background flow, U.)

and ~100 m, respectively, during November to December for *Case 3*. Owing to their small vertical scales, the subTIW-associated shear could be up to  $0.75 \times 10^{-2} \text{ s}^{-1}$ , comparable to that due to the surface-intensified TIWs. Particularly, the shear magnitude is larger in the lower than the upper portion of the zonal oscillating velocity peaks; enhanced shear extends into the central layers of the EUC and thermocline. Moreover, the subTIWs cause nearly out-of-phase shears in the upper and lower shear layers at the same time, in drastic contrast to the surface-intensified TIWs that generally cause shears with a same sign: the westward (eastward) oscillating velocity results in negative (positive) shear above the thermocline.

We now demonstrate that the two-layer shear pattern of the subTIWs is critical to generating complex shear structures. As for the surface-intensified TIWs (Liu et al., 2019), this effect can be achieved by the interactions of the zonal subTIW shear and the zonal mean flow shear (the meridional flow is close to zero; Figures 1a, 1c, and 1e). The subTIW induced change of shear squared, which is the denominator of the Richardson number (a proxy for shear instability occurrence), can be expressed by the nonlinear interactions

of the two processes:  $\Delta S'_{u}^{2} = \left(\frac{\partial(U+u')}{\partial z}\right)^{2} - \left(\frac{\partial U}{\partial z}\right)^{2} = \left(\frac{\partial u'}{\partial z}\right)^{2} + 2\frac{\partial U}{\partial z}\frac{\partial u'}{\partial z}$ . At the study site,  $\frac{\partial U}{\partial z}$  is negative above the EUC core (Figures 1a, 1c, and 1e); therefore, subTIWs could induce enhanced shear and more mixing when  $\frac{\partial u'}{\partial z}$  is negative (because  $2\frac{\partial U}{\partial z}\frac{\partial u'}{\partial z} > 0$ ), that is, in the upper portion of a westward velocity anomaly or lower portion of an eastward velocity anomaly; and vice versa. (Here we used the 30-day low-passed velocities as the

The calculated  $\Delta S'_{u}^{2}$  are shown in Figures 3g–3i. It is seen that the subTIWs can induce changes of shear squared, with a magnitude (~1–3 × 10<sup>-4</sup> s<sup>-2</sup>) comparable to the background values (Figures 1a, 1c, and 1e), primarily in two layers. One layer with significant  $\Delta S'_{u}^{2}$  is 20–30 m above the EUC core, which is almost coincident with the maximum stratification in the thermocline. A shallower layer with significant  $\Delta S'_{u}^{2}$ , usually with sign opposite to the former, is located at 25- to 80-m depths, varying from case to case. (This layer lay within 40–70, 25–70, and 25–80 m depths, respectively, for the three cases.) *Case 1* shows a well-defined maximum of  $\Delta S'_{u}^{2}$  at ~60 m and the magnitude of the shear change decreases both upward and downward. *Case 2* shows a broad peak in  $\Delta S'_{u}^{2}$  at about 70 m, but it decays slowly toward the upper layers.

At certain phases, the shear could be weakened at ~70 m and enhanced just above the EUC core, which may explain the observed similar shear structures during the EQUIX experiment (Inoue et al., 2012). Note that the signs of  $\Delta S'_{u}^{2}$  are not exactly out-of-phase between the two layers, possibly due to the gradual vertical phase shift of the waves.

The reduced shear squared associated with the subTIWs,  $\Delta S'^2_{ured}$ , which is defined as  $\Delta S'^2_{ured} = \Delta S'^2_u - 4N^{2'}$  and represents the ability of the waves to induce mixing via both shear and strain, is also calculated (Figures 3j–3l). Here,  $N^{2'}$  is the anomalous buoyancy frequency squared band passed at the specific periods. When  $\Delta S'^2_{ured} > (<)0$ , it stabilizes (destabilizes) the flow. Above ~50 m, the amplitudes of  $\Delta S'^2_{ured}$  are enhanced relative to  $\Delta S'^2_u$  (indicating dominant effects of the surface-intensified TIWs); below, the modulation by the N'2 is also significant, but varies from case to case: In *Case 1*, the sign is reversed between 45 and 70 m depths, and the amplitude reduced between 75 and 120 m. In *Cases 2* and 3, the pattern keeps similar to  $\Delta S'^2_u$  but the amplitude is enhanced till 1 December, showing a more obvious vertical phase change. We note the complexity is due to that a large portion of  $N^{2'}$  is caused by the stronger, surface-intensified TIWs at the same periods. Nevertheless, at specific times, out-of-phase  $\Delta S'^2_{ured}$  between ~50 m and just above the EUC core emerged, like observed by the EQUIX experiments.

#### 3.3. A Common Structure of the SubTIWs and Its Temporal Variations

In the previous sections we have used three example cases of subTIWs to show their basic characteristics. Here we extend the analysis to 11 years (2000–2010) to show that the subTIWs are regular processes in the study area. We applied an EOF analysis to the 11-year long, 5- to 30-day band passed u' to investigate the principal modes for variations of such periods (the band of 5–30 days encompasses the typical periods for the surface-intensified TIWs). We repeated this analysis for the three cases in 7-month-long periods (August–February). The first two EOF modes (EOF1 and 2) are shown in Figure 4a.



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**Figure 4.** (a) EOF1 (solid) and EOF2 (dashed) of the 5–30 days band passed *u'*. Thick black curves are for 2000–2010 (132 months), while the green, blue, and red curves are for August–February (7 months) of 2000/2001, 2005/2006, and 2008/2009, respectively. The variance explained by each mode is denoted in the legend. (b) PSD of PC1 and PC2 of the period 2000–2010 (thick solid and dashed curves, respectively, with the 95% confidence level denoted by thin solid and dashed curves). (c) Wavelet power spectrum (log10) of PC1 for the period of 2000–2010. (d) The same as (c), but for PC2. (e) Monthly climatology of the wavelet spectral power (log10) of PC1 (solid) and PC2 (dashed) at period of 15 days averaged over 2000–2010.

EOF1 shows the surface-intensified structure of u'. The velocity magnitude is nearly uniform between the surface and 50-m depth. Below this it decreases, vanishing near 125 m depth. This mode explains 51% of the total variance in the 5- to 30-day band for the 11-year period and ~64% for the 7-month sample periods. It well describes the zonal component of the surface-intensified equatorial mode TIW, which is similar to its meridional counterpart (see Figure 1f of Liu et al., 2019). EOF2 explains 19% for the 11-year period and 15–18% for the 7-month periods. It shows a vertically wave-like structure: The u' peak occurs at ~75–85 m with larger amplitude, while the trough occurs at ~135–150 m with smaller amplitude, and it changes phase at ~100–125 m. Unlike the first mode, there is no similar v' component. Also, the vertical variation of u' between the wave trough and peak is larger than that above the peak, indicating stronger shear of the former than the latter, resembling the shear pattern in Figures 3d–3f. Therefore, this mode of u' describes the oscillating velocities shown in Figures 3a–3c and the PSD peaks in Figures 2a, 2c, and 2e, that is, the subTIWs.

PSD and wavelet analysis were conducted to the principal components of the two EOFs for the 11-year period (Figures 4b–4d). It is found that EOF1shows significant periods of 5–21 days, and peaks at ~16 days, while EOF2 has periods of 5–20 days, with roughly constant amplitude in the band 7–17 days (Figure 4b). Both EOF1 and EOF2 occur in all the study years (Figures 4c and 4d). To investigate their temporal variations, wavelet spectral power of the two principal components (properties in Figures 4c and 4d) at period of 15 days were selected and made monthly climatology over 2000–2010 (Figure 4e). It turns out that both modes show significant seasonal variations, prominent in August to next February—the wellrecognized TIW seasons. Specifically, EOF1 is strongest in October and has a second peak in February; while EOF2 is highest in February and has a second peak in October. In January and February, the two modes have similar magnitudes, while in August through December, the amplitude of EOF2 is ~20% of EOF1.

### 4. Summary and Discussion

The vertical structure of the TIWs in the eastern tropical Pacific Ocean has been identified previously as surface-intensified, first baroclinic mode. Here we report on the subsurface-intensified TIWs at the equator, which manifest as prominent zonal velocity oscillations. These oscillations have amplitude of 0.1–0.2 m/s and peak at 70- to 90-m depth, so that are referred to as subsurface mode TIWs (subTIWs). They have significant period of 5–20 days, and it can extend to more than 20 days in some cases, overlapping with that of the first mode TIWs at the equator. Both u' and v' of the subTIWs tend to be in-phase and lead to positive correlation u'v'. Usually,  $U_y < 0$  here, which together results in positive barotropic energy conversion rate. The subTIWs are most significant during the commonly recognized TIW seasons and can last for 3–7 months. EOF analysis of the zonal velocity anomalies at the period of 5–30 days confirms that the subTIWs can be represented by EOF2, which explains ~20% of the variance (while EOF1 represents the surface-intensified equatorial mode TIWs and explains ~50% of the variance).

The subTIWs have a smaller vertical scale (a vertical half wavelength of about 50 m) compared to the first mode TIW and the mean flow, thus leading to comparable shear  $(1 \times 10^{-2} \text{ s}^{-1})$  to the latter. Particularly, the shears have opposite signs above and below the velocity peak, being often larger below than above the peak. The shears can interact nonlinearly with the shears of the mean flow and lead to great changes of total shear above the EUC core and at layers of 50–80 m as well. At certain phases, enhanced shear may occur just above the EUC core with weakened shear at ~50 m, which may explain the observed complex shear and mixing structures in the EQUIX experiment (Inoue et al., 2012; Moum et al., 2009).

The subTIWs therefore may play an important role in vertical heat transport, particularly in such a region being marginally unstable in the upper ~60 m (inferred from  $S^2 \approx 4N^2$  in Figures 1a, 1c, and 1e; Smyth & Moum, 2013). In addition, the subTIWs' horizontal structures, generation mechanisms, and large-scale impacts should also be of great importance. Those properties cannot be confidently determined yet due to the lack of observations. Regarding its generation, u' could be from an inertia-gravity wave while v' from a Yanai wave. Adopting the dispersion relationship of the equatorial waves (Philander, 1978), Peters et al. (1991) ever argued that the shear waves they observed in a non-TIW season (similar to the subTIWs here) could be inertia-gravity waves. Specifically, how the subTIWs dynamically relate to the surface-intensified TIWs are worth further exploration, particularly based on numerical simulations.

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### References

Bryden, H. L., & Brady, E. C. (1989). Eddy momentum and heat fluxes and their effects on the circulation of the equatorial Pacific-Ocean. Journal of Marine Research, 47(1), 55–79. http://doi.org/10.1357/002224089785076389

Flament, P. J., Kennan, S. C., Knox, R. A., Niiler, P. P., & Bernstein, R. L. (1996). The three-dimensional structure of an upper ocean vortex in the tropical Pacific Ocean. *Nature*, 383(6601), 610–613. http://doi.org/10.1038/383610a0

Halpern, D., Knox, R. A., & Luther, D. S. (1988). Observations of 20-day period meridional current oscillations in the upper ocean along the Pacific equator. Journal of Physical Oceanography, 18(11), 1514–1534. https://doi.org/10.1175/1520-0485(1988)0182.0.Co;2

Holmes, R. M., & Thomas, L. N. (2015). The modulation of equatorial turbulence by tropical instability waves in a regional ocean model. Journal of Physical Oceanography, 45(4), 1155–1173. http://doi.org/10.1175/JPO-D-14-0209.1

Inoue, R., Lien, R. C., & Moum, J. N. (2012). Modulation of equatorial turbulence by a tropical instability wave. *Journal of Geophysical Research*, 117, C10009. http://doi.org/10.1029/2011jc007767

Johnson, G. C., Sloyan, B. M., Kessler, W. S., & McTaggart, K. E. (2002). Direct measurements of upper ocean currents and water properties across the tropical Pacific during the 1990s. Progress in Oceanography, 52, 31–61. https://doi.org/10.1016/S0079-6611(02)00021-6

Kennan, S. C., & Flament, P. J. (2000). Observations of a tropical instability vortex. Journal of Physical Oceanography, 30(9), 2277–2301. http://doi.org/10.1175/1520-0485(2000)0302.0.CO;2

Legeckis, R. (1986). Long waves in the equatorial Pacific and Atlantic Oceans during 1983. Ocean-Air Interactions, 1, 1-10.

Liu, C., Köhl, A., Liu, Z., Wang, F., & Stammer, D. (2016). Deep-reaching thermocline mixing in the equatorial Pacific cold tongue. Nature Communications, 7(1), 1–11. http://doi.org/10.1038/ncomms11576

Liu, C., Wang, X., Köhl, A., Wang, F., & Liu, Z. (2019). The northeast-southwest oscillating equatorial mode of the tropical instability wave and its impact on equatorial mixing. *Geophysical Research Letters*, 46(1), 218–225. http://doi.org/10.1029/2018gl080226

- Luther, D. S., & Johnson, E. S. (1990). Eddy energetics in the upper equatorial Pacific during the Hawaii-to-Tahiti shuttle experiment. Journal of Physical Oceanography, 20(7), 913–944. https://doi.org/10.1175/1520-0485(1990)020<0913:EEITUE>2.0.CO;2
- Lyman, J. M., Johnson, G. C., & Kessler, W. S. (2007). Distinct 17-and 33-day tropical instability waves in subsurface observations. Journal of Physical Oceanography, 37(4), 855–872. http://doi.org/10.1175/Jpo3023.1
- Malardé, J. P., Mey, P. D., Périgaud, C., & Minster, J. F. (1987). Observations of long equatorial waves in the Pacific Ocean by Seasat altimetry. *Journal of Physical Oceanography*, 17, 2273–2279. http://doi.org/10.1175/1520-0485(1987)0172.0.CO;2
- McPhaden, M. J. (1995). The tropical atmosphere ocean array is completed. Bulletin of the American Meteorological Society, 76(5), 739–744. https://doi.org/10.1175/1520-0477-76.5.739
- McPhaden, M. J. (1996). Monthly period oscillations in the Pacific north equatorial countercurrent. Journal of Geophysical Research, 101, 6337–6359. https://doi.org/10.1029/95JC03620
- Menkes, C. E. R., Vialard, J. G., Kennan, S. C., Boulanger, J. P., & Madec, G. V. (2006). A modeling study of the impact of tropical instability waves on the heat budget of the eastern equatorial Pacific. *Journal of Physical Oceanography*, 36(5), 847–865. https://doi.org/10.1175/ Jpo2904.1
- Miller, L., Watts, D. R., & Wimbush, M. (1985). Oscillations of dynamic topography in the eastern equatorial Pacific. Journal of Physical Oceanography, 15(12), 1759–1770. https://doi.org/10.1175/1520-0485(1985)0152.0.CO;2
- Moum, J. N., Lien, R. C., Perlin, A., Nash, J. D., Gregg, M. C., & Wiles, P. J. (2009). Sea surface cooling at the equator by subsurface mixing in tropical instability waves. *Nature Geoscience*, 2(11), 761–765. https://doi.org/10.1038/Ngeo657
- Musman, S. (1989). Sea height wave form in equatorial waves and its interpretation. *Journal of Geophysical Research*, 94, 3303-3309. https://doi.org/10.1029/jc094ic03p03303
- Périgaud, C. (1990). Sea level oscillations observed with Geosat along the two shear fronts of the Pacific north equatorial countercurrent. *Journal of Geophysical Research*, 95, 7239–7248. https://doi.org/10.1029/JC095iC05p07239
- Peters, H., Gregg, M. C., & Sanford, T. B. (1991). Equatorial and off-equatorial fine-scale and large-scale shear variability at 140°W. Journal of Geophysical Researchs, 96(C9), 16,913–16,928. https://doi.org/10.1029/91JC01317
- Philander, S. G. H. (1978). Instabilities of zonal equatorial currents, 2. Journal of Geophysical Research, 83(C7), 3679–3682. https://doi.org/ 10.1029/JC083iC07p03679
- Qiao, L., & Weisberg, R. H. (1995). Tropical instability wave kinematics-Observations from the tropical instability wave experiment. Journal of Geophysical Research, 100(C5), 8677–8693. https://doi.org/10.1029/95jc00305
- Smyth, W. D., & Moum, J. N. (2013). Marginal instability and deep cycle turbulence in the eastern equatorial Pacific Ocean. Geophysical Research Letters, 40, 6181–6185. https://doi.org/10.1002/2013gl058403
- Wei, Y., Kang, X., & Pei, Y. (2018). An empirical tropical instability wave-induced wind stress model in the equatorial Pacific and its incorporation into the ocean model. *Atmosphere-Ocean*, 56(5), 350–361. https://doi.org/10.1080/07055900.2018.1549016