Influence of ocean-atmosphere coupling on the properties of tropical instability waves

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[1] In this study we investigate how the modulation of surface wind-stress by tropical instability waves (TIWs) feeds back onto TIWs and plays a role in their fundamental properties. An ocean general circulation model is used, that reproduces qualitatively well the properties of TIWs when forced by climatological winds, although with a 30% underestimated amplitude. The ocean model is coupled to the atmosphere through a simple parameterization of the wind stress response to SST. The properties of the TIWs in the coupled simulations are compared with those without active coupling. Active coupling results in a negative feedback on TIWs, slightly reducing their temperature and meridional current variability, both at the surface and sub-surface. This reduced activity modulates the meridional heat and momentum transport, resulting in modest changes to the mean state, with a cooler cold tongue and stronger equatorial currents. *INDEX TERMS:* 3339 Meteorology and Atmospheric Dynamics: Ocean/atmosphere interactions (0312, 4504); 4231 Oceanography: General: Equatorial oceanography; 4572 Oceanography: Physical: Upper ocean processes; 4520 Oceanography: Physical: Eddies and mesoscale processes; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes. **Citation:** Pezzi, L. P., J. Vialard, K. J. Richards, C. Menkes, and D. Anderson (2004), Influence of ocean-atmosphere coupling on the properties of tropical instability waves, *Geophys. Res. Lett.*, *31*, L16306, doi:10.1029/2004GL019995.

1. Background

[2] Tropical Instability Waves (TIWs) appear in the tropical Pacific and Atlantic oceans as westward-propagating oscillations of the temperature front between cold water of the equatorial upwelling and warmer water to the north [*Legeckis*, 1977]. They have a longitudinal scale of 1000–2000 km and propagation speed of about 30 cm s^{-1} to 60 cm s^{-1} [*Qiao and Weisberg*, 1995; *Chelton et al.*, 2000]. Although there is no consensus on the exact nature of these instabilities, lateral shear associated with the equatorial undercurrent (EUC), south equatorial current (SEC), north equatorial countercurrent (NECC) and density gradients between the equatorial cold tongue and warmer water north of it are thought to be the main structures conducive to the appearance of these instabilities [e.g., *Cox*, 1980; *Philander*, 1978].

[3] Two studies using satellite data [*Liu et al.*, 2000; *Chelton et al.*, 2000] described the spatial patterns associated with the TIW signal: wind is accelerated over warm anomalies and decelerated over cold ones, producing centers of convergence and divergence collocated with maximum SST gradient regions. The convergence (divergence) centers in turn lead to increased (decreased) water vapor content in the lower layers of the atmosphere. These spatial patterns are consistent with the mechanism proposed by *Hayes et al.* [1989], who proposed that the modulation of the wind is linked to the impact of TIW temperature anomalies on the stability of the atmospheric boundary layer (ABL).

[4] In situ data analysed by *Hashizume et al.* [2002] is also consistent with this mechanism suggesting that the TIW signal propagates through the whole ABL modulating its vertical extent. However, *Hashizume et al.* [2001], and a modeling study by *Small et al.* [2003], suggest that the zonal pressure gradient driven by the temperature anomalies is also an important factor, as initially suggested by *Lindzen and Nigam* [1987].

[5] In this study, we will not focus on the detailed mechanism of the wind modulation by TIWs. Rather, we will investigate if the wind modulation by TIWs feeds back onto the properties of the TIWs themselves. To this end, we will compare TIW properties in a forced OGCM

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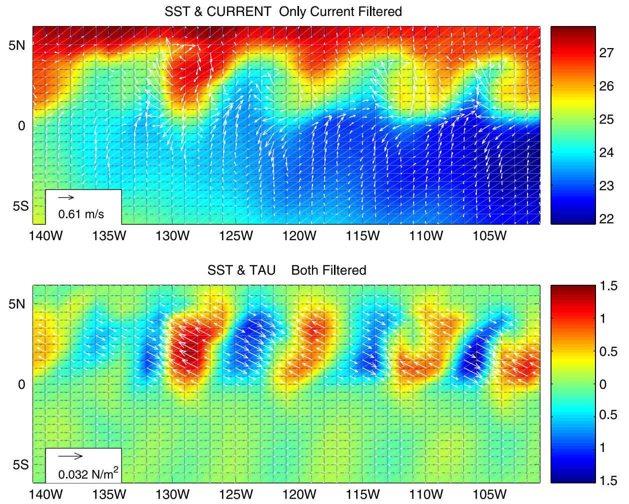

Figure 1. SST with filtered currents (upper panel). Filtered SST and filtered wind stress (lower panel). STD experiment.

simulation, with and without a simple parameterization of the wind-stress response to TIWs.

2. Experimental Setup

[6] We use the OPA OGCM [*Madec et al.*, 1998] in a tropical Pacific configuration, similar to *Vialard et al.* [2003] and *Pezzi and Richards* [2003]. The domain covers 30°S to 30°N and 130°E to 70°W, with realistic coastlines. The meridional resolution is 0.5° within 5°S–5°N smoothly increasing to 2° at the southern and northern boundaries. The zonal resolution is 1°. There are 31 levels, with 10 m resolution in the upper 150 m. The lateral mixing coefficient for tracers and momentum is 2×10^3 m^{2}s^{-1} and it is applied along isopycnal surfaces. Vertical mixing is parameterized using a 1.5 turbulent closure prognostic scheme.

[7] In order to investigate whether there is a feedback between the wind stress patterns and TIWs we assess the differences between a control and a number of coupled experiments. The control experiment is defined as follows. The ocean model is forced with October climatological wind stress, using a combination of scatterometer and in situ data, as in *Vialard et al.* [2003], and a relaxation towards October climatological SST observations [*Levitus and Boyer*, 1994a, 1994b] using a relaxation coefficient of -40 W.m^{-2}K^{-1}. October is chosen because it is the month of strongest TIW activity. The model is spun-up for 60 years, starting from rest with *Levitus and Boyer* [1994a, 1994b] temperature and salinity fields. At the end of the spin-up, the model reaches a statistically steady state. As in *McCreary and Yu* [1992], the only internal variability that appears in this experiment takes the form of TIWs, and will be described in the next section. Two extra years are run, and are used as the control (uncoupled) integration.

[8] The coupled experiments consist of introducing a very simple coupling parameterization. The wind stress is specified as follows:

$$\vec{\tau} = \vec{\tau_0} + \begin{pmatrix} \alpha\left(SST - \overline{SST}\right) \\ \beta\left(SST - \overline{SST}\right) \end{pmatrix} \qquad (1)$$

where $\vec{\tau_0}$ is the wind stress used for the CTL experiment. SST is the model instantaneous surface temperature and $\overline{SST}$ is the CTL time average at each grid point. Since TIWs are the only source of variability, this difference will be that produced by the TIW SST patterns. The active coupling region is restricted to an area encompassing the region of TIW activity, namely (9°S–9°N, 160°E–90°W). The α and β values in equation (1) (respectively -0.02 and -0.008) were computed from a statistical regression between the 10–80 days filtered Quikscat wind stress and observations of SST by the Microwave Imager (TMI) on board the Tropical Rainfall Measuring Mission (TRMM) at 140°W, 2°N (the region where the highest correlation (0.5) between these two data sets was found) covering the period 1999–2001. This is an approach similar to that used in *Hashizume et al.* [2001], but here it is applied to relate the wind stress (rather than wind) to SST. While we are aware that this is a crude approach, the results obtained with our simplified scheme produce wind stress anomalies consistent with observations, as will be seen in the next section.

[9] The coupling is applied at the end of the spin-up phase of the CTL experiment, and the model run for a further two years. The adjustment of the TIW field to the change in atmospheric forcing is relatively swift (less than 100 days).

[10] The coupled experiment above is named STD. Two sensitivity experiments with stronger coupling were run. Experiment MID was run with α and β multiplied by 1.5. Experiment HIG was run with α and β multiplied by 2.5. Only results from CTL, STD and HIG will be shown below, since MID always displayed a response to the coupling between those of STD and HIG.

3. Results

[11] In this section, we first show that TIWs in our experiments have properties consistent with observations and that our simple coupling approach reproduces qualitatively the wind response to TIWs. Then we assess how the coupling modifies TIW properties and investigate how changes in TIW properties feed back onto the mean state of the model.

3.1. The Simulated TIWs and Wind Response

[12] Figure 1 shows a snapshot of the SST, surface currents and wind stress in the region of TIW activity, for the STD experiment. The fields are filtered using a Finite Impulse Response (FIR) 2-D digital filter [e.g., *Polito et al.*, 2000], selecting zonal scales ranging from 5° to 25° and periods from 10 to 80 days.

[13] The model simulates the gross features of the cold tongue, as shown in Figure 1 (upper panel), and also exhibits a well defined cusp-shaped wave pattern similar to the TIW patterns described in the literature [*Chelton et al.*, 2000]. The phase propagation speed of the waves is around 30 cm s^{-1}, in the lowest part of the observed speed range [*Chelton et al.*, 2000; *Kennan and Flament*, 2000]. The period of TIWs is around 30 days, in good agreement with estimates from observations [*Qiao and Weisberg*, 1995]. Overall, the spatial pattern of SST variability and eddy kinetic energy in the control experiment (not shown) match those observed by *Baturin and Niiler* [1997] and *Chelton et al.* [2000]. However, the amplitude of these quantities in the model is about half that of the observations (i.e., the typical amplitude of TIW SST and current anoma-

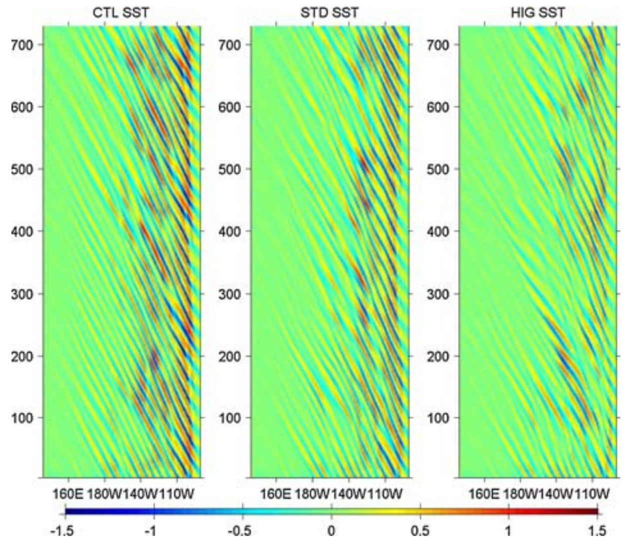

Figure 2. Filtered time-longitude SST displaying TIWs for the CTL, STD, and HIG experiments averaged over the latitudinal band from 1°N to 3°N. Units are °C.

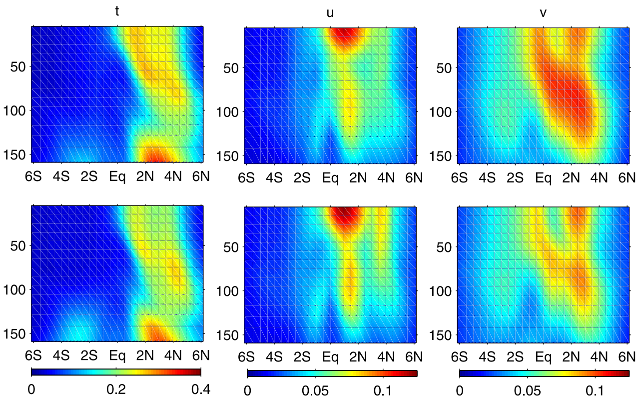

Figure 3. First and second row show the variability of the CTL and STD experiments, respectively, averaged over 150°W to 90°W. The standard deviation of T is on the left (°C), of u in the central column and of v on the right (m s^{-1}).

lies are 70% of those observed). We will discuss possible consequences of this in section 4.

[14] Figure 1 (lower panel) shows filtered wind stress and SST in experiment STD. The westward stress is increased over warm water and decreased over cold water. This results in convergence and divergence centers over the SST gradients, consistent with observations (compare Figure 4 of *Liu et al.* [2000] with Figure 1). The typical amplitude of wind stress anomalies in STD is 0.03 N m^{-2}. This is of the order of magnitude of observations by *Chelton et al.* [2001]. The simple linear relation that we use between SST and wind stress anomalies will however produce an underestimated wind stress modulation (roughly 70% of the observed one). Despite this, our simple coupling approach produces a response which is in reasonable agreement with observations, both in pattern and amplitude.

3.2. Impact of Coupling on TIW Variability

[15] The CTL experiment exhibits larger SST variability than the two coupled experiments, especially in the eastern portion of the domain, as shown in Figure 2. Although there are significant changes in the amplitude of TIWs, the wavelength and phase speed of the TIWs show little sensitivity to the coupling coefficient. Figure 3 allows a more quantitative estimate of the changes of temperature and current variability over the active TIW region. Active coupling results in a diminution of the temperature variability, especially above the thermocline and near the surface (Figure 3). The meridional velocity variability is also reduced, both close to the surface near the equator and around 100 m. The TIW heat budget analysis of *Baturin and Niiler* [1997], showed that the meridional current is the main contributor to TIW-induced temperature variability. The reduction of the meridional current activity in our coupled experiments is thus consistent with the reduced temperature variability. The zonal current variability, on the other hand, is increased with a second maxima appearing around 4°N. The detail of the mechanisms behind the change in current variability described above needs to be further explored. Possible explanations include the role of Ekman currents, or of the wave induced wind-curl anomalies as observed by *Chelton et al.* [2001].

3.3. Rectification of the Mean State

[16] Table 1 shows a number of gross measures of mean state and how they vary with the strength of the coupling. Increasing the strength of the coupling leads to a decrease of the SST in the cold tongue. This decrease is the result of two competing effects. First, the reduction in TIW activity has reduced the equatorward flux of heat (not shown), consistent with the reduction in the T and v variability. On the other hand, the equatorial upwelling is decreased (by 30% between CTL and HIG), which would imply a warming. The fact that the SST cools suggests that the changes in TIW associated meridional heat flux dominates.

[17] The SEC does not display any significant change in STD and MID, though it slightly increases in HIG. On the other hand, the EUC is significantly increased in all the experiments with active coupling (by more than 25% between CTL and HIG). This increase in the EUC is consistent with the decrease in the divergence of $\langle u'v' \rangle$ close to the equator around 100 meters depth as the coupling strength is increased (not shown).

[18] Finally we ask the question: are the changes to the TIW activity a direct result of the coupling of the TIWs and the atmosphere, which in turn affects the mean state, or are they associated with changes in the forcing on the broader scale (a form of 'climate drift' of the model), where changes in the mean state affect the TIW activity? The results presented above are consistent with the first alternative, but to fully answer the question we have performed additional experiments as follows. The wind forcing of each coupled experiment is low-pass filtered and used to force a new control experiment, with no active coupling, but retaining

Table 1. Maximum Values of Current Speed (cm s^{-1}) for Each Experiment[a]

Variable	CTL	STD	MID	HIG
EUC	61	68	70	77
SEC	−52	−53	−52	−59
SST	23.3	23.1	23.0	22.9

[a]SST has been averaged in the box extending from 120°W to 100°W, 0 to 6°N.

the low–frequency changes due to climate drift. The results (not shown) show no significant change in the amplitude of TIW variability (compared to CTL). We therefore conclude that the bulk of the change in TIW variability is a result of the active coupling and not to changes in the mean state.

4. Discussion

[19] A simple wind stress parameterization has been used to investigate if the observed modulation of wind stress by TIWs has any impact on the properties of the waves themselves. Despite the simplicity of the parameterization scheme we find a broad agreement between the model and observations in terms of TIWs and their imprint in the wind stress. Active coupling between the ocean and atmospheric boundary layer is found to produce a negative feedback on TIWs, slightly reducing their temperature and meridional current variability, both at the surface and sub-surface. The coupling however slightly increases the zonal current activity.

[20] The reduced TIW activity changes the meridional heat and momentum transport, leading to changes in the mean state (a cooler cold tongue SST and stronger EUC as the coupling is increased). The effects are moderate (an increase of around 10% in the strength of the EUC for moderate values of the coupling), but significant. Sensitivity experiments allowed to verify that the change in TIW variability in our experiments were due to active coupling, rather than to the changes in mean state mentioned above.

[21] There are a number of caveats to this study. First, as already mentioned, the TIW SST, current and wind stress variability is underestimated by about 30% in our experiments. Although the ratio of the wind modulation to the TIW currents remains correct, it is difficult to anticipate how this influences our quantification of the negative feedback of the coupling on TIWs. Second, our experimental framework with constant winds is also highly idealised. Further, we chose to investigate only the impact of the wind stress modulation on the TIWs. The heat flux feedback is parameterized in all the experiments in a similar way by a relaxation to climatological SST. This is a rather crude parameterization of the flux modulation by the TIW variability. For example, phase differences between the TIW SST anomalies and atmospheric flux response could be expected because of the modulation of surface winds and humidity by the TIWs. For a discussion of air-sea heat fluxes associated with TIWs see, for instance, *Thum et al.* [2002]. Similarly, the parameterization of the wind stress response in this study is simplified. Despite its relative success in reproducing the observed wind stress pattern, it oversimplifies the variety of atmospheric responses that can stem from the various ABL processes. Experiments with a more sophisticated coupled model should be undertaken, in order to quantify more precisely the amplitude of the negative feedback of windstress modulation onto the TIW variability. It will be done in a future study. However we contend that our results do demonstrate the potential importance of the coupling between the atmospheric boundary and upper ocean and that such effects might need to be considered in studies of the equatorial ocean.

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