On the Relationship between Winds and Upper Ocean Temperature Variability in the Western Equatorial Pacific

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ABSTRACT

In this study we examine the relationship between winds and upper ocean temperature variability using data from an equatorial mooring at 0°, 165°E. The analysis focuses primarily daily to monthly time scale variations during 1986 and 1987 at the height of the 1986-87 El Niño/Southern Oscillation event. The period is one of high mean sea surface temperatures (≥29°C) and frequent outbreaks of westerly winds. We infer that in general wind-driven vertical advection and entrainment from the thermocline are not likely to be important processes affecting surface temperatures in the western equatorial Pacific. Conversely, we conclude that variations in evaporative cooling may account for a significant percentage of the observed surface layer temperature variance during the study period.

1. Introduction

Mean sea surface temperatures ≥29°C in the western equatorial Pacific are among the warmest in the world ocean. Thus, this region is characterized by vigorous air-sea interaction because turbulent heat exchange between the ocean and the atmosphere is a highly nonlinear function of sea surface temperature (SST). In extreme cases, air-sea interactions in the western Pacific may lead to El Niño/Southern Oscillation (ENSO) events which are coupled ocean-atmosphere phenomena occurring every 4–7 years [*Rasmusson and Wallace,* 1983]. ENSO has global climatic impacts, some of which can be traced to western Pacific SST anomalies of ≤1°C (e.g. *Nicholls,* 1985; *Palmer and Mansfield,* 1984). These impacts may be predictable months to years in advance provided the processes involved in SST change can be understood and reliably modeled.

While it is generally conceded that understanding SST variability is important for understanding and predicting ENSO, little is known quantitatively about the atmospheric and oceanic processes that control this variability. The purpose of this study therefore is to examine the relationship between wind forcing, SST and surface layer heat content using data from an equatorial current meter mooring at 0°, 165°E. The analysis is based on data collected during 1986 and 1987 and focuses mainly on time scales of days to months. This period coincides with the 1986–87 ENSO during which pronounced interannual variations occurred throughout the tropical Pacific (*Kousky and Leetmaa,* 1989; *McPhaden et al.,* 1990).

The paper is outlined as follows. Section 2 briefly describes the data used in this study. This is followed in Section 3 by discussion of how wind variations may be related to turbulent fluxes across the air-sea interface, vertical advection and entrainment from the thermocline. Major results and conclusions are summarized in Section 4.

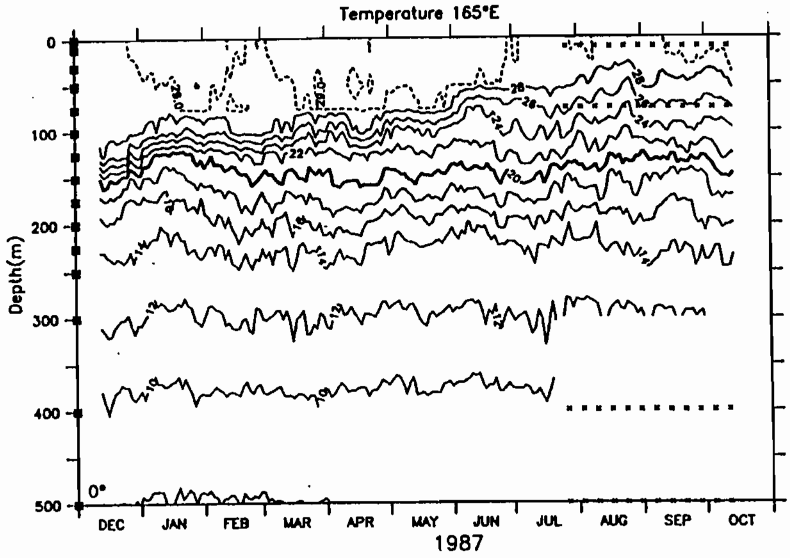

Figure 1. Contours of daily averaged temperatures at 0°, 165°E for 13 December 1986 to 14 October 1987. Contour interval is 2°C, except that the 29°C contour is shown as a dashed line. Sensor depths are indicated on the left axis; 7 days of missing data is indicated by an x.

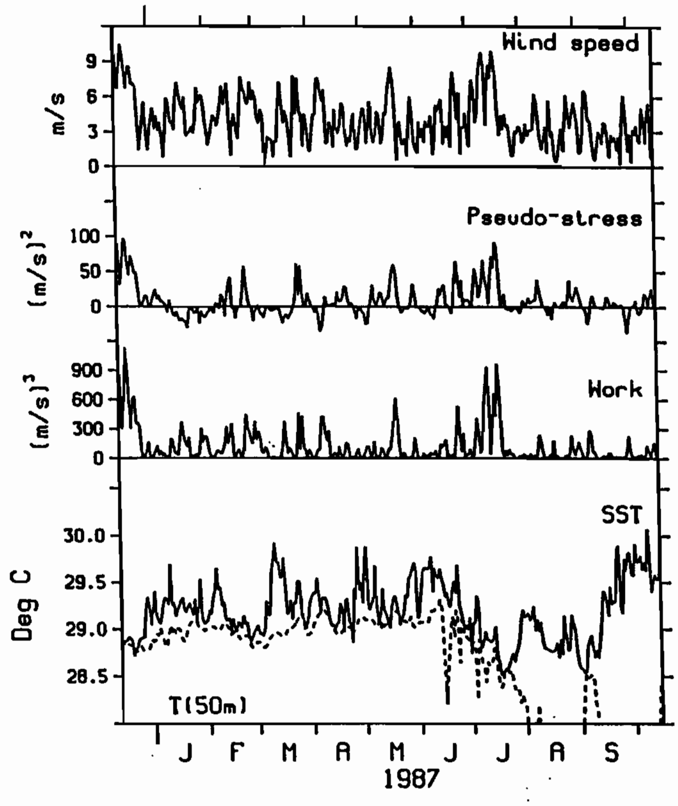

Figure 2. Time series of daily averaged wind speed (|U|), zonal wind pseudostress (|U|U$^{(x)}$), wind pseudowork (|U|^3), SST and temperature at 50 m (dashed line) from the current meter mooring at 0°, 165°E for the period 13 December 1986 to 14 October 1987.

2. Data

The data used in this study were collected from a surface mooring located at 0°, 165°E in the western Pacific warm pool. Winds were measured at 4 m height above mean sea level from a wind recorder mounted on the surface toroid. Temperatures were measured at 15 depths with the shallowest measurement at 1 m (nominally termed SST) and the deepest at 500 m (Figure 1). Details concerning instrumental accuracies, sampling characteristics and data processing can be found in *Freitag et al.* [1987] and *McPhaden et al.* [1990].

3. Surface turbulent fluxes, vertical advection and entrainment

Figure 2 shows daily time series of wind speed ($|\vec{U}|$), zonal wind pseudostress ($|\vec{U}|U^{(x)}$) and pseudowork ($|\vec{U}|^3$) from the mooring at 0°, 165°E for December 1986 to October 1987. Ignoring the weak wind speed dependence of surface turbulent exchange coefficients for the range of speeds shown in Figure 2, turbulent air-sea heat exchange will be proportional to $|\vec{U}|$, Ekman pumping proportional to $|\vec{U}|U^{(x)}$, and wind work proportional to $|\vec{U}|^3$. Also shown in Figure 2 is SST and 50 m temperature from the mooring.

Table 1 summarizes the means and standard deviations of the time series in Figure 2. The mean wind speed is only 4.0 m s^{-1} and the mean zonal pseudostress is westward at 8.2 m^2 s^{-2} (for a constant drag coefficient of 1.2×10^{-3}, this pseudostress translates into a mean zonal stress of 0.01 N m^{-2}). Standard deviations in both of these variables are also small: 2.1 m s^{-1} for $|\vec{U}|$ and 22 m^2 s^{-2} for $|\vec{U}|U^{(x)}$ (equivalent to 0.03 N m^{-2}). SST is high on average (29.2°C) with a standard deviation of 0.31°C. Temperature at 50 m is 29.0°C on average with a standard deviation of only 0.11°C.

Table 1. Summary of means and standard deviations for wind speed ($|\vec{U}|$), zonal wind pseudostress ($|\vec{U}|U^{(x)}$), pseudowork ($|\vec{U}|^3$), SST and temperature at 50 m depth from the current meter mooring at 0°, 165°E. All statistics are calculated for the period 13 December 1986–14 October 1987, except T(50 m), which is for 13 December 1986–31 May 1987 (i.e. when the 50 m level was always found in the surface layer above the thermocline).

	Wind Speed (m s^{-1})	Zonal Pseudostress (m^2 s^{-2})	Pseudowork (m^3 s^{-3})	SST (°C)	T(50 m) (°C)
Mean	4.0	8.2	127	29.2	29.0
Standard Deviation	2.1	22.3	188	0.31	0.11

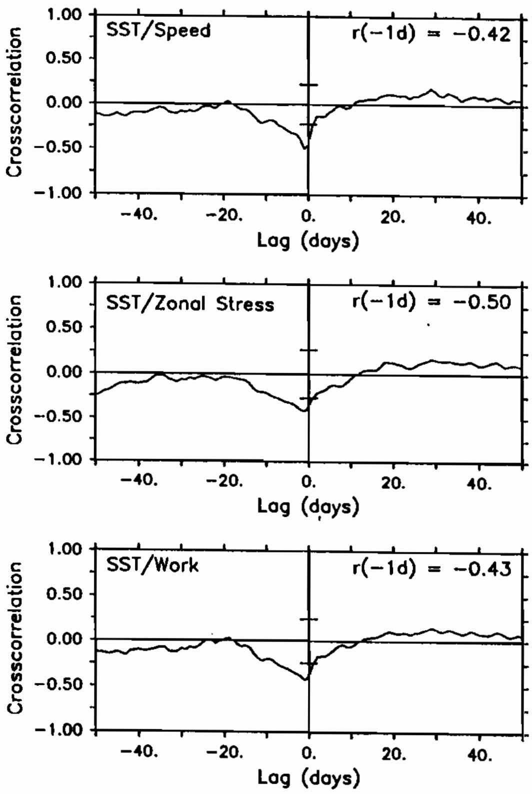

Figure 3. Crosscorrelations between SST and wind speed, zonal wind pseudostress, and wind pseudowork. Crosscorrelation extrema (r) and the lag (in days) at which they occur are shown. In each case, the lag indicates that cold SST follows high winds by one day. 95% confidence limits for the null hypothesis of uncorrelated variability are indicated by horizontal bars on the abscissa.

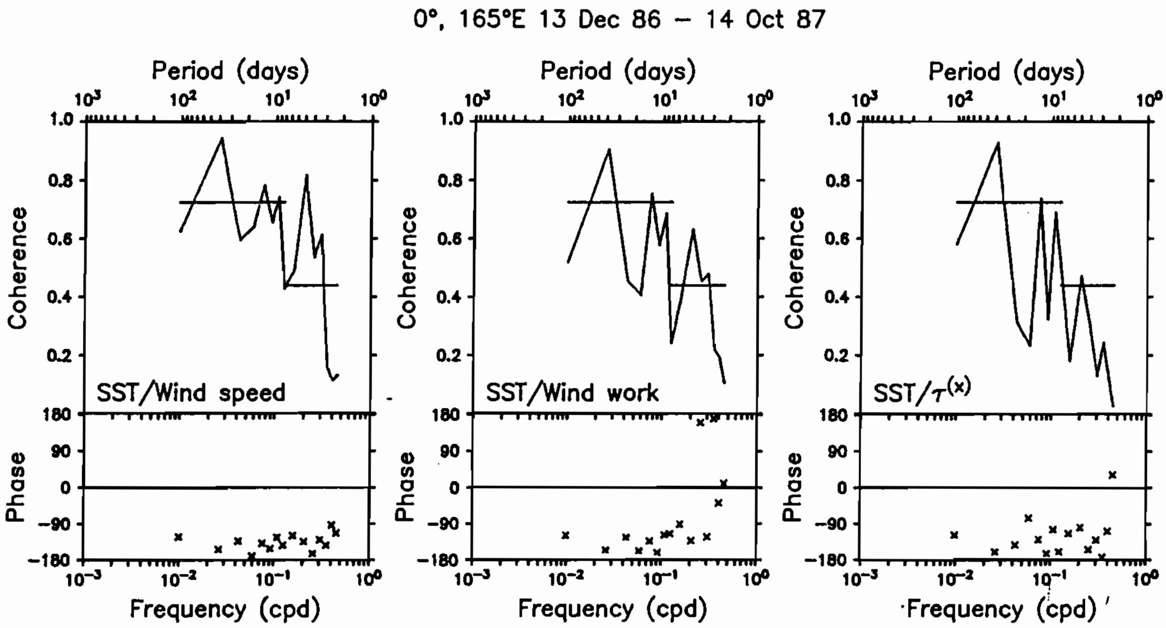

Figure 4. Coherence and phase spectra for SST and wind speed, zonal wind pseudostress, and wind pseudowork at 0°, 165°E for the period 13 December 1986 to 14 October 1987. Positive phase indicates that high winds lead high SST. Observed negative phases imply that high winds lead low SST.

Figure 3 indicates that crosscorrelations of the three wind constructs with SST are significantly nonzero at the 95% level of confidence and range between –0.42 (for zonal pseudostress) and –0.50 (for wind speed). The negative correlation indicates that high wind speed, high wind work and westerly wind stress (relative to the mean) are associated with cool SST; and that low wind speed, wind work and easterly wind stress (relative to the mean) are associated with warm SST. In each case the maximum crosscorrelation occurs with SST lagging the winds by 1 day, consistent with the atmosphere forcing the ocean on these time scales. Although not presented, the magnitude of the crosscorrelation between meridional wind pseudostress and SST is generally ≤0.2 over the range of lags shown in Figure 3.

Another way to view these relationships is in the frequency domain. Figure 4 shows the coherence and phase as a function of frequency between the 3 wind constructs and SST. Two bands of high and statistically significant coherence are evident. These are at periods between approximately 3–8 days and 30–60 days; to a lesser extent, variations at 10–20 days are also coherent. Consistent with the crosscorrelation statistics, the phase in most frequency bands is between –90° and –180° implying that maxima in the winds are followed by cold SST and minima by warm SST. Coherence at periods shorter than 20 days may be related to westerly wind burst activity. Coherence at periods of 30–60 days could be related to atmospheric fluctuations associated with *Madden and Julian* [1972] waves.

Note that although there are differences among the coherence and phase diagrams in Figure 4 and the crosscorrelation analyses summarized in Figure 3, the statistical relationships of the 3 wind constructs with SST share many similarities; indeed, wind speed, zonal wind pseudostress and wind work are highly correlated among themselves (0.61–0.90). Based on these statistics alone, one cannot unambiguously identify which of the processes related to the wind field are most important in affecting SST. Hence, we now examine the coherence structure as a function of depth for temperature and the 3 wind constructs in Figure 2.

Figure 5 shows coherence amplitude as a function of depth in the 3–8 day period band. The coherence profiles in other period bands, e.g. for the 30–60 day band, are similar to those shown in Figure 5. Also shown in Figure 5 is the mean temperature profile for December 1986-October 1987. Wind speed, wind stress and wind work are all significantly coherent with temperature variations between 1–10 m. Coherence drops rapidly below these depths however, and is statistically insignificant at the 95% level in the lower part of the surface layer between 50–75 m. In the thermocline, wind speed and wind work are generally incoherent with temperature fluctuations; on the other hand, zonal pseudostress shows a clear pattern of coherence between 125–300 m. Figure 6 shows that the phase of zonal pseudostress coherence is such that warm thermocline temperatures lag relative westerly winds by 90° and cold thermocline temperatures lag relative easterly winds by the same amount. This is consistent with an Ekman pumping hypothesis for thermocline variations. However, phase changes by 180° across the base of the surface layer, indicating the temperature variations are of opposite sign in the surface layer and thermocline. Vertical advection from the thermocline is therefore not likely to be the principal mechanism controlling SST on these time scales. Similarly, the rapid decrease in coherence with depth below 10 m in Figure 5 suggests that entrainment from the thermocline is not important in controlling SST. One would expect coherence between temperature and $|\vec{U}|^3$ to be much higher at 50–75 m if the thermocline were the source of cold water for the surface layer. This leaves turbulent surface fluxes proportional to $|\vec{U}|$ as the most likely candidate for affecting SST and surface layer heat content.

Further evidence to support the role of wind related surface turbulent heat flux variations can be found in an examination of upper ocean heat content, defined as $H = \rho C_p hT$. We calculated $\partial H/\partial t$ over 2 depth ranges: 0–10 m (where coherence with the wind speed is highest) and 0–75 m (the average depth of the surface layer). Heat content standard deviations are 34 W m^{-2} in the 0–10 m layer and 102 W m^{-2} in the 0–75 m layer. As expected from our earlier

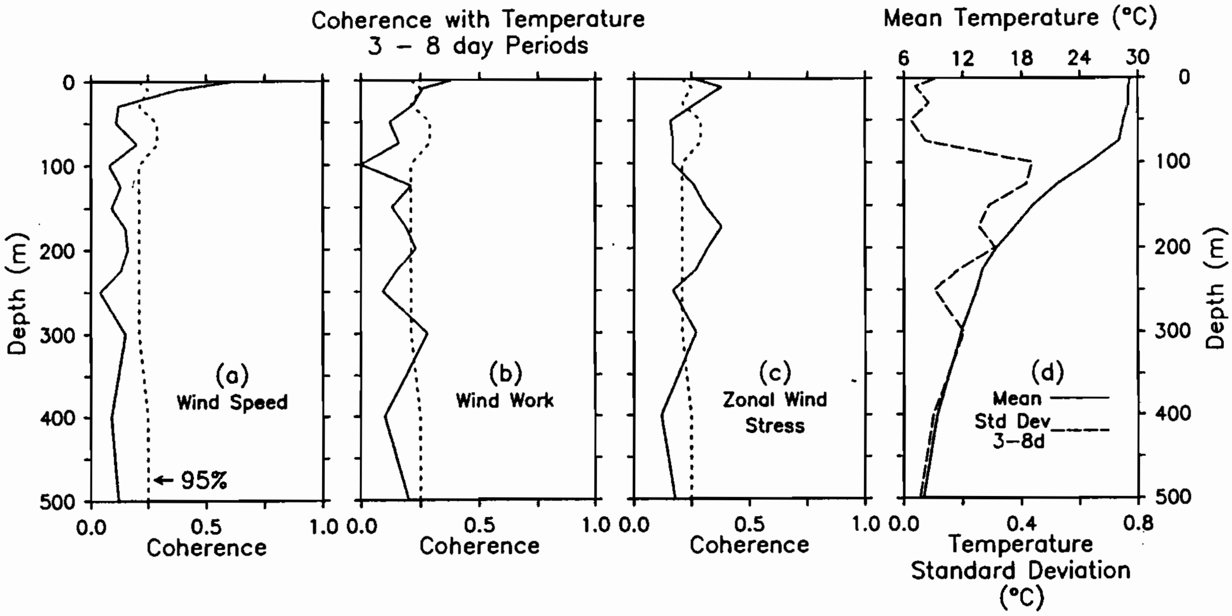

Figure 5. Coherence amplitude as a function of depth averaged over periods of approximately 3–8 days (i.e. 36–65 frequency bands depending on depth) for temperature and wind speed, zonal wind pseudostress, and wind pseudowork at 0°, 165°E. 95% confidence limits for the null hypothesis of incoherent variability are indicated by the dashed lines. Note that the temperature record lengths for this analysis were chosen such that the statistics were stationary; e.g. the period June-October 1987 was excluded at 50 m and 75 m. Shown on the right are the mean temperature profile (solid curve) and the standard deviation of temperature variations at periods of approximately 3–8 days (dashed curve) for 13 December 1986 to 14 October 1987.

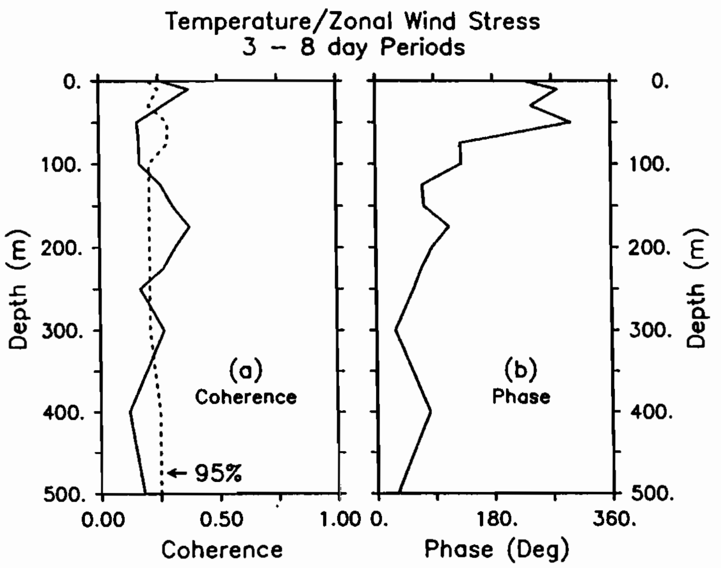

Figure 6. Coherence amplitude and phase as a function of depth averaged over periods of approximately 3–8 days (i.e. 36–65 frequency bands depending on depth) for temperature and zonal wind pseudostress at 0°, 165°E. 95% confidence limits for the null hypothesis of incoherent variability are indicated by the dashed lines.

results, the crosscorrelation with $|\vec{U}|$ is negative, and higher over the shallower layer (–0.38) than over the deeper layer (–0.29). When multiplied together, these standard deviations and crosscorrelation statistics imply that $|\vec{U}|$ accounts for 13 W m^{-2} in the layer 0–10 m and 30 W m^{-2} in the layer 0–75 m. The 0–75 m estimate is comparable to what would be expected for latent heat flux variations (Q_L) and typical observed parameter values. Specifically, $Q_L \approx 35$ W m^{-2} for wind speed variations of 2.1 m s^{-1} (Table 1), an exchange coefficient of 1.2×10^{-3} [*Large and Pond,* 1982] and a typical air-sea specific humidity difference of 5 g kg^{-1} [*Reed,* 1985; *Liu,* 1988].

These calculations, and Figure 5, indicate that surface cooling associated with Q_L converges nonlinearly in the upper 75 m. The upper 10 m (13% of the surface layer depth) takes up 13 W m^{-2} (43% of the latent heat flux forcing). The remaining 17 W m^{-2} (57% of the forcing) is absorbed over 10–75 m, which represents 87% of the surface layer depth. Using an integral time scale (t_i) for wind speed and temperature variations of 3–4 days (based on the crosscorrelation analysis in Figure 3) and a $\frac{\partial H}{\partial t}$ of 13 W m^{-2} (0-10 m) and 17 W m^{-2} (10-75 m), we find the expected magnitude of temperature variations associated with latent heat flux variations in each of these depth ranges to be 0.1°C and 0.02°C, respectively. The latter number is close to the instrumental accuracy of our temperature sensors (e.g. *McPhaden et al.*, 1990) and probably accounts for the insignificant temperature and wind coherences on a pointwise basis for depths greater than 10 m in the surface layer.

4. Conclusions

We have inferred that wind-related latent heat flux variations of about 30 W m^{-2} lead to temperature changes in the upper 75 m of 0.02°–0.1°C. The largest of these variations occur in the upper 10 m, perhaps because of the existence of surface layer salinity stratification as discussed in *Lukas and Lindstrom* [1987] and *Godfrey and Lindstrom* [1989]. Salinity stratification would act to isolate the near surface from the thermocline, trapping surface heat fluxes while at the same time reducing the effect of vertical advection and entrainment on SST. These results are consistent with those of *Meyers et al.* [1986], who found that evaporative fluxes led to significant surface cooling in the western Pacific during the 1982-83 ENSO, whereas entrainment from the thermocline was relatively unimportant. This would also explain why surface layer temperature variations at 50 m are less than those for SST as noted in Table 1.

It is however clear that evaporative cooling accounts for only a fraction of SST and surface layer heat content changes. Other processes, e.g. lateral advection and radiative heating and cooling, must also be important. A complete analysis of the upper ocean heat budget in the western equatorial Pacific thus requires information on the velocity field and on the surface radiation balance.

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