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OCEAN-ATMOSPHERE INTERACTION WITHIN EQUATORIALLY TRAPPED ATMOSPHERIC WAVES

George N. Kiladis[1] and Katherine H. Straub[2]
[1]NOAA Aeronomy Laboratory, Boulder, CO
[2]Susquehanna University, Selinsgrove, PA

1. Introduction

Near-equatorial atmospheric convection is known to occur on a wide variety of temporal and spatial scales. Some of this convection has been shown to be organized by equatorially-trapped disturbances having characteristics of linear shallow water modes (Wheeler et al., 2000). In addition, the Madden Julian Oscillation (MJO) also modulates a substantial portion of tropical convection, and is associated with significant signals in air-sea fluxes and sea surface temperature (SST). In this study we extend our previous work on the potential for the MJO and higher frequency equatorial wave activity to affect the ocean, and examine in more detail the case of the demise of the 1997-98 warm event, which appeared to be forced by a complex interaction involving the MJO and an atmospheric Kelvin wave.

Zonal wind stress and associated oceanic wave dynamics are believed to be intimately linked to the demise of warm events. McPhaden and Yu (1999) cite evidence that upwelling Rossby waves were responsible for the shoaling of the east Pacific thermocline at the end of the 1997-98 warm event. Harrison and Vecchi (1999) argue that a shift in equatorial surface westerly wind anomalies to around 5ºS during the beginning of the year following a warm event (Year+1) is responsible for the shoaling of the east Pacific thermocline during early 1998 and in previous events, which provided the necessary background state to the return of cold SST once the

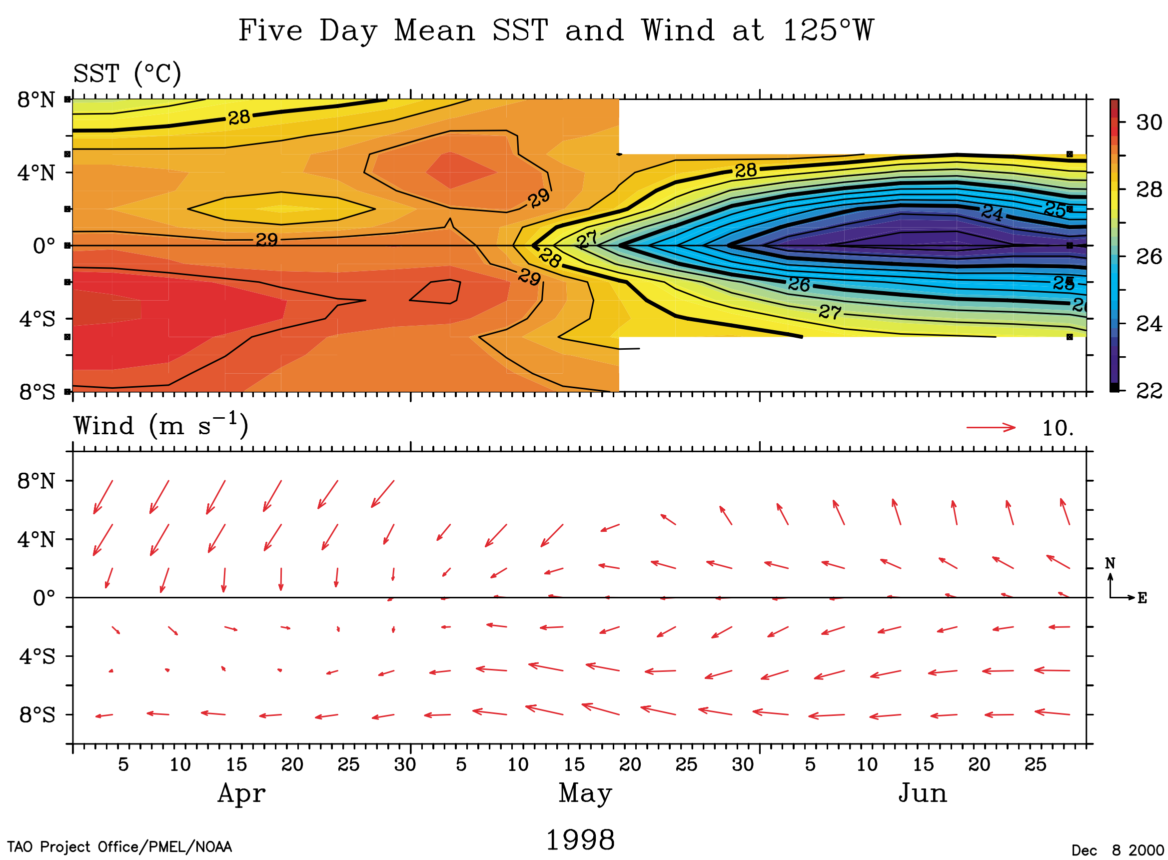

Figure 1. Sea surface temperature (top) and total wind vectors (bottom) at 125ºW for the period April-June 1998, from 5 day averaged TAO data. All TAO data were provided by the TAO Project Office at: www.pmel.noaa.gov/tao/

Corresponding author address: George N. Kiladis, Aeronomy Laboratory, NOAA, R/AL3, 325 Broadway, Boulder, CO 80305-3328; email: gkiladis@al.noaa.gov

trade winds became re-established over that region. While these mechanisms provide plausible explanations for the slow evolution of the equatorial thermocline late in warm events, they do not specifically address the sudden return of the trade winds frequently observed at the end of these episodes, as was observed for example during May 1983, May 1992, and May 1998.

Following the record strength warm event of 1997-98, SST in the central and eastern equatorial Pacific was observed to plummet by more than 8ºC in some locations, as seen at 125ºW in Fig. 1 (see also McPhaden and Yu, 1998). This rapid change has been attributed primarily to the local increase in low level easterly flow, as seen at the bottom of Fig. 1, since the effect of wave dynamics is thought to have a more gradual effect on thermocline variability.

In a provocative study, Takayabu et al. (1999; hereafter referred to as T99) examined the evolution of the zonal wind stress across the Pacific during the sudden demise of the 1997-98 warm episode, and specifically addressed the very rapid cooling of SST during May 1998. T99 pointed out that an increase in the surface easterly flow during that period, which presumably led to the abrupt surfacing of the already very shallow thermocline, was linked to an MJO which induced anomalous easterly flow to its east over the Pacific basin. Such easterly anomalies at low levels are a well-known feature of the phase of the MJO when convection is located over the western Pacific (e.g. Madden, 1998). In this study, we examine the evolution of the zonal wind stress over the central and eastern Pacific, and the accompanying evolution of the near-surface oceanic response during May 1998, in more detail. We will present evidence that a rapid eastward propagating convectively coupled Kelvin wave in the atmosphere was also involved in producing the wind stress responsible for the rapid SST change during that time frame.

2. Data and Methodology

Satellite-derived Outgoing Longwave Radiation (OLR) data are used to identify the deep convective and cloudiness signals associated with the MJO and Kelvin waves. Tropical Atmosphere Ocean Project (TAO) buoy data provide a high resolution picture in time and space of the SST, surface wind, and subsurface oceanic conditions during the event. Since the events under consideration occurred at the end of the 1997/98 warm event, highly anomalous conditions existed over the study region. Anomalies are therefore defined with respect to the study period April 15-June 9, 1998.

3. Observations

During May 1998, the thermal structure in the equatorial Pacific Ocean featured a lens of anomalously cold subsurface water trending downward to the west

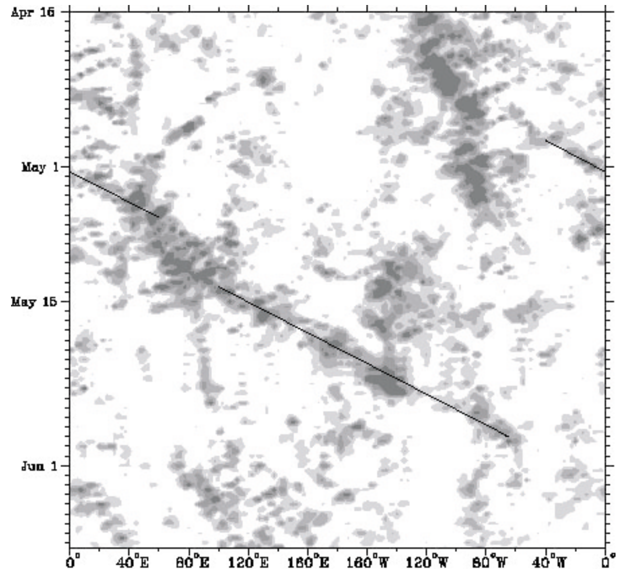

Figure 2. Longitude-time diagram of negative OLR anomalies averaged between 5ºN-5ºS from April 15-June 9, 1998. Shading starts at -10 Wm-2.

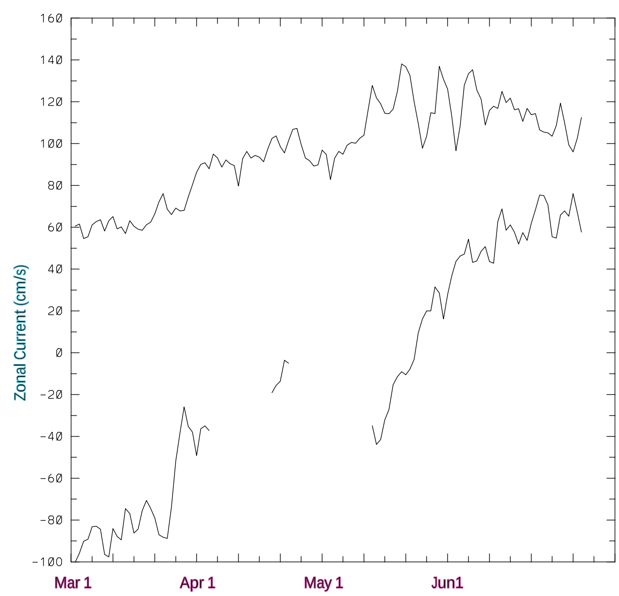

Figure 3. Time series of the zonal currents at 10 m (bottom) and 80 m (top) depths, measured at the TAO mooring located at the equator, 140ºW, during March-June 1998. Missing data are not plotted.

from depths of less than 100 m near 110ºW to greater than 200 m near 160ºE. As shown in Figs. 1 and 4, SST at the beginning of the month was still well above normal, as it was over almost the entire basin. We argue that the sudden decrease in SST was related to the upwelling-induced wind forcing due to the rapid reestablishment of the trade wind regime over the Pacific basin, which was in turn induced by sudden changes in the organization of subseasonal convection, forced initially by an atmospheric Kelvin wave.

Convectively coupled Kelvin waves propagate eastward at a phase speed of around 15 ms-1, and have a substantial cloudiness signal within the ITCZ as well as a dynamical signal in wind and temperature from the surface well into the stratosphere (Wheeler et al., 2000; Straub and Kiladis 2002; hereafter referred to SK). Fig. 2 shows a time-longitude diagram of the OLR signal for the period April 15 to June 9 1998 along the entire zonal strip of the globe, averaged between 5ºN and 5ºS. During late April equatorial convection was most active between 110ºW and 70ºW, as it had been over the previous year due to the anomalously high SST associated with the 1997-98 warm event. On April 23, a separate zone of convection developed over South America at around 60ºW, which then propagated rapidly eastward across the Atlantic sector, Africa, and then into the western Indian Ocean by May 6. The phase speed of this convective envelope is shown by the dark line in the figure to be around 15 ms-1. Once in the Indian Ocean, this disturbance becomes more MJO-like, with convection becoming deeper, and the phase speed of the envelope slowing down somewhat to around 10 ms-1. On the 14th of May, convection then begins to move more rapidly across the Pacific, again at a phase speed of 15 ms-1, arriving at the coast of South America on May 27. Thereafter, convection at 90ºW becomes much more sporadic, with activity increasing instead over the Australasian sector. This re-establishment of the convection at its more typical longitude farther west marked the end of the 1997-98 warm event.

Fig. 4 shows the evolution of equatorial SST anomalies from the TAO array for the same period as in Fig. 2. SST is relatively high in the central and eastern Pacific until the middle of May, then decreases dramatically thereafter. This cooling occurs first at around 110ºW, then propagates rapidly westward to 170ºW by early June, with some interesting local fluctuations superimposed.

Fig. 5 shows the evolution of the surface zonal wind anomaly from the TAO array during the same period. During late April and early May, the wind is anomalously westerly with respect to the period examined. With respect to a longer climatology (as seen for example at 125ºW in Fig. 1) westerly or northerly anomalies had been dominant over the equatorial Pacific since the onset of the warm event in the middle of 1997, consistent with the high SST in this region. By May 10, however, the zonal wind anomaly has become easterly and in fact is easterly in the total wind field as well (not shown, but see Fig. 1) over the

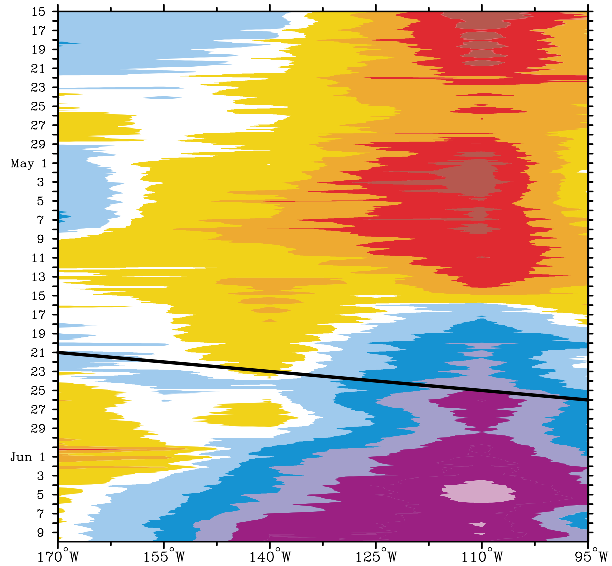

Figure 4. Longitude-time diagram of sea surface temperature anomalies averaged between 5ºN-5ºS from April 15 through June 9 from TAO data. Negative anomalies are shown as darker shading, at intervals of 0.4ºC, starting at 0.1ºC. The diagonal line marks the passage of the Kelvin wave cloudiness from Fig. 2.

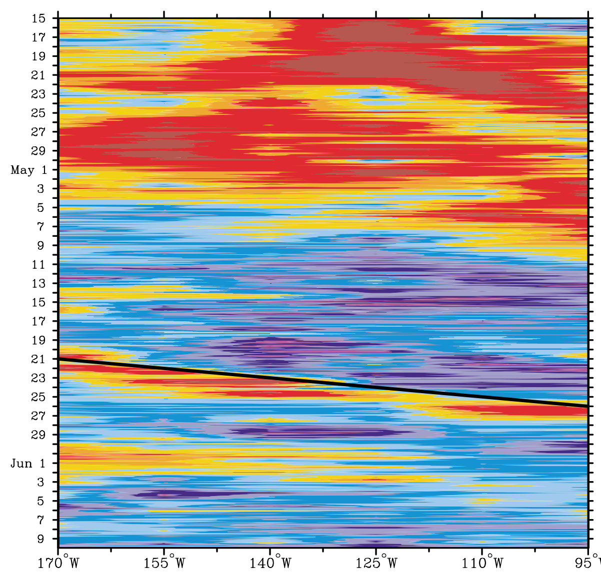

Figure 5. Longitude-time diagram of surface zonal wind anomalies averaged between 5ºN-5ºS from April 15 through June 9 from TAO data. Positive anomalies are shown as darker shading, at intervals of 2 ms-1, starting at 1 ms-1. The diagonal line marks the passage of the Kelvin wave cloudiness from Fig. 2.

entire longitude range of the TAO array. These winds remain easterly through the rest of the study period, with the exception of a westerly signal which propagates rapidly eastward across the basin starting on May 21, which appears as a westerly anomaly in Fig. 5. The dark line in Fig. 5 is the center of the Kelvin wave cloudiness from Fig. 2, so this westerly anomaly is clearly associated with that disturbance crossing the basin. The sign of this wind signal is consistent with that expected from a theoretical Kelvin wave, with surface westerly anomalies to the west of the convection, and surface easterly anomalies to the east (SK; Wheeler et al., 2000).

The behavior of the SST during this period can be readily explained by the forcing due to the re-establishment of the trades. As discussed above, the sudden onset of the easterlies coincided with the appearance of the deep MJO convection over the Indian Ocean at the beginning of the month. This forcing appears to be consistent with the arguments made by Kessler and McPhaden (1995) to explain the demise of the 1991-92 warm event, at least heuristically. Using TAO observations, Kessler and McPhaden parameterized the effect of equatorial upwelling on SST through the use of a regression relationship between the zonal wind stress and the depth of the 23ºC isotherm. As might be expected, SST is colder when the 23ºC isotherm is shallower, or the easterly wind stress is stronger. The westward propagation of the SST signal in Fig. 4 appears to arise from the fact that the subsurface isotherms sloped downward toward the west, so that, farther west, given the same wind, it takes a longer period of easterly stress to upwell the cold subsurface water.

Another interesting feature of Fig. 4 is the rapid eastward propagation of a relatively cold region of SST immediately following the Kelvin wave cloudiness. It is unlikely that this cooling can be explained by either upwelling or mixing, since the surface winds go from strong easterly to weak westerly with the passage of the wave. It seems more likely that an influx of cold precipitation and/or a decrease in incoming shortwave radiation due to the cloudiness associated with the wave is responsible, although a more detailed analysis will be necessary to establish this.

Along with the rapid changes in SST, abrupt changes in zonal currents were also observed by the TAO moorings during May 1998. Fig. 3 shows time series of the zonal currents at 10 m and 80 m depths, measured at the equator, 140ºW during the study period. The near-surface flow goes from strong westward at the beginning of the period to eastward by the end, with the change in flow direction occurring on May 22. This change is actually opposite to the mean seasonal cycle observed at this location, which normally goes from eastward to westward in the transition from northern spring to summer (Seidel and Giese, 1999). This flow appears to have been temporary, since later sections show a return to more normal westward flow in a thin near-surface layer (Johnson et al., 2000). At 80 m, the equatorial undercurrent slowly strengthens in response to the increasing zonal pressure gradient as the trade winds strengthen (Johnson et al., 2000).

4. Discussion

We have presented evidence that the short-term behavior of SST over the Pacific in May 1998 may ultimately be due to the occurrence of an atmospheric Kelvin wave, resulting in the initiation of an MJO in the Indian Ocean, which in turn forced the trade wind field remotely. Once the SST decreased to levels unable to support convection, the convective field was re-established farther west in its more usual position, and the 1997-98 warm event was terminated. At lower frequencies, it is likely that oceanic wave dynamics were responsible for the depletion of the Pacific heat content, assuring that once the SST was lowered, warm conditions could not be easily re-established.

5. References

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