The 1997-1998 El Niño: "Old El Niños do die, and they die quickly"

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In early May of 1998 we saw the sea surface temperature signature of one of the strongest El Niños on record decay within a span of several weeks. At 125W the SST dropped over 5 ºC in 17 days. What caused this abrupt end to the 1997-1998 El Niño? It is my goal to attempt to answer this question, at least in part, through the investigation of TAO mooring data including wind velocity, ocean SST, ocean currents, and sub-surface temperatures.

There are number of mechanisms by which the SST of the eastern equatorial Pacific can be changed:

1. We know that upwelling of colder ocean water results from Ekman divergence at the Equator due to the persistent Easterlies. During El Niño, when these Easterlies are weakened and westerly wind bursts are present, this upwelling can be shut down.
2. Westward advection of colder waters by the North Equatorial Current may play a significant part in the SST variability.
3. The strength of the shear layer above the Equatorial Undercurrent may play a role in the entrainment of colder water into the mixed layer. The strength of this shear is dependent upon the zonal pressure gradient set up by the Easterlies.
4. The wind stress itself may have been sufficient to churn up colder water from the ever-shallowing thermocline, especially if we consider the winds acting with the nighttime convection driven by diurnal forcing.
5. We have seen that ENSO can be described by equatorial wave dynamics that tend to shift the depth of the thermocline in the eastern and western Pacific.

To determine if one or a combination of these mechanisms brought on the demise of the 1997-1998 El Niño, I am going to attempt to investigate causality between the measured variables. Did the easterly winds pick up after the SST changed, or did the winds lead the SST change? If the Easterlies caused the SST to drop, what caused the Easterlies? Did the shear in the EUC increase before the SST dropped? What did the 20º isotherm look like when the SST plunged? These are all questions that I will attempt to answer.

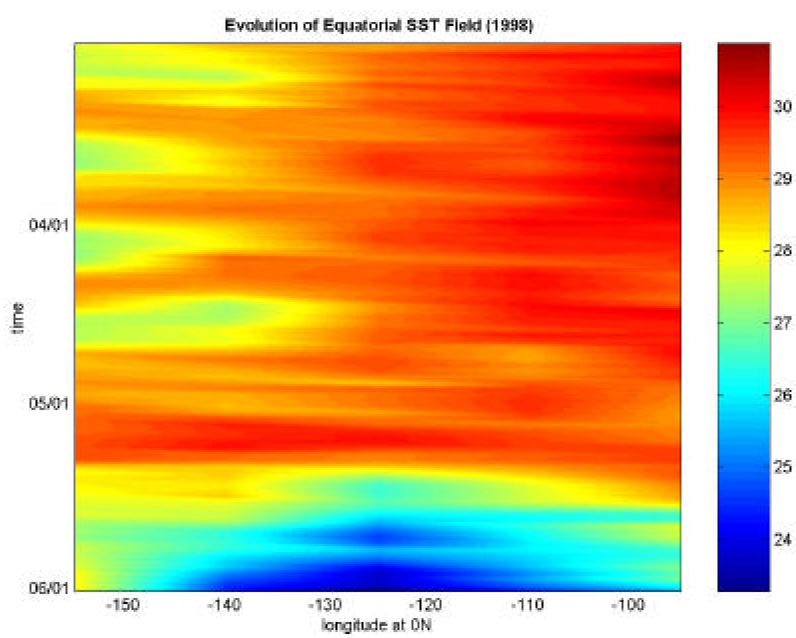

Figure (1): Evolution of SST at 0N in the eastern Pacific. Temperature is in degrees Celsius and are daily averages.

A reasonable first step to take in this investigation is to look at the change in the SST over the period of interest. Note that in figure (1) the first indication of dropping SST's occurred almost at the same time at each longitude west of 120W, with the most rapid drop in the SST occurring at about 125W. Another feature in this plot that may be significant to the demise of the 1997-1998 El Niño is the presence of strong tropical instability waves at 140W and 155W. The wind field for the same period of time is shown in figure (2).

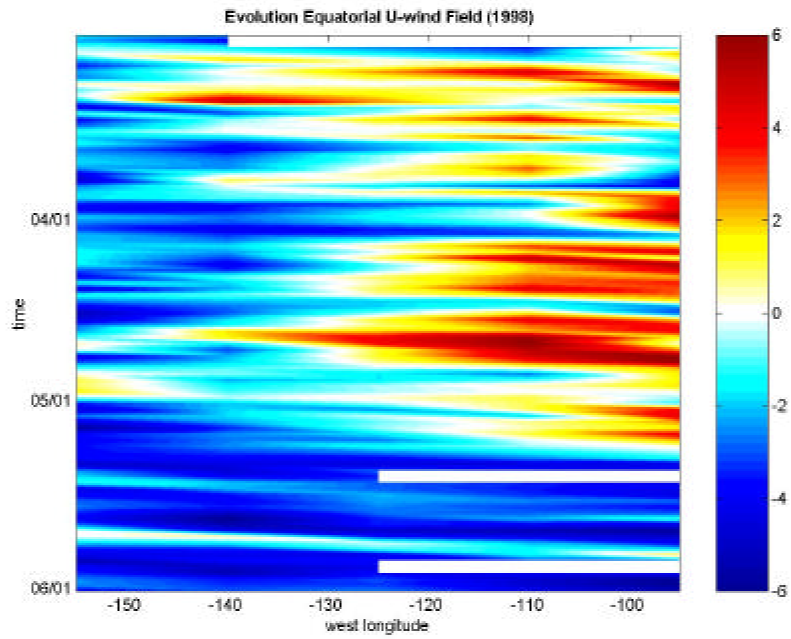

Figure (2): Daily averaged zonal winds in m/s (westerly is positive, easterly is negative) at 0N.

The zonal winds in figure (2) show that there were periodic strong westerly wind bursts centered over the eastern portion of the study region up until just before the dramatic change in SST. Although I am unable to determine a strong connection between the end of these westerly wind bursts and the onset of the SST decline, the timing of the two events points to the wind as a key player in the SST decline. Further investigation shows that the end of the westerly wind bursts/beginning of the strong easterlies preceded the large drop in SST by about 3 days (locally). When figures (1) and (2) are compared, however, one can see that the locations of the most rapid drop in SST (125W) are not necessarily the locations that experienced the first strong Easterly wind bursts. This led me into an investigation of the mechanisms that can cause upwelling at the Equator. Equatorial upwelling has been shown to result from Ekman divergence on the Equator, though we know that Coriolis is extremely small there. On the Equator we might also consider the irrotational case in which the wind stress drives the surface current. A divergent wind stress would result in divergent currents; thus, under this simplification upwelling is related to the gradient of the wind stress. Figure (3) is a plot of the gradient of the zonal winds, with blue regions suggesting areas of surface divergence or upwelling and red areas suggesting areas of surface convergence or downwelling…of course we assume that the divergence/convergence isn't accounted for by meridional flows. Comparison of figures (1) and (3) show a relationship between the location of the strongest surface cooling and the location of strong zonal divergence.

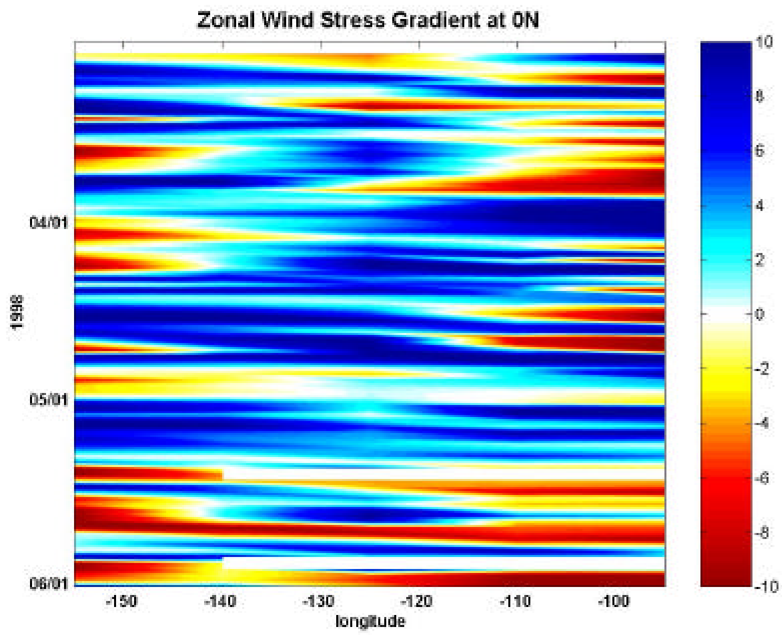

Figure (3): Gradient of the zonal wind stress (wind velocity squared) at 0N.

But why were there other times of large surface divergence during which the SST remained relatively unchanged? They answer may lie in the depth of the thermocline and the depth of the EUC. If the thermocline is sufficiently deep, water brought to the surface via upwelling will be water from the mixed layer—and will subsequently not be much cooler than the surface water. If the thermocline is shallow, however, upwelling can bring colder water from below the mixed layer to the surface. Additionally, a shallowing of the EUC would dramatically increase the shear between the eastward flowing EUC and the westward surface wind-driven currents. Increased shear above a shallow EUC could result in vigorous mixing and entrainment of colder water toward the surface. Figure (4) shows the evolution of the 20° isotherm, which is a proxy for the depth of the thermocline on the Equator.

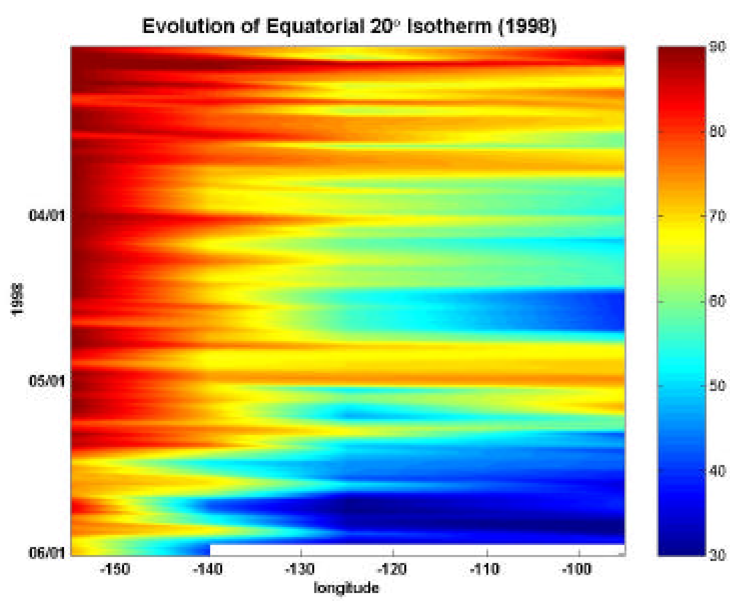

Figure (4): 20° isotherm depth (meters) on the Equator.

We can clearly see a general trend toward a shallow thermocline that appears to be progressing from east to west—opposite in direction to a eastward propagating Kelvin wave. Again, if we look long enough, we can see a relationship between the 20° isotherm depth, the wind stress gradient and the SST. One possible explanation is that the gradient of the wind stress results in a shallower thermocline due to upwelling (along with Ekman divergence), and the wind stress is able to mix the colder thermocline water up to the surface to drop the SST. Just before we see the large drop in SST, there is a persistent easterly wind burst in the middle to western part of the study region that leads to favorable upwelling conditions. But this may not be the entire picture, even if we aren't on the right track. The Equatorial Undercurrent, which exists because of the east-west pressure gradient set up by the persistent Easterlies, shows a gradual shallowing over the time period of interest. Past studies have show that there is a region of strong shear and mixing just above the EUC [*Peters and Gregg*, 1988]. *Battisti and Briedenthal* [1998] have suggested the presence of a shallow EUC results in 4 times the amount of entrainment that would be present with just surface wind stress and no EUC. Thus, an extremely effective mixing mechanism would exist if the shear layer above the EUC were shallow enough to reach into the mixed layer above. The TAO data, in fact, show that this may have happened, and may be a large reason for the rapid drop in SST. Figure (5) shows that the EUC at 140W was in a constant state of shoaling in the spring of 1998. The data from the 110W also show the same trend with the shoaling occurring weeks earlier in the east. The increased shear above the EUC that resulted from this shoaling could have extended into the mixed layer (30-50 meters deep) and quickly dropped the SST through mixing and entrainment of colder water.

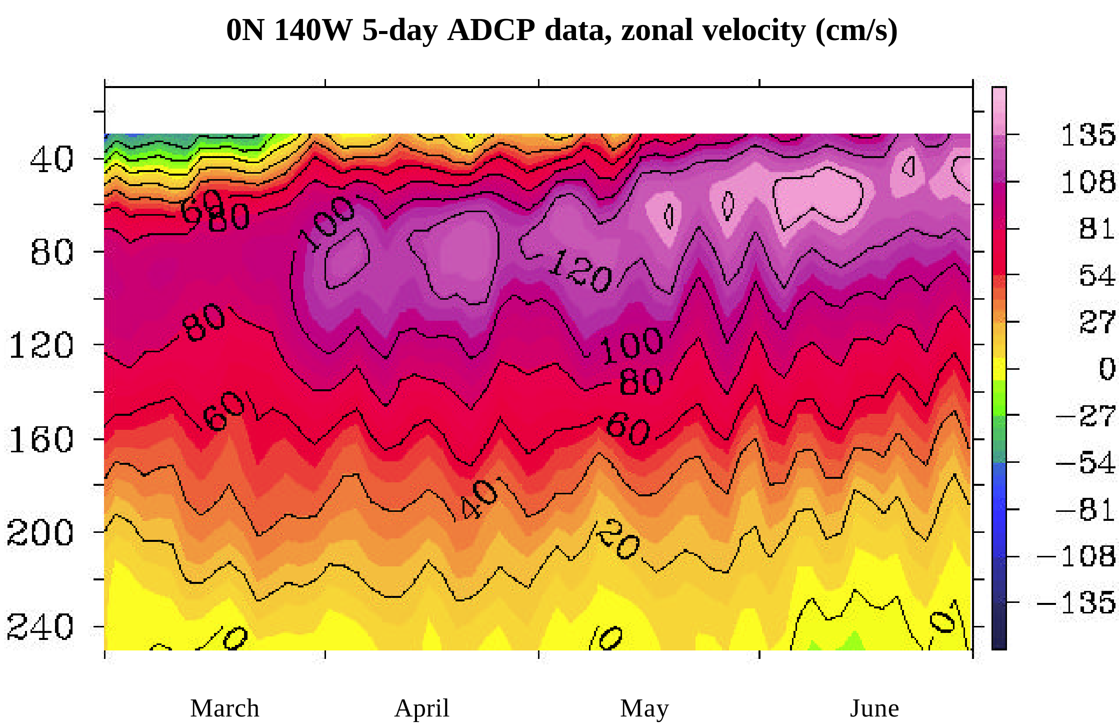

Figure (5): 0N 140W 5-day ADCP data, zonal velocity (cm/s).

Calculations of the Richardson number, a non-dimensional parameter that shows the relationship of the stabilizing force of stratification to the destabilizing force of shear, show extremely high values above the EUC. ADCP velocities at 110W on May 15th, 1998 show values of 1 m/s to the east at a depth of only 30 meters. With easterly winds of about 5 m/s at this time, setting the zonal surface bulk wind stress, τ_x, equal to the friction at the surface of the ocean, $\rho K_z \partial u/\partial z$, we can approximate the surface currents. With the diapycnal diffusivity, K_ρ, set to a typical mixed-layer value of 1×10^{-3} m^2/s and assuming a mixed layer depth of about 30 meters, we can approximate westerly surface currents to be on the order of 0.5 to 1 m/s. The shear between the EUC and the surface currents is then ~2 m/s over 30 meters, or 0.066 s^{-1}. The Richardson number (N^2/S^2) for a typical N^2 value at the bottom of the mixed layer of 5×10^{-5} s^{-2} is ~0.01, which is sufficiently low for instabilities and turbulence to exist. The necessary Richardson number for instabilities to exist is ¼. Below this value the conditions are favorable for overturns to vertically mix the water.

To summarize the findings, it looks as though there may be an interaction of a number of processes working together to result in the rapid surface cooling. The shutdown of westerly wind bursts and re-establishment of the Easterlies set the stage for increased upwelling and a shallower equatorial thermocline. Divergence of zonal currents caused by the gradient of zonal wind stress could have contributed to the rate of upwelling caused by Ekman divergence. Additionally, the progressive shoaling of the EUC, which is possibly related to the eastward propagation of a Kelvin wave reflected from the western boundary [*Vialard et al*., 2000], could have reached a critical depth that allowed vigorous mixing of cold thermocline water up into the mixed layer. Finally, the presence of tropical instability waves and the closely associated westerly wind bursts could have acted as a temporary impediment to equatorial upwelling and thermocline shoaling. Once these waves disappeared, they may have exposed the El Niño Grim Reaper that was waiting…

Side note on TIW's

When we compare the equatorial SST (figure 1) and the equatorial zonal winds (figure 2) it looks as though westerly wind bursts are modulated by the tropical instability waves, which really should be absent during El Niño conditions since the SEC is weak--but they are very clear in 155W record. The presence of the TIW's result in a periodic zonal gradient of SST on the equator. If the winds respond to the SST of the ocean (through convection--air rising at the warmest location), then we expect the Easterlies to be strongest when the TIW's bring warm water to the equator in the west, and there to be westerly wind bursts when the TIW's result in colder water in the west. There seems to be a lead of the SST gradients by a few days over the responding winds (3-5) (Figure 6). Note the four main peaks of the westerly wind bursts that follow the four temperature minimums of the TIW. Spectral analysis of the SST and wind time series also shows a matching of peaks with a period of about 27 days—a typical period of TIW's.

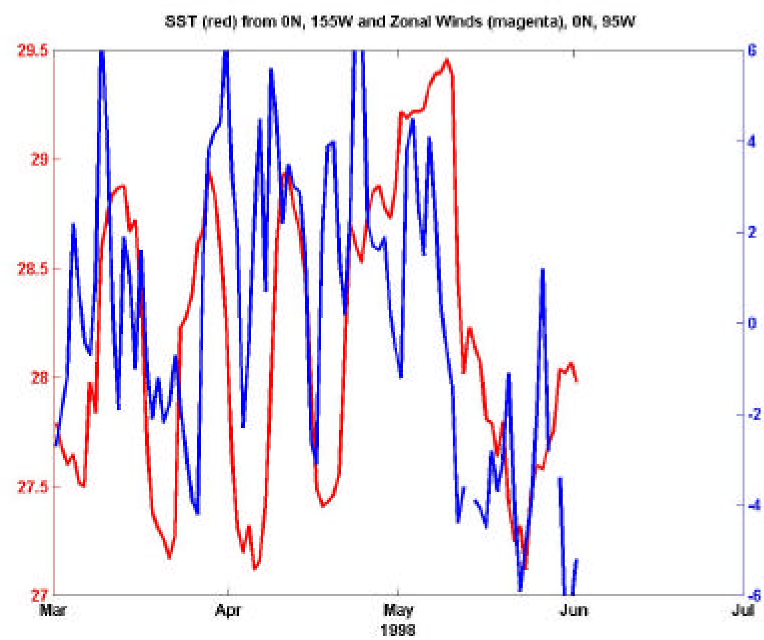

Figure (6): SST at 0N 155W (°C) (red) plotted against 0N 95W zonal winds (m/s) (blue).

References

Battisti, D.S. and R.E. Breidenthal, 1998: Thermocline entrainment during El Niño. unpublished.

McPhaden, M.J., 1999: Genesis and evolution of the1997-98 El Nino. *Science*, 283, 950-954.

Peters, H. and M.C. Gregg, 1989: Meridional variability of turbulence through the Equatorial Undercurrent. *J. Geophys. Res*., 94, 18,003-18,009.

Takayabu, Y. N., et al., 1999: Abrupt termination of the1997-98 El Nino in response to a Madden-Julian oscillation. *Nature*, 402, 279-282.

Vialard, J., C. Menkes, J.-P. Boulanger, P. Delecluse, E. Guilyardi, M.J. McPhaden, and G. Madec, 2001: A model study of oceanic mechanisms affecting equatorial Pacific sea surface temperature during the 1997-98 El Nino. *J. Phys. Oceanogr.*, in press.

Wyrtki, K., 1981: An Estimate of Equatorial Upwelling in the Pacific. *J. Phys. Oceanogr.*, 11, 1,205-1,214.