NOTES AND CORRESPONDENCE

Comments on "The Fast-Wave Limit and Interannual Oscillations"

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Neelin (1991, henceforth N) presents an analysis of oscillating instabilities that occur in models of tropical ocean–atmosphere interactions. I believe his central finding, a slow sea surface temperature (SST) mode in a fast-wave limit, is a useful tool for understanding model results. However, an apparently overlooked aspect of the equatorial-wave adjustment process restricts the applicability of the SST mode and modifies the interpretations he offers.

In N the pure form of the SST mode occurs in a "fast-wave limit": the time for equatorial waves to dynamically adjust the equatorial ocean to wind changes is short compared to the coupling time involving thermodynamics. This fast-wave limit is contrasted with the "delayed oscillator" mechanism (Schopf and Suarez 1988), which grants the leading role to the finite time it takes equatorial Kelvin and Rossby waves to adjust the equatorial ocean to wind changes. Thus, the SST model is offered as a marked alternative to explanations of El Niño–Southern Oscillation (ENSO) in all the versions that rely on (linear) ocean dynamics (e.g., Cane and Zebiak 1985, 1987; Battisti and Hirst 1989; Schopf and Suarez 1988, 1990; Cane et al. 1990). Neelin also states that a hallmark of the fast-wave limit is Sverdrup balance; on the equator this is Eq. (50) of N:

$$g\partial_x h'_e = A_e \qquad (1)$$

where h'_e is the thermocline displacement, A_e is the zonal wind stress divided by layer depth, and g is the acceleration of gravity.

Now, in *all* the ocean-dynamics explanations this same relation holds to leading order in ω, the frequency of the oscillation nondimensionalized by the time for a Kelvin wave to cross the ocean. The earliest recognition that (1) holds in relevant circumstances appears to be in Cane and Sarachik's (1981) solution for the response of an equatorial ocean to a periodic zonal-wind stress of the form $\exp(-\mu y^2/2 + i\omega t)$; see their Eq. (29) and following pages. They make the point that is the core of my present argument: $\partial h'_e/\partial x$ is in Sverdrup balance but h'_e is not. What is overlooked in N's analysis is the crucial role for the ocean-dynamics explanations of the *boundary condition* in (1).

Integrating (1) zonally yields

$$h'_e = g^{-1} \int_{X_E}^{x} A_e + h_E, \qquad (2)$$

where h_E is the value of h'_e at the eastern boundary $x = X_E$. Neelin notes that a boundary condition for (1) [his (50)] is required, but sidesteps the issue by assuming the solution is periodic in x. This is the crucial departure from the ocean-dynamics mechanism. In the bounded basin h_E, and hence h'_e everywhere, need not be in phase with the wind stress; it is this phase difference that allows oscillations of long period even while (1) holds.

Of the several variants of wave dynamics governed oscillations in the literature, the model of Cane et al. (1990) provides the starkest contrast to the slow SST mode. This model reduces the SST equation to $T = T(h_E)$, where T, the SST anomaly in the eastern end of the basin, is the SST anomaly influencing the winds. Thus, the model denies the thermodynamics the freedom to cause an oscillation; it allows nothing resembling the SST mode. Its oscillations depend solely on ocean dynamics, though the Sverdrup balance of the fast-wave limit is met for the low-frequency, ENSO-like modes. The variations of h_E, a consideration beyond Sverdrup dynamics, are responsible for the unstable oscillations. With the linear relations

$$A_e = AT = A\alpha h = Kh \qquad (3)$$

with A, α, K, all constants, the solutions of Cane et al. (1990) show that a pure neutral oscillation does not allow h_E and A_e to be in phase; growth is inevitable. It is important to note that all the wave dynamical/delayed-oscillator models rely on this mechanism, wherein the waves set the boundary condition on (1). They abide by the Sverdrup balance (1), going beyond it to achieve unstable oscillations with periods of many wave-crossing times.

Whether SST or wave modes prevail depends on *geometry*. The SST mode is independent of boundaries, whereas these wave model modes are *bounded* basin

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modes, nonexistent in an x-periodic domain. They depend on a geometry where the winds depend on the SST to the east, which is coupled tightly to thermocline displacements via upwelling. [Cane et al. (1990) discuss such geometric factors at some length.]

Low-resolution ocean models (Meehl 1990; Lau et al. 1992) are too coarse to properly resolve equatorial upwelling: if the scale of equatorial upwelling is 1° of latitude, a 4° model reduces upwelling by a factor of 4 or more (more because of higher lateral viscosity). This weakens the link from thermocline displacement to SST, effectively disabling the wave mode. The oscillations in such coupled models must rely on the SST mode (cf. N).

Coupled models with high enough resolution to adequately represent equatorial upwelling contain the physics needed for both the SST mode and the wave mode. In all such models the wave mode appears to be the dominant cause of interannual oscillations: it has the higher growth rate. This category includes both coupled GCMs (Philander et al. 1992) and intermediate models including one used to make predictions (Cane et al. 1986). These models are more likely to be correct by virtue of their higher resolution, and the success of the predictions further argues for the greater importance of the wave mechanism in nature. However, the case is not conclusive.

We may look further for distinguishing features of the two modes. Both involve propagation of thermocline anomalies, but, as noted in N, the SST mode tends to propagate SST anomalies westward while the wave-mode SSTs tend to be stationary, concentrated in the eastern ocean. Similarly, the wind anomalies of the SST mode are propagating while those of the wave mode are nearly stationary to the west of the SST anomalies.

Figures 1 and 2 illustrate the behavior of the SST and wind anomalies during an ENSO event. These figures are based on the Rasmusson and Carpenter (1982) composite of six ENSO events. Individual events have their idiosyncracies, which may or may not be extraneous to ENSO. The composite should be more representative of quintessential ENSO behavior. The figures exhibit both propagating and standing aspects, but the latter dominate. This reinforces the argument of the preceding paragraph, that the wave mode is the more important for the real ENSO. At the same time, as noted by Cane et al. (1990), it fails to simulate the early warming at the date line—among other things. So while the wave mechanism appears the more important of the two, a role for the SST mode is certainly not ruled out.

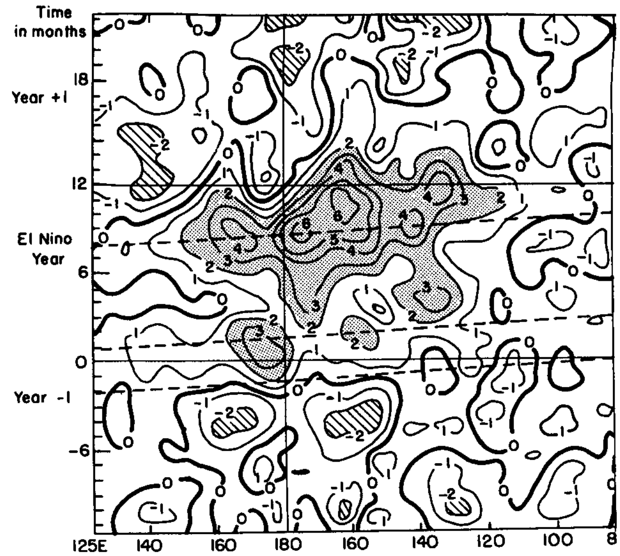

FIG. 2. Zonal wind stress along the equator, based on the composite El Niño wind anomaly field of Rasmusson and Carpenter (1982). Dotted lines, which indicate the path of an oceanic Kelvin wave, give a reference for propagation speed.

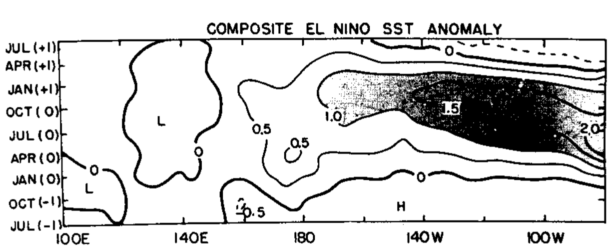

FIG. 1. SST composite El Niño anomalies, after Rasmusson and Carpenter (1982). El Niño year is year 0. The section follows the equator to 95°W and then follows the climatological cold axis to its intersection with the South American coast at 8°S.

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