13D.7 APPARENT COUPLING BETWEEN ATMOSPHERIC CONVECTION AND OCEANIC KELVIN WAVES

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1. INTRODUCTION

Observations suggest that atmospheric convection initially associated with the Madden-Julian Oscillation (MJO) occasionally becomes coupled to oceanic Kelvin waves in the Pacific Ocean. This convection propagates more slowly eastward than the average MJO signal but more quickly than that attributed to the El Niño/Southern Oscillation. Surface westerly winds associated with the convection increase sea surface height and generate anomalous or total eastward currents that suppress cool water advection or advect warm water eastward.

The atmospheric convection associated with these oceanic Kelvin waves is the paramount convective signal in the tropics when it occurs. Such dominant atmospheric convection might initiate Rossby wave trains that emanate into the extratropics. Roundy and Gribble-Verhagen (2010) revealed a significant statistical relationship during boreal winter between coupled wave events and high-latitude 300 hPa geopotential height anomalies. Because the convection moves more slowly than the convection attributed to the conventional MJO, a longer lead-time may exist for predicting global flow pattern anomalies once an event has been identified in real-time.

Another consequence of the slow moving, intense convection is the potential for tropical cyclones to form within or near the convective envelope. Gribble-Verhagen and Roundy (2010) showed a greater concentration of tropical cyclone genesis events within the convective envelope of an apparently coupled event in November-December 1986. Our own results show a significant relationship between these events (in addition to the 1986 case) and tropical cyclone formation in the tropical Pacific Ocean.

This presentation will assess processes involved in the coupling, including zonal water advection, upwelling suppression, atmospheric convection, zonal wind evolution, and solar radiation. In-situ and remotely sensed atmospheric and oceanic data from two well-observed events will be analyzed to illustrate some typical characteristics of the atmosphere and ocean in a coupled event.

2. DATA AND METHODOLOGY

Atmospheric convection was identified by anomalies of interpolated outgoing longwave radiation (OLR; Liebmann and Smith 1996). The OLR data were obtained from the Physical Sciences Division of the Earth System Research Laboratory. These OLR anomalies were computed by subtracting the seasonal cycle and first three harmonics. Incoming solar radiation data were provided by the Woods Hole Oceanographic Institution (WHOI) Objectively Analyzed Flux (OAFlux) project. The surface zonal wind, 10 m zonal current, 20°C isotherm depth, and sea surface temperature (SST) data were supplied by the Tropical Atmosphere and Ocean (TAO) array of moored buoys in the equatorial Pacific. The zonal SST gradient was computed from the NOAA Optimum Interpolation 1° x 1° weekly mean SST dataset (Reynolds et al. 2002). This gradient was calculated as the centered finite difference of the SST at two gridpoints separated by 4° of longitude.

This study adopted the selection criteria of Roundy and Gribble-Verhagen (2010). Those criteria consisted of a negative correlation between negative OLR anomalies and positive sea surface height anomalies that were approximated by dynamic height anomalies (Roundy and Kiladis 2007). The OLR anomalies had to have been locally less than -1 standard deviation. This correlation needed to be found at three or more adjacent TAO buoys.

3. RESULTS AND DISCUSSION

3.1 *Overview*

Figure 1 shows a Hovmoeller diagram of a coupled event that occurred in late 1992 and early 1993, seen in anomalous OLR and dynamic height. This coupled event began as a typical

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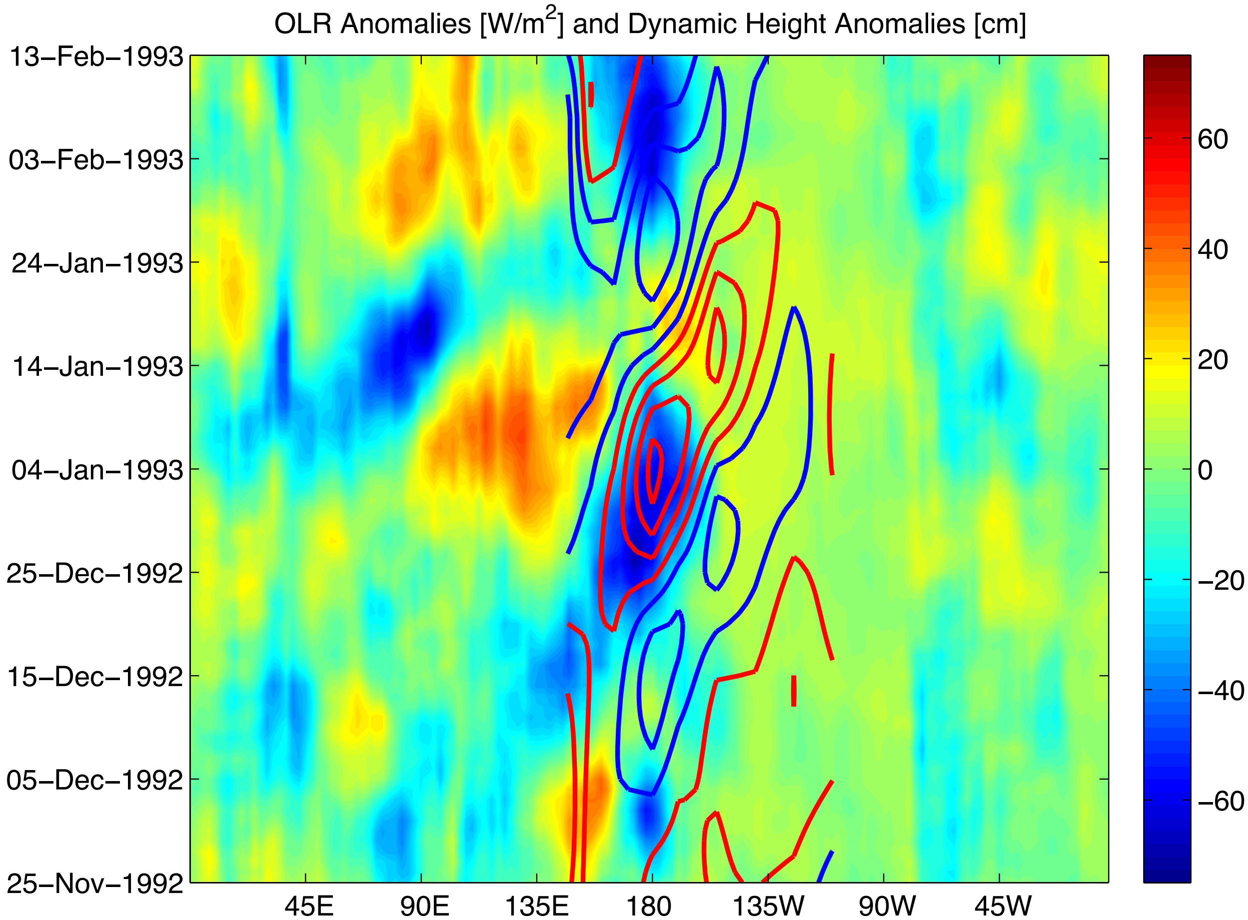

Figure 1. Hovmoeller diagram of a convectively coupled oceanic Kelvin wave that occurred in late December 1992 through early January 1993. OLR anomalies (W/m^2) are shaded. Positive (negative) dynamic height anomalies (cm) are contoured every 4 cm in red (blue), beginning at +/– 2 cm.

MJO event with active convection propagating eastward at around 5 m s^{-1} over the Indian Ocean in late November and December 1992 that then propagated over the western and central Pacific warm pool. The convection then intensified. As the convection intensified, surface winds increased surrounding the convection (not shown here). The faster westerly winds on the western side of the convection caused an oceanic Kelvin wave to develop, as seen by the positive sea surface height anomalies that are approximated by the dynamic height anomalies plotted in Figure 1. These positive sea surface height anomalies occurred directly under the convection. The convection and Kelvin wave propagated eastward together at 1-2 m s^{-1} until roughly 10 January.

The detection algorithm discussed in section 2 found 40 events in addition to the one discussed above. The reduction in phase speed and intensification of the convection as seen in Figure 1 are common characteristics of all events. Roundy and Gribble-Verhagen (2010) checked all cases of negative OLR anomalies propagating at 1-2 m s^{-1} on 30 to 100 day timescales in the equatorial Pacific and found an oceanic Kelvin wave to be associated with each case.

3.2 ***Oceanic mixed layer heat balance***

This section focuses on oceanic processes that might have positive effects on atmospheric convection development or maintenance. One such process is zonal advection of warm or cool water. Advection depends on the SST gradient and current. Either a reduction in westward ocean current or a complete reversal to eastward current occurs when the surface westerly winds strengthen due to intensifying convection. We see this behavior in in-situ zonal current data.

In-situ data from the TAO buoy located at 0°, 170°W exist for 7 events. The length of the data record is 4,673 dates, beginning in May 1988. A gap in the current (velocity) record exists from 1994 to 2002. Over all dates, the mean 10 m zonal current is 0.23 m/s to the west. We focus only on the zonal current u because zonal ocean temperature advection contributes at least four times more to the variance of the SST tendency in the central Pacific than meridional advection (McPhaden 2002) and the meridional gradient of SST in the central Pacific is weak. Qualitative comparisons between the current and dynamic height anomaly time series show that the two quantities evolve with the same phases. In other words, the most eastward current values tend to occur when the dynamic height anomaly is positive and vice-versa. Because of this tendency, we have focused on the dates on which the dynamic height anomalies ϕ' were positive at 170ºW and recorded the mean current during those periods. The results are in Table 1.

Crest date at 0º, 170°W	Mean u (m/s)	Period length (days) $\phi' > 0$
15 Feb. 1990	–0.23	33
22 Nov. 1991	0.56	33
19 Mar. 1992	0.08	23
7 Jan. 1993	–0.14	36
14 Dec. 2002	0.20	29
20 Apr. 2004	0.10	38
20 Feb. 2005	–0.33	47

Table 1. Mean zonal current (u) values for the higher sea surface height ($\phi' > 0$) phase of oceanic Kelvin waves that crested on the dates listed at 0º, 170ºW.

In some events, the current does switch from westward to eastward. In other events, the current reduces its westward magnitude but does not switch to eastward. In some of these events, net eastward current developed farther west and was offset of background westward current at 170°W.

To consider the effects of the changing current and changes in ocean vertical velocity, we consider the approximated mixed layer oceanic heat balance equation

$$\left(\rho_0 c_p H\right)\frac{\partial T}{\partial t} \approx -\left(\rho_0 c_p H\right)\left(u\frac{\partial T}{\partial x} + \frac{\mathrm{H}(w)w\Delta T}{H}\right) + Q_{SW} + Q_{LH} \quad (1)$$

where ρ_0, the ocean water density, is 1035 kg m^{-3}; c_p, the specific heat capacity for ocean water, is 3993 J kg^{-1} K^{-1}; H, the mixed layer depth, is 100 m; T is SST; x is zonal distance; w is vertical velocity at the bottom of the mixed layer, ΔT is SST – $T_{H+20\,\mathrm{m}}$, where $T_{H+20\,\mathrm{m}}$ is the temperature at a depth 20 m greater than the mixed layer depth; $\mathrm{H}(w)$ is the Heaviside step function, defined as $\mathrm{H}(w) = 1$ for $w > 0$ (upwelling) and $\mathrm{H}(w) = 0$ for $w < 0$ (downwelling); Q_{SW} is incoming shortwave radiation flux and Q_{LH} is latent heat flux (McPhaden 2002). We ignore meridional advection, outgoing longwave radiation flux and sensible heat flux because these processes contribute less to SST tendency on intraseasonal timescales (McPhaden 2002; Shinoda et al. 1998) in the central Pacific where the cold tongue is not as pronounced as it is farther east. Prior to most of the dates listed above, the zonal SST gradient was near the climatological mean value of about 0.5 × 10^{-6} °C/m, increasing toward the west. During some events, this westward gradient increased in magnitude to about 1.0 × 10^{-6} °C/m. Assuming that the zonal current prior to the dates on which the Kelvin wave ridge reaches the buoy is the mean westward current of 0.23 m/s, the equivalent heat flux due to zonal advection ranges from -48 to -96 W/m^2. If u reduced to 0, the mixed layer would then no longer be losing thermal energy at the rates of 48-96 W/m^2. That suppression of cool water advection could yield more energy available to be given up to the atmosphere. In addition, in some events, the current flips sign but retains its previous magnitude or even exceeds its previous magnitude during the sea surface height ridge periods with the zonal SST gradient roughly left unchanged. Such current reversals could lead to a doubling of the energy available to the ocean mixed layer compared to its state during cool water advection.

As convection develops, the incoming solar radiation flux is roughly reduced from 250 W/m^2 to 150 W/m^2. If insolation was reduced by 100 W/m^2 and the rest of the processes affecting SST tendency were held constant, SST would decrease by about 0.4ºC. In actuality, the SST did decrease by 0.2–0.4°C for 5 of the 7 events, and it increased by 0.2–0.3°C for 2 of the 7 events. These SST changes were obtained by observing the SST prior to onset of the intraseasonal convective events and the local SST minimum that occurred during or just after active convection. So, for the events during which SST increased, some process(es) other than changes in insolation must account for the warming. For the events during which SST decreased, some physical processes could still switch signs and change magnitudes while yielding a net change of zero in the sum of those quantities. Suppression of cool water advection is one process to consider. Another is suppression of upwelling.

McPhaden (2002) described upwelling/downwelling (or vertical advection and entrainment) as $\mathrm{H}(w)w\Delta T/H$. He found that the time-mean of w at 50 m depth (close to the base of the mixed layer) at 170°W is $\overline{w} = 2.1 \times 10^{-5}$ m s^{-1}, directed upward. We get a rough estimate of the vertical velocity at the base of the mixed layer with the time-rate of change of the 20°C isotherm depth. During each of the events listed in Table 1, the vertical velocity is 0 or downward during the onset of the convection and while the dynamic height anomaly is increasing. After shutting off upwelling, the ocean mixed layer is no longer losing roughly 173 W/m^2, as determined by $\overline{w}$ and an average ΔT of 2.0°C.

When considering altogether the reduced insolation, halted cool water advection and halted upwelling, the mixed layer could be gaining energy at the rate of 121 to 169 W/m^2, which could then be given off to the atmosphere in the form of latent and sensible heat fluxes. Johnson et al. (2007) have shown that convection is sensitive to latent heat fluxes of these magnitudes. If warm water advection occurs, the increase in energy flux could be even greater.

4. CONCLUSION

The superposition of OLR anomalies, dynamic height anomalies, and surface zonal winds for some MJO events suggests coupling between the oceanic Kelvin wave and atmospheric convection. The first event in the coupling process is the active phase of an MJO event that enters the western Pacific. Then the convection intensifies, slows its eastward propagation, and narrows its zonal width. During the early stages of convection intensification, increased surface westerly winds cause an oceanic Kelvin wave to develop. The convection and Kelvin wave then propagate together for the next few weeks.

The Kelvin wave facilitates energy transfer from the ocean to the atmosphere through alterations in the ocean velocities. During the downwelling phase of the Kelvin wave, vertical entrainment (upwelling) and cool water advection are inactive. The removal of vertical entrainment and cool water advection from the mixed layer heat budget allows for more energy to be given up to the atmosphere in the form of latent heat fluxes. Latent heat fluxes do increase as convection approaches from the west, because surface winds intensify in response to the convection.

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