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INCORPORATION OF EQUATORIAL WAVE MODES INTO TROPICAL SYNOPTIC METEOROLOGY: IS IT WORTH THE TROUBLE?

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1. INTRODUCTION:

A number of recent studies have shown the importance of lower-tropospheric, convectively-coupled equatorial waves (i.e., linear solutions on the equatorial beta plane) in modulating tropical cloudiness and weather (Takayabu 1994; Wheeler and Kiladis 1999; Wheeler et al. 2000; Yang et al. 2003; Roundy and Frank 2004). Evidence is growing that equatorial waves play a role in tropical cyclogenesis as well (Takayabu and Nitta 1993; Dickinson and Molinari 2002; Frank and Roundy 2006; Bessafi and Wheeler 2006; Molinari et al. 2006). There is no doubt that knowledge of such waves contributes enormously to understanding tropical circulations, including the response to diabatic heating (Gill 1980). The value of the direct use of equatorial wave theory in tropical weather forecasting is less certain. A number of researchers have already developed tools to bring equatorial waves into the forecast process (e.g., Wheeler and Weickmann 2001; Frank and Roundy 2006). This writeup and subsequent talk will address some of the issues of real-time use of equatorial wave concepts.

2. NATURE OF WEATHER FORECASTING:

LaSeur (personal communication 1975) noted the importance of "synoptic models" in weather forecasting. These represent a conceptual model of how a disturbance looks on satellite images and on weather maps. The Norwegian frontal cyclone model and the mesoscale convective complex represent two examples. Synoptic models make it possible to identify the disturbance type in real time.

To our knowledge, few forecasters in the deep tropics use synoptic models of equatorial waves in their predictions. Nevertheless, more general synoptic models are being used. Smith et al. (2001) held a workshop that brought together researchers and forecasters in tropical meteorology. The forecasters, who represented a wide range of locations within the tropics, each noted that the most difficult-to-forecast heavy rain events in their region (other than tropical cyclones) arose from "easterly waves". However, the physical description of what was meant by the term varied from location to location. A general conclusion could be made: significant rainfall events occurred within westward propagating low pressure areas in every region. The extent to which such events are associated with equatorial waves remains an open question.

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The modal solutions for equatorial waves contain rough synoptic models. Distinguishing features include whether the waves are symmetric or anti-symmetric with respect to the equator, whether the disturbances are moving eastward or westward, and whether vorticity and convective maxima lie on or off the equator. In nature, however, equatorial waves often vary from their modal solutions, especially in the western Pacific (Yang et al. 2003; Wheeler et al. 2000; Hoskins 2006). The most significant variations relate to the degree of equatorial symmetry and to the location of strongest convection and precipitation. Thus one aid to developing forecasting applications is the continued development of good synoptic models for each significant wave type.

3. ADVANTAGES AND DISADVANTAGES OF REAL-TIME APPLICATION OF EQUATORIAL WAVE THEORY:

Given the overriding importance of equatorial waves shown in recent papers, it might seem clear that such waves must be adapted into forecasting practice. But some natural limitations occur that must be addressed. Figure 1a shows a time series of 850 hPa meridional wind averaged from 5-20ºN over the west Pacific during summer of 1991 from Molinari et al. (2006). This rather typical field shows numerous mostly westward-propagating disturbances of varying speeds and wavelengths, including tropical cyclones. One aspect of equatorial wave identification becomes apparent: it requires filtering to separate out the various wave types.

Figure 1b shows the same field after bandpass time filtering (15-40 d). A remarkable equatorial Rossby (ER) wave packet emerges from the filter that lasted almost 3 months. Tropical cyclones formed repeatedly east of low pressure centers within the packet. Of the 13 tropical cyclones present during the lifetime of the packet, 11 formed in the above manner. The coherence shown in Figure 1b, and the apparent influence of the waves on tropical cyclogenesis, seems like an advertisement for the value of thinking in terms of equatorial waves. The existence of such coherent patterns over fairly long periods led Hoskins (2006) to state that "forecasting should be easy in the tropics".

The limitations of such thinking relate to the need for filtering. In Figure 1b the time filtering was done after the fact, i.e., the wind field was known for all future times when the filtering was done. In real time such is not the case. Figure 2 shows the same packet as it would look if the date were 20 September 1991. All future times were simply set to zero

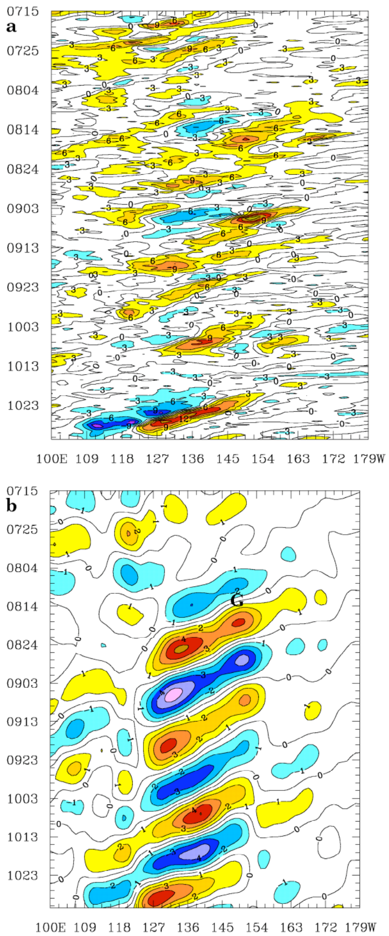

Figure 1. Longitude-time series of 850 hPa meridional wind, averaged 5ºN-20ºN, for the period 15 July - 30 October 1991. (a) Unfiltered; (b) Bandpass-filtered with half-power points at 15 and 40 days. Contour increment (a) 3 m s^{-1} and (b) 1 m s^{-1}. Shading in warm and cool colors represents, respectively, southerly and northerly wind components exceeding (a) 3 m s^{-1} and (b) 1 m s^{-1}. The letter "G" indicates the initial appearance at 15ºN of the monsoon gyre described by Lander (1994).

following Wheeler and Weickmann (2001). It is clear that the duration of the packet cannot be identified in real time. Nevertheless, Figure 2 offers some encouragement. First, the "forecast" packet remains accurate out to about one half wave period into the future (11 days in this case). Thus some extrapolation can be made with reasonable lead times. The second encouraging aspect of Figure 2 is the accurate identification of the existing wave packet. In this case a forecaster could say that *if* the packet continues, low pressure areas can be expected to grow starting at the east end of the packet and to produce heavy precipitation and/or tropical cyclone formation to their east as they move westward.

Figure 3 provides an example of a synoptic model for the ER waves in the packet above, represented in terms of total 850 hPa winds and OLR composited about the time and location of tropical

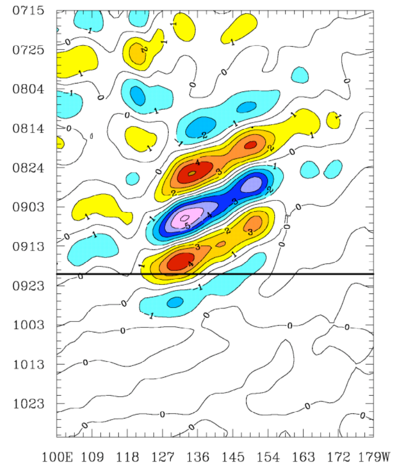

Figure 2. As in Figure 1b, assuming no information is available after 20 September 1991. This gives a measure of real-time filtering for the day in question.

cyclone formation. The storms form east of the ER wave low, not in its center. Maximum convection exists east of the low, but also equatorward. The Southern Hemisphere reflection of the ER wave (not shown; the composite southern boundary of Figure 3 is 4.3ºN) is much weaker and shifted to the east. The structure shown in Figure 3 closely resembles that found by Wheeler et al. (2000), Frank and Roundy (2006), and Hoskins (2006). It appears to be a good representation of a synoptic model of an ER wave low in the northwest Pacific. In satellite pictures it will appear as a zonally extended cloudy region moving westward with strong Northern Hemisphere near-equatorial convection. An additional convective region north of the eastern part of the equatorial band represents a potential "hot spot" for tropical cyclone development. Convection is much weaker or non-existent at the center of the associated ER wave low pressure area.

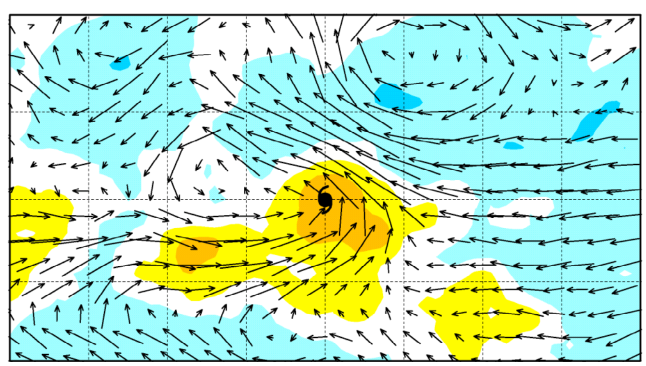

Figure 3. Unfiltered OLR and unfiltered 850 hPa wind, composited with respect to the genesis location of 8 ER wave-related tropical cyclones that formed east of 135ºE. The mean genesis point, indicated by the hurricane symbol, lies at 14.3ºN, 152.5ºE. OLR shading: red: ≤ 150 W m^{-2}; orange 150-180 W m^{-2}; yellow 180-210 W m^{-2}; light blue: 240-270 W m^{-2}; darker blue > 270 W m^{-2}. Latitude and longitude lines are plotted in 5º increments.

Figures 1-3 represent a single case study, but Dickinson and Molinari (2002) found analogous results for a mixed Rossby-gravity wave packet that produced three tropical cyclones. The construction of real-time Hovmöller diagrams appears to have potential value as a forecasting tool. However, many questions remain: which variables to use; what filtering parameters; what latitude range; what wave types; etc. Much has been done (e.g., Wheeler and Weickmann 2001), but much work remains. We argue that there is considerable potential value for forecasting in developing synoptic models of equatorial wave signatures on satellite and on weather maps.

4. ROLE OF BACKGROUND FLOW:

Webster and Chang (1988) proposed a conceptual model for tropical flows based on equatorial waves and their interaction with the background flow. Their study considered the upper troposphere, but the same concepts can be applied (with more value in terms of weather forecasts) in the lower troposphere, as was noted by Holland (1995). The idea is as follows: strong lower-tropospheric waves in the tropics (and thus large precipitation and the potential for tropical cyclone development) occur in regions where the lower-tropospheric background flow contains $du/dx < 0$, representing zonal flow convergence and negative stretching deformation. In a forecasting situation it might be possible to follow the background convergence and/or deformation fields in a Hovmoeller diagram like Figure 1, and simultaneously track waves using time filtering (or space-time filtering following Wheeler and Kiladis 1999). Wave growth would be expected in convergent regions. It might be possible to predict significant weather events with several days lead time. These ideas will be developed further in the talk.

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