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NOTES AND CORRESPONDENCE

On the Dynamics of Easterly Waves, Monsoon Depressions, and Tropical Depression Type Disturbances

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Abstract

The authors argue that certain aspects of the rotational, synoptic-scale disturbances of the wind field that are observed in ITCZ or monsoon trough regions can be understood by considering the linear response of a dry, initially resting atmosphere to a pulse of heating whose amplitude and spatial and temporal scales are characteristic of a large mesoscale convective system. The key points are that short Rossby waves have small intrinsic group and phase velocities, and that a heating pulse projects much more energy on the Rossby modes if it is located slightly off rather than on the equator. It follows that synoptic-scale Rossby waves, with characteristics broadly similar to those of observed disturbances, should be present in off-equatorial regions of persistent deep convection, since large mesoscale convective systems tend to develop in such regions.

1. Introduction

Synoptic-scale weather disturbances of a certain type are common to a number of tropical oceanic regions. We refer to the disturbances known variously as "easterly waves," "monsoon depressions," and "tropical depression type" (TD-type) disturbances. There are regional differences, but some basic features appear generic (Lau and Lau 1990).

The disturbances have a rotational character, possessing strong signatures in the low-level meridional wind and vorticity fields. Typical wavelengths are on the order of 2000 km. They tend to be tightly coupled to deep convection, which generally occurs preferentially near the "trough" or maximum in low-level cyclonic relative vorticity. They tend to occur in regions of persistent deep convection centered near, but not on, the equator, i.e., intertropical convergence zones (ITCZs) or monsoon troughs, particularly in the summer hemisphere. They often are precursors of tropical cyclogenesis.

It has been argued that these disturbances' propagation is consistent with Rossby wave dynamics (e.g., Holton 1970; Shapiro 1978; Davidson and Hendon 1989; Sobel and Bretherton 1999). On the other hand, Liebmann and Hendon (1990) and Takayabu and Nitta (1993) used observational composites for the western North Pacific to estimate intrinsic frequencies which were too large to be consistent with linear Rossby or mixed Rossby-gravity waves on an equatorial β plane with no background shear. Possible reasons for this apparent disagreement include the difficulty of estimating a small intrinsic phase speed in the presence of a larger "steering" flow which has some horizontal and vertical shear, actual physical effects of shear on the frequency (e.g., a meridional relative vorticity gradient

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which could augment β, thereby increasing the intrinsic frequency of Rossby waves), or perhaps nonlinear effects.

The generation of disturbances of this type over the Atlantic region is relatively well understood (see Thorncroft and Hoskins (1994) for a recent review), involving shear instability over Africa. However, in all other regions where similar disturbances occur, their generation and maintenance mechanisms are at least to some extent controversial. Some of the dynamical arguments which have been proposed to explain the disturbances' existence are regional in character, such as flow past the Sierra Madre in the case of the eastern North Pacific (Mozer and Zehnder 1996), or wave accumulation via the strong low-level time-mean zonal convergence in the western North Pacific (Holland 1995; Sobel and Bretherton 1999). It is unclear to what extent the disturbances in the various regions are fundamentally similar dynamical phenomena.

The purpose of this note is to suggest that some aspects of these synoptic-scale tropical disturbances may be understood by considering the linear response of a hypothetical dry, initially resting tropical atmosphere to an imposed pulse of heating, such as might represent (in an idealized way) a large mesoscale convective system. Studies in which the response of an otherwise adiabatic atmosphere to an imposed heating is examined are extremely numerous.[1] A number of these are similar to the present work either in the form of the heating or the emphasis on some aspects of the Rossby wave part of the response (Silva Dias et al. 1983; Salby and Garcia, 1987; Lim and Chang 1987; Bergman and Salby 1994; Holland 1995; Horinouchi and Yoden 1996; Mapes 1998). The present work reveals no fundamentally new physics.

However, to our knowledge, certain aspects of the dynamical relevance of calculations using a pulse of heating to easterly waves and their ilk have not been directly pointed out. The fundamental points emphasized here are that synoptic-scale Rossby waves have very small intrinsic group and phase velocities, and that the projection of a pulse of heating onto the Rossby modes is much larger if the heating is imposed slightly off, rather than on the equator. Additionally, we know observationally that large mesoscale convective systems occur in regions of persistent deep convection, where by "large" we mean having spatial scales of several hundred to 1000 km (implying a large areally integrated heating) and time scales on the order of a day (e.g., Nakazawa 1988; Mapes and Houze 1993). The calculations show that observed amplitudes of such systems are at least broadly consistent with observed synoptic-scale wind perturbations. These facts together imply that disturbances whose wind fields have the general character of easterly waves should be expected to occur in regions of persistent deep convection centered off the equator, even if the waves are assumed to lack any dynamical mechanism for influencing convection. The relatively low intrinsic frequencies of the waves may also make them more effectively stimulated by certain mechanisms, discussed in the recent literature, which tend to cause convection to persist in a given air column once initiated there.

1 A list of such studies can be found, for example, in Mapes (1998).

2. Calculations

2.1 Basic results

We present calculations using the linear model of Horinouchi and Yoden (1996, hereafter HY), with modest changes in some of the parameters compared to that study. The model is spectral in the horizontal, with the meridional structure resolved in terms of Hough functions. This allows the simulated fields to be unambiguously separated into contributions from Kelvin, Rossby, mixed Rossby-gravity, inertio-gravity, and negative equivalent depth modes. A basic state of no motion is assumed, with constant static stability below the tropopause at 1.9 scale heights above the surface, and a larger (but still constant) static stability above that level, with values typical of earth's atmosphere and identical to those used in HY. The boundary conditions are linearized free slip at the lower boundary and a radiation condition at the upper boundary. The zonal resolution is 72 wave numbers, and the meridional resolution corresponds roughly to a rhomboidal truncation, but with a slightly larger number of modes so that the meridional resolution is slightly higher than the zonal. In the present calculations, temperature perturbations are damped using a Newtonian cooling with a time scale of 20 days. No momentum damping is used. A more detailed description of the model can be found in HY.

We show calculations which are very similar to ones shown in HY, though we focus here on different aspects than did that study. As in HY, the heating is a half-sine in the vertical

$$J = J_0 \sin(\pi\zeta/\zeta_T) \exp[-t^2/2T^2 - (\lambda-\lambda_0)^2/2\Lambda^2 - (\phi-\phi_0)^2/2\Phi^2]; \quad 0 < \zeta < \zeta_T \tag{1}$$

$$J = 0; \quad \zeta > \zeta_T \tag{2}$$

where ζ is the log-pressure vertical coordinate in scale heights, λ and ϕ are latitude and longitude, respectively, t is time, and $\zeta_T = 1.5$. Λ and Φ are equivalent to 3 degrees of latitude unless specified otherwise.

Figure 1 shows the evolution of the surface winds for two calculations in which T is 0.5 day and $\phi_0 =$ 10N and the equator. The peak heating, J_0, is 30 K

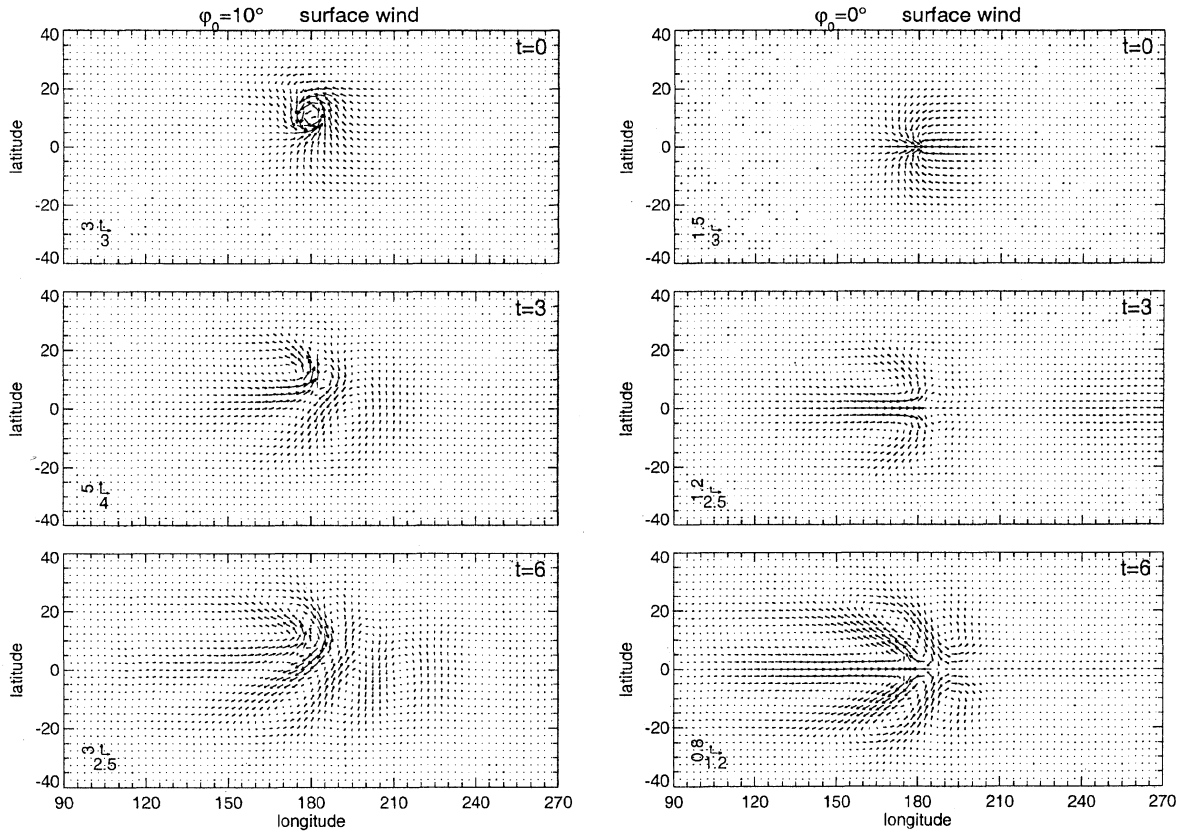

Fig. 1. Surface winds for calculations in which $\phi_0 = 10$N (left) and the equator (right) at 0, 3, and 6 days after the time of maximum heating. Note different arrow scalings in each panel. Further details given in text.

per day. The time origin is defined as the time when the heating is at its maximum (so the calculation actually begins at $t < 0$). For the times shown here, the winds at ζ_T (not shown) are very similar to those at the surface, but with opposite sign, though at later times there are some differences in the far field due to the vertical propagation of gravity and mixed Rossby-gravity waves.

At $t = 0$, the wind field in Fig. 1 is almost entirely divergent for the equatorial heat source, while it has a large rotational component for the off-equatorial heat source. This is easily understood; off the equator, where the magnitude of the coriolis parameter $|f| > 0$, the heating can stretch the ambient planetary vorticity to create relative vorticity, while at the equator $f = 0$ and this cannot occur. The subsequent evolution reflects this difference, with the equatorial response showing a clear Kelvin wave signature. The off-equatorial heating produces a wind field that has a greater Rossby wave component, with a dominant wavelength around 2000–2500 km. Even many days after the heating has ended, a substantial response remains near the heating's former location for the off-equatorial case, clearly reflecting the near-zero group velocities of the short Rossby waves. Mapes (1998), discussing similar calculations, very briefly noted a similar short Rossby response trapped near the initial heating region for an off-equatorial heating pulse. Besides the different structure, the equatorial heating leaves behind altogether weaker winds near the heating region at later times.

Figure 2 shows the total, potential and kinetic energies in the solutions, partitioned into Rossby and gravity components. The energy is horizontally averaged over the globe and integrated in time, but shown as a function of height. Modes with negative equivalent depths are also plotted for completeness. Kelvin waves and inertio-gravity waves are included in the gravity wave component, as are mixed Rossby-gravity waves with zonal wave numbers equal to four or less. Mixed Rossby-gravity waves with zonal wave numbers equal to five or greater are counted with the Rossby modes. This distinction for the mixed mode cannot be made precisely given the smooth transition from gravity-like to Rossby-like dynamics which occurs as the wave number increases, but small changes in the definition will not make large differences in the present results. The figure shows, as expected, that the

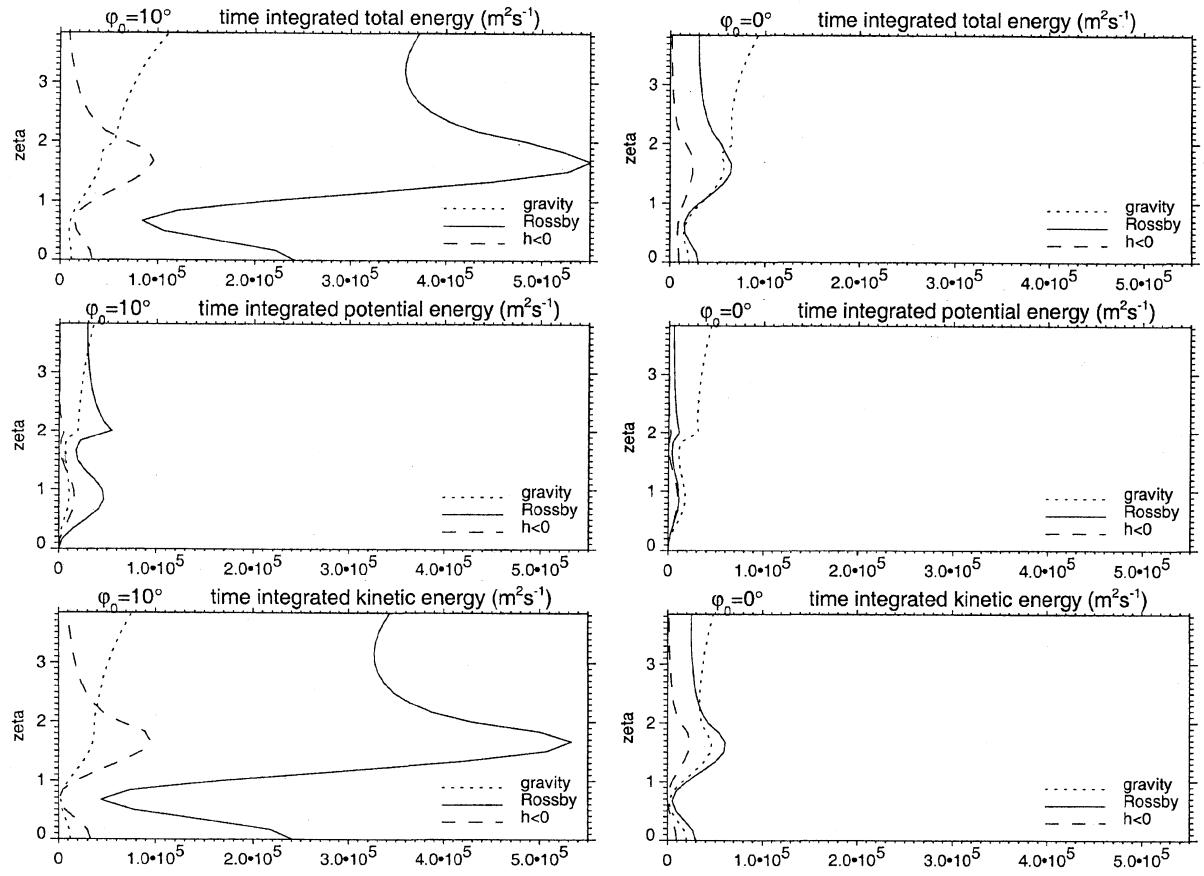

Fig. 2. Energy partitioning for calculations shown in Fig. 1. Details in text.

off-equatorial heating projects an order of magnitude more energy on the Rossby mode than does the equatorial heating.

2.2 Vertical structure

The meridional wind field of the perturbations has a vertical structure (not shown) which corresponds to a first baroclinic mode, as is essentially mandated by the deep heating profile used, with maxima at the surface and near the tropopause. Temperature perturbations are consistent with the wind perturbations through thermal wind balance, so that the cyclonic wind anomalies in Fig. 1 are warm core, with maximum surface temperature anomalies around 0.5 K at $t = 3$. Calculations have also been performed with a "top-heavy" heating profile such as may be expected from a mesoscale convective system (Houze 1982; Johnson 1992). As might be expected, this change causes the lower-level wind maxima to occur above rather than at the surface, and accordingly induces a surface cold core in the cyclonic phase, in better agreement with observational composites (e.g., Reed and Recker 1971; Lau and Lau 1990; Takayabu and Nitta 1993; Chang et al. 1996). The response is otherwise similar to the deep heating case.

2.3 Effect of the heating's horizontal scale

The heating in the above calculations has a horizontal scale on the order of 400 km. It is of interest to know how a reduction in the horizontal scale of the heating affects the result. We performed a calculation identical to the off-equatorial one presented above, but with a heating half the size in both horizontal dimensions, that is Λ and Φ equivalent to 1.5 degrees of latitude. T was kept at 0.5 days. To resolve the small heating region, the resolution of the model was doubled, and the frequency resolution quadrupled. The spatial scale of the wind pattern was approximately halved, compared to that in Fig. 1a, but the wave structure was very similar to that shown in Fig. 2. Likewise, the energy partitioning was extremely similar to that shown in Fig. 2; the Rossby response was essentially identical, and the gravity wave response was in fact slightly reduced.

2.4 Effect of the heating's temporal scale

Sensitivity of the energy partitioning to the heating time scale (T) is shown in Fig. 3 as the perturbation total energy, integrated over all time, at $\zeta = 1.5$ (the analogous plot at $\zeta = 0$, not shown, is nearly identical). Time-integrated heating rate is kept con-

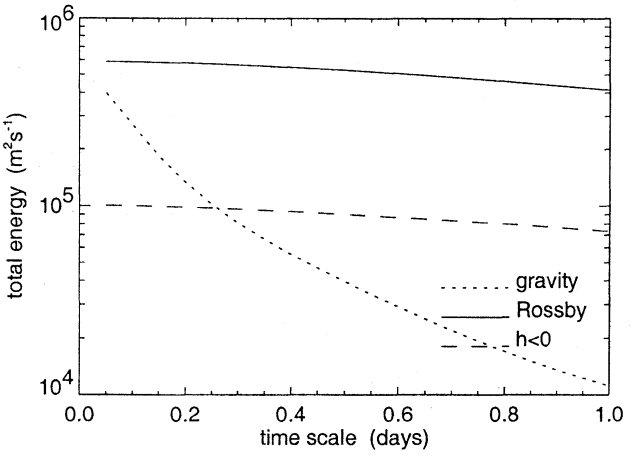

Fig. 3. Total energy in Rossby, gravity, and negative equivalent depth modes, for a heating with spatial structure identical to that used for calculations shown in Fig. 1, but with variable time scale T. Total integrated heating is held fixed.

stant for this plot, and the spatial structure is also held the same as that used in Fig. 1. As expected, the energy of gravity waves rapidly increases with decreasing T, while that of the other components is less sensitive. It is noteworthy, though, that gravity waves have less energy than Rossby waves even at $T = 0.05$ days. The total energy of the latter is enhanced by their large kinetic-to-potential energy ratio; the potential energy of gravity waves is larger than that of Rossby waves at $T = 0.2$ days or less.

2.5 Amplitude

If J is averaged over a circle centered on the maximum with a radius equal to that at which it falls to $1/e$ times its maximum value (a radius of 4.2 degrees) and the corresponding e-folding time interval $-\sqrt{2}T < t < \sqrt{2}T$), an average vertical maximum heating rate of roughly 15 K/day is obtained, similar to typical values obtained for mesoscale convective systems (Houze 1982; Johnson 1992). This is sufficient to produce wind anomalies of several ms^{-1}, which is consistent with observed wind anomalies. The area over which the heating is imposed in our calculations is, however, fairly large compared to a typical mesoscale system, implying a similarly large areally integrated heating; this is discussed further below.

3. Discussion

The above calculations are sufficiently idealized that detailed comparison with observations is not warranted. Broadly, though, the near-field Rossby response to the off-equatorial heating pulse has the character of observed easterly waves, monsoon depressions, and TD-type disturbances, in that these are transient, rotational, Rossby wave-like disturbances with horizontal scales comparable to the dominant scale in Fig. 1a. The presence of vertical shear can be expected to have a substantial modifying effect on the vertical structure (Holton 1971). A surface cold core, consistent with observations, is obtained if the heating vanishes in the lower troposphere. Observed frequencies and phase speeds, which are typically on the order of three–five days and a few ms^{-1} respectively, but are regionally variable to some extent, will according to this explanation be strongly affected by the basic flow since the intrinsic frequencies and phase speeds are small. The small group velocities explain the fact that the disturbances are observed in ITCZ or monsoon trough regions, which are off-equatorial regions containing persistent deep convection. The synoptic-scale flow disturbances are forced in such regions, and their energy cannot propagate away quickly.

Regarding the disturbances' amplitude, discussed above, a single mesoscale system which sustains a 15 K/day heating rate over an area with 400 km radius over a day and a half is surely a fairly extreme event. However, the same effect could be produced by a few smaller-amplitude heating events occurring sequentially in time. There need not be a two-way feedback between the wave and convection in order for convection to be favored in the trough region. *Any* mechanism by which an air mass in which convection initially occurs is maintained in a condition favorable to further convection may enhance the generation of short Rossby waves, because of their low intrinsic frequencies and phase speeds. If consecutive convective events are not spaced widely in time and space, the wave trough which develops in response to the first will not be able to travel far (relative to the mean flow, assuming weak vertical shear) before the second event occurs, and so on (though its amplitude will be locally reduced somewhat due to dispersion). This is nothing but a statement that modes with low intrinsic frequencies are efficiently stimulated by forcings with low intrinsic frequencies.

Mechanisms by which one deep convective system may condition an air mass so as to favor the development of others include moistening of the troposphere (e.g., Raymond et al. 1998; Raymond 2000a), radiative-convective feedbacks (e.g., Auld Miller and Frank 1993; Raymond 2000b), increased surface fluxes (Emanuel 1993; Jabouille et al. 1996), or the initiation of "subgrid-scale" variability, such as gravity waves or gust fronts, which may help near-surface conditionally unstable air parcels overcome convective inhibition (Mapes 1993, 1999). All of these mechanisms can operate independently of the large-scale wave dynamics, so the wave response can be entirely passive in this view. The argument is imprecise, but the essential point is that the unique

place occupied by short Rossby waves on the equatorial wave dispersion diagram may have implications for their coupling to convection.

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偏東風波動、モンスーン低気圧、熱帯低気圧型擾乱の力学について

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ITCZ やモンスーントラフ域で観測される回転性の総観規模風速擾乱の幾つかの側面は、大きなメソスケール対流システムに特徴的な振幅や時・空間スケールを持つパルス的加熱に対する、乾燥・静止大気の線形応答を考えることで理解できることを議論する。その鍵は、短波長のロスビー波の平均流から見た群速度、位相速度は小さいことと、加熱が赤道上よりも赤道から少し離れた位置にあるほうがロスビーモードの応答は遥かに大きなエネルギーを持つことである。故に、観測される擾乱に似た特徴を持つ総観規模ロスビー波は、大きなメソスケール積雲システムが発達する赤道を少し離れた領域に存在するということになる。