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Transition from an eastern Pacific upper-level mixed Rossby-gravity wave to a western Pacific tropical cyclone

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[1] The ancestor of unseasonal Typhoon Nanmadol (2004) over the western North Pacific is traced back to the Eastern Pacific (near 120°W) as an upper tropospheric, counter-clockwise rotating mixed Rossby-gravity (MRG) wave. The temporal and spatial evolution from an equatorial trapped MRG-wave-type disturbance to an off-equatorial tropical depression is documented by utilizing NOGAPS (Navy's Operational Global Atmospheric Prediction System) analysis data. It is found that the MRG wave moved away from the equator after a dramatic reduction in its zonal dimension and downward development and amplification in the lower troposphere. These dramatic changes in MRG wave properties are attributed to the modulation of the easterly vertical shear, low-level westerly-easterly confluence in the large-scale background flows, and convective coupling, as well as underlying high sea surface temperature (SST). The boundary layer convergence associated with asymmetric pressure field of the MRG wave is likely responsible for the transition from an equatorial MRG to an off-equatorial tropical disturbance. This case study addresses the possibility that upper tropospheric MRG waves over the far eastern Pacific may provide "seeds" for tropical cyclogenesis over the western North Pacific. **Citation:** Zhou X. and B. Wang (2007), Transition from an eastern Pacific upper-level mixed Rossby-gravity wave to a western Pacific tropical cyclone, *Geophys. Res. Lett.*, *34*, L24801, doi:10.1029/2007GL031831.

1. Introduction

[2] Two kinds of westward-propagating synoptic disturbances in the lower troposphere have been identified over the tropical Pacific – Mixed Rossby-gravity (MRG) waves and tropical depression (TD) - type disturbances [e.g., *Wallace*, 1971; *Liebmann and Hendon*, 1990; *Takayabu and Nitta*, 1993; *Dunkerton and Baldwin*, 1995]. The former are equatorially trapped waves, where the convection lags the low-pressure center by about a quarter wavelength [*Matsuno*, 1966], whereas the latter are off-equatorial wave perturbations that are characterized by deep convection occurring in the vicinity of the cyclone center. MRG waves with wavelengths of 6,000–10,000 km prevail over the central Pacific [*Liebmann and Hendon*, 1990; *Takayabu and Nitta*, 1993; *Dunkerton and Baldwin*, 1995]. In contrast, the TD-type disturbances are often seen as off-equatorial wave trains over the western Pacific with shorter wavelengths (2,000–4,000 km).

[3] Upper tropospheric MRG waves were also identified over the central Pacific, but a consensus on the connection between the upper and lower tropospheric MRG waves have not been reached. *Randel* [1992] suggested that there is no close connection between the upper and lower MRG wave branches. *Yanai et al.* [1968] have shown that the lower tropospheric MRG waves feed the lower stratospheric MRG by upward-energy-transport. *Dunkerton and Baldwin* [1995] found significant correlation to 200 mb MRG waves a few days prior to the arrival of waves in the lower troposphere.

[4] Despite the different structure and preferred regions, the MRG-type and TD-type disturbances have some dynamical connections. It is found that the lower tropospheric MRG waves can subsequently evolve into an off-equatorial TD-type disturbance when they propagate to the western Pacific, and may further develop into mature tropical cyclones [*Chang et al.*, 1996; *Takayabu and Nitta*, 1993; *Dickinson and Molinari*, 2002]. However the detailed evolution from an equatorially trapped wave to an off-equatorial TD and its associated mechanism is not well understood.

[5] The present study overcomes a number of deficiencies in the previous studies. High-pass (3–10 days) filtering was usually adopted to isolate the synoptic-scale MRG/TD-type disturbances, but the processes of the transition and genesis often take place within 3 days. Moreover, the previous works mainly focused on the linkage between the lower-level MRG waves and TD-type disturbances. The upper tropospheric MRG wave as an antecedent of tropical cyclones has not been reported. We found that an upper tropospheric MRG-wave-type disturbance acts as the precursor to a western Pacific typhoon.

2. Observed Transition From Equatorial MRG to an Off-Equatorial TD

2.1. Data and Methodology

[6] Twice daily data obtained from US Navy Operational Global Atmospheric Prediction System (NOGAPS) model with 1° × 1° latitude-longitude grid on 27 pressure levels were used for circulation analysis. The 3-hourly Tropical Rainfall Measuring Mission (TRMM) 3B42RT data with a 0.25° × 0.25° spatial resolution was used to analyze the convective activities. The TC best track data are obtained from the Joint Typhoon Warning Center (JTWC). The 11-day mean field is taken as the low frequency background flow. The synoptic perturbations were obtained by subtracting the low frequency background flow from the original twice daily data.

2.2. Scenario

[7] Figure 1 shows the track of Typhoon Nanmadol (2004) from a counter-clockwise rotating MRG gyre east

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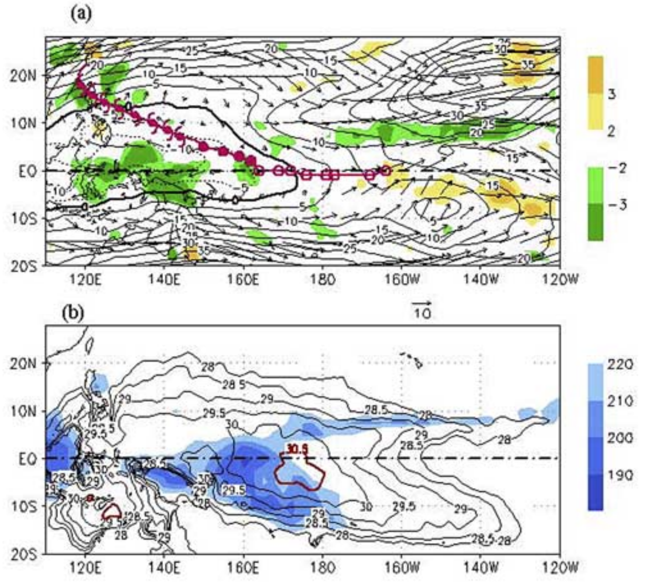

Figure 1. (a) The 11-day (22 Nov.–2 Dec. 2004) mean amplitude of the vertical shear (200 hPa–850 hPa) of horizontal wind (contour, m/s) and the divergence ($\times 10^{-6}$ s^{-1}, shading) at 850 hpa. The line marked with the open circles, closed circles, and typhoon signs represents the movement of typhoon Nanmadol during the period of MRG wave, tropical depression/tropical storm, and typhoon respectively. (b) Time-mean (13 Nov.–12 Dec.) OLR (shading <220 w/m^2) and sea surface temperature (°C).

of the dateline to a tropical cyclone over the west Northern Pacific (WNP). The locations of MRG gyre/TD-type disturbances before reaching tropical storm intensity are defined by the circulation centers with minimum wind speed based on NOGAPS analysis data. On 12Z 26th November, the equatorial trapped MRG gyre began to move away from the equator near 160°E, where the mean easterly wind shear became prominent (about −5 m/s) and sea surface temperature (SST) becomes higher than 30°C. Thereafter, it turned into a TD-like disturbance and further developed into a tropical storm on 00Z 29th November. The unseasonal storm tracked northwestward, and made landfall over Luzon Island on 2nd December with maximum sustained wind speed near 220 km/hr. It left 75 people dead and $34 million in damage. Then it moved east-northeastward across southern Taiwan. Nanmadol became the first known December tropical cyclone in the past 108 years to make landfall on the island.

2.3. Evolution of Equatorial Mixed Rossby-Gravity Wave

[8] To demonstrate the MRG-induced tropical cyclogenesis, a sequence of synoptic maps of 500 hPa mean wind field anomalies is shown in Figure 2. A wave train with alternating cyclonic-anticyclonic circulation is depicted in the entire tropical Pacific (Figures 2a, 2b, and 2c). The counter-clockwise MRG circulation of interest initially appeared east of the dateline (about 130–170°W) (Figure 2a). The heavy rain region is located downstream of cross-equatorial flow, which coincides with the MRG convergence zone, although the unfiltered rainfall may partially reflect the convection associated with the low-frequency ITCZ. During its continuous westward journey, the MRG wavelength was reduced significantly and deep convection occurred around the MRG gyre, exhibiting hybrid properties of both MRG- and TD- type disturbances (Figures 2b, 2c, and 2d). The reduction in wavelength agrees fairly well with the results of the previous studies [*Liebmann and Hendon*, 1990; *Takayabu and Nitta*, 1993; *Dunkerton and Baldwin*, 1995].

[9] To better understand the evolution of the MRG, its vertical structure is displayed in Figure 3. Initially, a clear wave train with alternating southerlies and northerlies is identified in the upper troposphere with maximum amplitude of meridional wind at 100 hPa on 00Z 20th November (Figure 3a). Note that the counter-clockwise rotating MRG gyre located over the Eastern Pacific tilts eastward with elevation (Figures 3a and 3b). While it faded away in the next 2 days in the upper troposphere, the counterpart in the middle troposphere became robust (Figure 3b), eventually in the lower troposphere (Figures 3c and 3d). Interestingly,

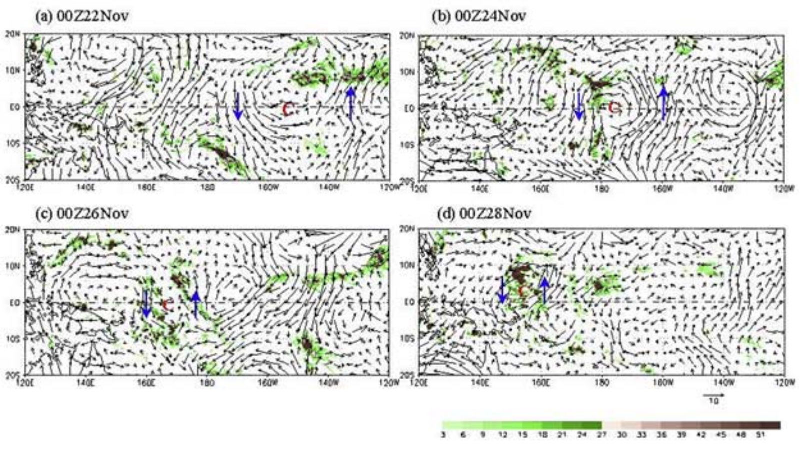

Figure 2. Wind anomaly (streamline) on 500 hPa level and the unfiltered TRMM precipitation rate (shading >0.3 mm/hr) on (a) 00Z 22 Nov. 2004, (b) 00Z 24 Nov. 2004, (c) 00Z 26 Nov. 2004, and (d) 00Z 28 Nov. 2004.

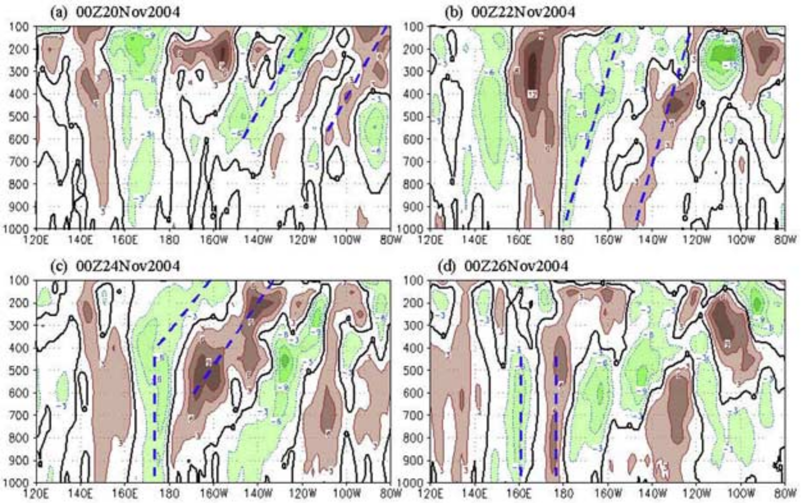

Figure 3. Longitude-height section of meridional wind anomaly on the equator at (a) 00Z 20 Nov. 2004, (b) 00Z 22 Nov. 2004, (c) 00Z 24 Nov. 2004, and (d) 00Z 26 Nov. 2004.

the northerly branch of the MRG wave became upright while it moved to the dateline, whereas the southerly branches to the east remain the eastward-tilting (Figure 3c). Associated with this vertical structure change, the upper-level wavelength became longer than that of the lower level (Figures 3b and 3c). The structure of MRG gyre became vertically upright after it moved completely to the west of the dateline (Figure 3d).

2.4. Transition to a Tropical Cylone

[10] When the MRG gyre moved to the neighbourhood of 160°E, it started to turn away from the equator and evolved into an off-equatorial TD-type disturbance (Figures 1 and 4). Before the northwestward turning, the zonal velocity and geopotential height of MRG gyre exhibited a typical anti-symmetric structure about the equator with low pressure north of the equator and high pressure south of the equator at both 850 hPa and 600 hPa (Figure 4a). The deep convection was located in the outer regions of MRG gyre. In the subsequent 24 hr, the main body of the 850 hPa cyclonic circulation as well as the convection contracted toward the low-pressure area in the Northern Hemisphere (Figure 4b). Corresponding to the northward shift of the deep convection, the low-level cyclonic vorticity amplified through vertical stretching, so that the positive vorticity center also displaced northward (about 3°N). By contrast the circulation center at 600 hPa remained on the equator until the next time step. It demonstrates that the northward movement of the MRG gyre circulation started earlier at 850 hPa than 600 hPa. Concurrent with the diminishing phase difference between the pressure and cyclonic vortex, the cyclonic circulation shifted to the Northern Hemisphere completely (Figure 4c) on 12Z 27 Nov., forming an off-equatorial TD-type disturbance with well-organized convection concentrated in the low-pressure area.

3. Interpretation

[11] We have illustrated the variation of the structure of an MRG/TD-type disturbance during its westward propagation, but a number of questions remain to be addressed. First of all, how does the MRG wave develop in the lower levels? In addition to the downward energy propagation of the upper-level MRG wave as shown in Figure 3, the development of the lower-level MRG wave is likely related

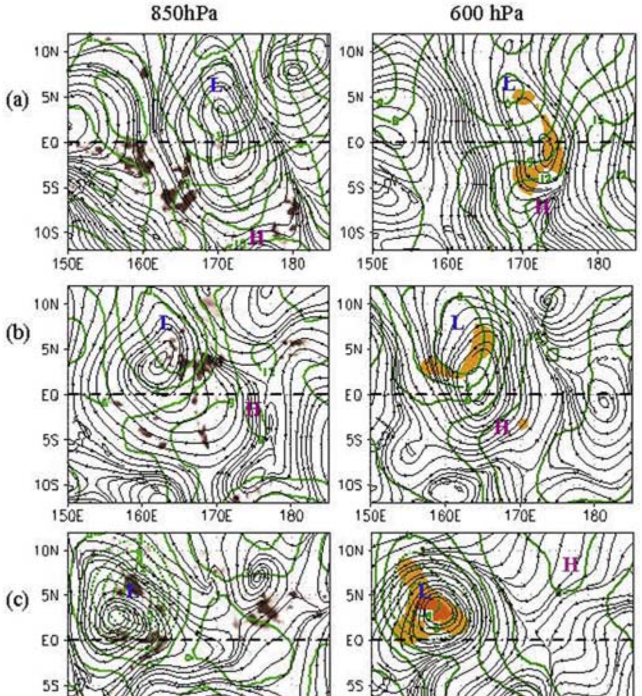

Figure 4. Wind anomaly (streamline), geopotential height anomaly (contour) at (left) 850 hPa and (right) 600 hPa on (a) 12Z 25 Nov., (b) 12Z 26 Nov., and (c) 12Z 27 Nov. The shadings in Figure 4 (left) are rain rate (>0.3 mm/hr) and in Figure 4 (right) vorticity ($>2 \times 10^{-5}\ s^{-1}$).

to the zonal variation of the mean flow vertical wind shear. The prevailing vertical wind shear changes its sign across the dateline (Figure 1a). To the west of the dateline, easterly wind shear prevails, while westerly shear prevails to the east. It has been shown that a mean flow with westerly vertical shear tends to trap the westward propagating MRG wave in the upper troposphere, whereas an easterly vertical shear tends to trap westward propagating MRG to the lower troposphere [*Wang and Xie*, 1996; *Xie and Wang*, 1996]. Thus, the MRG wave tends to extend downward and develop in the lower troposphere once it moves into the western Pacific (west of the dateline) where easterly vertical shear prevails.

[12] What causes the reduction of zonal wavelength of the MRG wave? We speculated that convective heating plays a significant role in this aspect. The development of convectively coupled equatorial waves involves a positive feedback between the latent heat released in deep convection and the large-scale circulation (CISK). An important feature of CISK is that the waves with the shorter wavelength grow faster when instability occurs [*Ooyama*, 1964]. Figure 3 illustrates that the notable reduction starts when the MRG gyre moved to the west of the dateline. Due to the effects of prevailing easterly shear and downward energy propagation, the MRG wave developed in the lower levels near the dateline. Once the lower-level cyclonic circulation is established, it generates strong Ekman-pumping and planetary boundary layer moisture convergence, which reinforces deep convection and favors the growth of shorter waves. Note also that the lower tropospheric background flow consists of a strong equatorial convergent zone in the vicinity of 160°E where the equatorial westerlies meet easterlies (Figure 1a). As suggested by *Webster and Chang* [1988], this strong confluent flow can amplify equatorial disturbance and cause zonal scale contraction of MRG waves. Furthermore, the warmest SST (30.5°C) at the equator near 160–180°E (Figure 1b) would also favor the development of convection and reduce the MRG wavelength.

[13] Why does the equatorial MRG gyre shift to the Northern Hemisphere and become an off-equatorial TD? By investigating a summer MRG case, *Dickinson and Molinari* [2002] suggested that asymmetric large-scale heating with respect to the equator would result in the departure of MRG wave away from the equator and then the development of off-equatorial wave train at the heating side. An idealized numerical study carried out by *Aiyyer and Molinari* [2003] supported this speculation. Figure 1b shows 30-day mean OLR (13th Nov. –12th Dec.), which is viewed as low-frequency convection. Apparently the low-frequency OLR in this case was located south of the equator. Thus, the asymmetry in the large-scale heating is not responsible for the northward propagation of MRG/TD type disturbances. What additional processes then are in action?

[14] As mentioned above the low pressure leads deep convection by about a quarter wavelengths in free-atmosphere MRG-wave-type disturbances, whereas the deep convections in the TD-type disturbances occur near the depression center. *Holton* [1975] found the boundary layer effects in MRG waves would distort the pressure-convection phase relation in a manner that the convergence area comes closer to the low-pressure center. It implies that the boundary layer effects might play a significant role in the transition from MRG waves to TD-type disturbances.

[15] The boundary layer frictional effects will boost up when the MRG gyre emerges at the lower levels. The boundary layer flows converged into the low-pressure area, reducing the phase lag between the low pressure and convection. When the convection matches the depression, the cyclonic vortex center shifted from the equator to the low-pressure area north of the equator, forming a TD-type vortex. This argument is supported by the fact that the transition followed the enhancement of the low-level MRG wave. Furthermore, the timing of the off-equatorial movement at lower level leading to the upper-level counterpart (Figure 4b) provides evidence of the importance of the boundary layer effects. *Takayabu and Nitta* [1993] suggested that the boundary layer effects may become more influential when the wavelength of MRG is reduced. *Wang and Li* [1994] have shown that the boundary layer convergence in the vicinity of the equator is proportional to the Laplacian of the pressure field. As zonal scale shrinks, the Laplacian of pressure increases, thus the boundary layer convergence enhances. In our case, the wavelength did show a remarkable reduction leading to its detachment from the equator, which agrees fairly well with the assertion made by *Takayabu and Nitta* [1993]. Thus, the reduction of wavelength may promote the transition from MRG wave to TD disturbance.

[16] The large-scale easterly shear is primary confined to the Northern Hemisphere over the western Pacific (Figure 1a). While the MRG wave turns into off-equatorial TD-type wave, the easterly vertical wind shear further favors its development and northward propagation [*Wang and Xie*, 1996].

4. Summary

[17] An unusual tropical cyclogenesis event over the western North Pacific (WNP) in 2004 winter is documented. We found that an upper tropospheric counterclockwise rotating mixed Rossby-gravity wave (MRG) developed near 120°W, and traveled almost the whole Pacific, turning into an off-equatorial TD over the WNP and developing into a Super typhoon later. Novel features of the MRG wave evolution are identified. The upper tropospheric MRG gyre that initially tilted eastward with height propagated progressively downward and westward. When approaching the dateline, the MRG circulation rapidly developed in the lower troposphere. Meanwhile, its wavelength reduced and the vertical phase line became upright. Thereafter, the cyclonic vortex center moved off the equator, forming a TD-type disturbance.

[18] The significant reduction of horizontal scale is attributed to the convective interaction with MRG, the zonal variation of large-scale environmental flows (both vertical shear and low-level confluences) and high SST. Following the reduction of the wavelength and change of the vertical structure, the boundary layer effect becomes effective and tends to collocate the boundary layer convergence and the low-pressure area. When the convergence areas match the low-pressure area, the vortex detached from the equator. It then further developed into a tropical storm through the

positive feedback between frictional convergence and cyclonic circulation.

[19] The present study provides an observational linkage between the tropical waves over the upper troposphere in the East Pacific and tropical cyclones over WNP. Given that the tropical waves have a long life span it offers the potential for long-lead forecasts of tropical cyclogenesis.

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