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Numerical Study on the Formation of Typhoon Ketsana (2003) in the Western North Pacific

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1. Introduction

This is part II of a previous study Lu et al. (2012), which simulated the formation of Typhoon Ketsana (2003) in the western North Pacific using the Weather, Research and Forecasting (WRF) model from the National Center for Atmospheric Research. In particular, the mesoscale dynamics associated with the generation of mesoscale convective vortices (MCVs) and the roles of mesoscale convective systems (MCSs) during the formation process of the Typhoon were investigated. Lu et al. concluded that with the successive occurrence of MCSs, midlevel average relative vorticity was strengthened through generation of MCVs via mechanisms such as vertical stretching and eddy fluxes. Through sensitivity experiments to modify the vertical humidity profile in each MCS, it was found that the development of a MCS depends substantially on that of the prior ones through remoistening of the midtroposphere, and thus leading to different scenarios of system intensification during the typhoon formation.

This study further analyzes the formation mechanisms of this typhoon case by investigating several processes: (1) the warm core formation process, (2) contribution from convective-scale systems, and (3) responses of incipient vortex to mesoscale heating within MCSs. After the brief description of the synoptic situation associated with the Typhoon these processes will be discussed.

2. Brief Synopsis of Typhoon Ketsana (2003)

Typhoon Ketsana initially developed from a disturbance embedded in a reversed-oriented monsoon trough about 1296 km east of Luzon Island on 15 Oct 2003. The monsoon trough provided a favorable large-scale environment with high humidity and abundant low-level cyclonic vorticity for tropical cyclone (TC) formation. The disturbance developed to tropical depression at 1200 UTC 18 Oct (taken as formation time) and 12 h later to tropical storm.

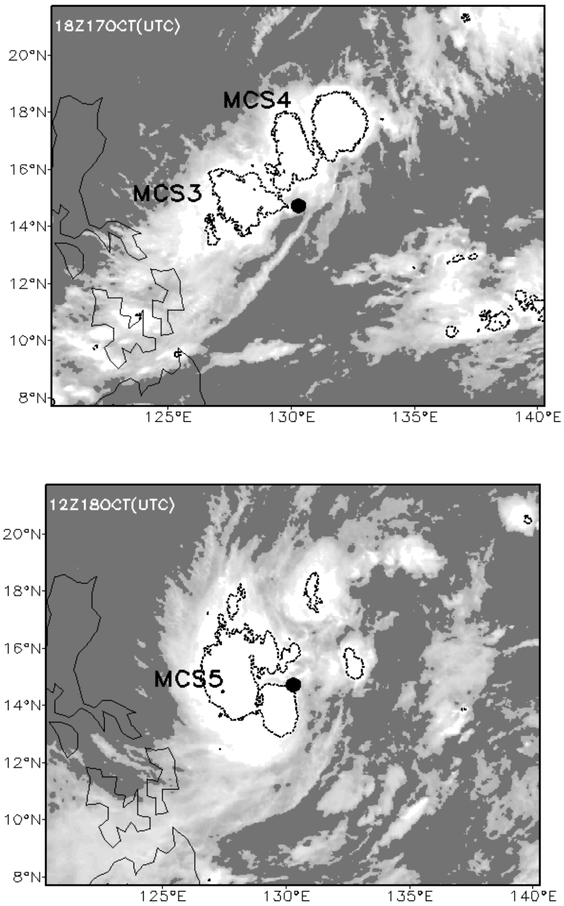

Fig. 1 Satellite IR1 images at 1800 UTC 17 Oct (upper) and 1200 UTC 18 Oct 2003 (lower). The contour is brightness temperature of -75°C and dot the best-track location of Typhoon Ketsana (adapted from Lu et al. 2012).

One characteristics of TC formation in the monsoon trough is frequent development of MCSs due to

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low-level convergence that enhances convection. During the 48 h prior to Ketsana's formation, five MCSs are observed. The first two developed on 16 and early 17 Oct respectively. Later, MCS3 and MCS4 developed almost simultaneous near 1500 UTC 17 Oct but then dissipated. The fifth MCS5 developed at 0600 UTC 18 Oct near the low-level circulation center, and led to formation of the Typhoon 6 h later. The meoscale processes and contribution of these MCSs to the TC formation have been discussed in details in Lu et al. (2012).

3. Warm Core Formation

In general, the development of the warm-core structure is due to the diabatic heating at the eyewall. When the inner-core temperature anomaly increases at the mid to upper levels, the static stability increases and then the TC reaches a steady state. Consequently a dynamical balance is obtained between the TC circulation [especially the transverse circulation, see Vigh and Schubert (2009)] and the temperature field. However, depending on the synoptic environment there are possibly different mechanisms of developing the warm-core structure during the formation stage and early development stage. For example, Dolling and Barnes (2012) reported that during the development of Hurricane Humberto (2001) a pathway existed for a mesoscale convective system (MCS) to evolve into the warm-core structure. In other hurricanes that develop from initially cold-core, low-level wave disturbances such as pre-Hurricane Felix (2007) as simulated by Wang et al. (2010), other pathways may exist.

For the warm core generation in Typhoon Ketsana, it is identified in the WRF simulations that every MCS is associated with strong mid- to upper-level heating as typically found in stratiform clouds. However, how these heating associated with the MCSs, especially the early ones, lead to the warm core when the TC forms has not been extensively discussed in previous studies, and will be one of the key questions to answer. The heating associated with MCS3 and MCS4 is northwest of the low-level circulation center, which is consistent with the MCSs' location (Fig. 2 upper). Their heating diminishes a bit later, and when MCS5 develops, its associated heating almost co-locates with the surface depression (Fig. 2 lower). Eventually this heating of MCS5 persists and develops to the mature warm-core structure of the simulated TC. Thus, it is believed that the inner-core heating associated with MCS5 is effective facilitating the TC formation and developing the dynamical balance of the vortex.

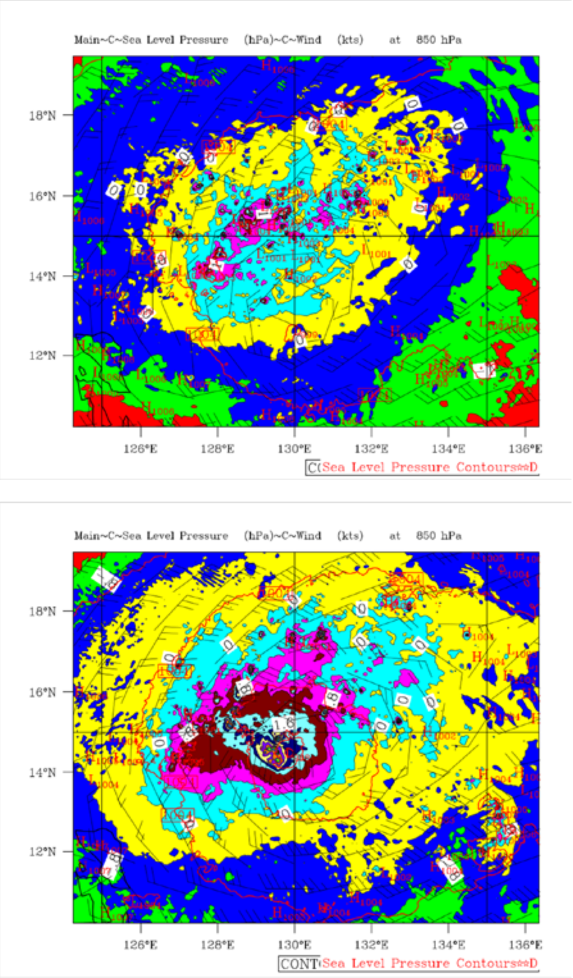

Fig. 2 Mean sea-level pressure (red contours), 850-hPa winds and 200-400-hPa temperature anomaly (shaded) at 1800 UTC 17 Oct (upper) and 0900 UTC 18 Oct 2003 (lower).

4. Contribution from Convective-scale Systems

On the other hand, scale separation performed in Lu et al. (2012) showed that the activity of the convective-scale systems correlate well with the development of the MCSs. When these convective-scale systems posses both large relative vorticity and heating, they are referred to as vertical hot towers (Montgomery et al. 2006), or in general as convectively induced vorticity anomalies (CVAs; Fang and Zhang 2011) These CVAs have large values of positive relative vorticity induced by intense low-level convergence, and was suggested by Lu et al. (2012) to contribute substantially to the surface vortex necessary for TC formation besides the mesoscale processes.

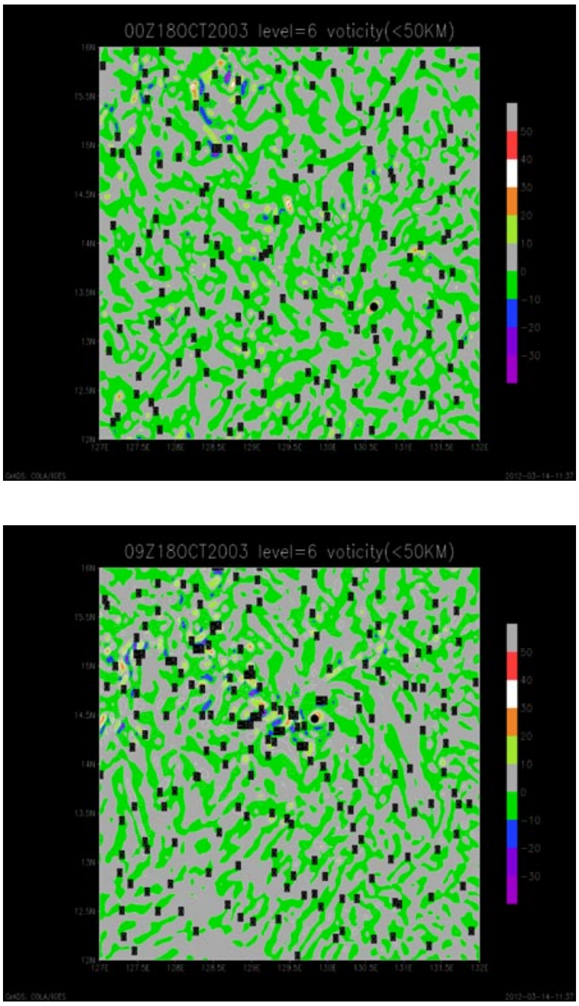

Fig. 3 Simulated 925-hPa relative vorticity with horizontal scale less than 50 km.

One issues associated with CVAs is that large downdraft and associated negative relative vorticity is always accompanying the CVAs (Fig. 3 upper). It was discussed in Fang and Zhang (2011) that eventually both the negative and positive vorticity anomalies accumulate into a large single-sign vorticity region through larger-scale convergent (secondary or transverse) circulation that is driven by latent heating. The negative vorticity anomalies are weaker and shorter-lived compared with the positive ones, and are then absorbed. However, in our simulation of Typhoon Ketsana it is found that although the CVAs accumulate to form the intense core vortex during formation, the negative vorticity anomalies actually persist (Fig. 3 lower). A measure of self-organization is being computed on how the CVAs aggregate, and the up-scale energy cascade process of the CVAs enables minimal impact from the negative vorticity anomalies.

5. Responses to meoscale heating from MCSs

In relation to the issue of warm core generation with contribution from MCS heating, Vigh and Schubert (2009) and early studies such as Hack and Schubert (1986) argued through theoretical calculations based on balanced vortex model that the development of the transverse (secondary) circulation depends not only on the diabatic forcing but also on largely on the spatial distributions of the static stability, baroclinity and inertial stability. Among the three parameters the inertial stability is the most critical. Vigh and Schubert (2009) demonstrated that the vortex response to a point-source diabatic heating depends critically on whether the heating occurs in the low-inertial-stability region outside the radius of maximum wind or in the high-inertial-stability region inside the radius of maximum wind. In the latter situation, at least some of the eyewall convection is within the inner core.

In the case of the formation of Typhoon Ketsana, the earlier MCSs (MCS1-4) are more than 100 km away from the incipient vortex center. It is likely that their efficiency in generating the transverse circulation is low because the highest inertia stability concentrates within 50 km in the WRF simulation (Fig. 4). However, when the last MCS5 develops near the center, its associated heating should be able to induce more response in terms of the transverse circulation generation. It is depicted from the WRF simulation that during the several hours after the formation of Ketsana, the inner-core stability increases slightly, which indicates that it is less favorable for further convection development. According to Vigh and Schubert (2009) the vortex is approaching a steady state at this stage. Indeed, the convection associated with MCS5 is reduced after the formation of the Typhoon, and later new convection develops associated with other rain band structures.

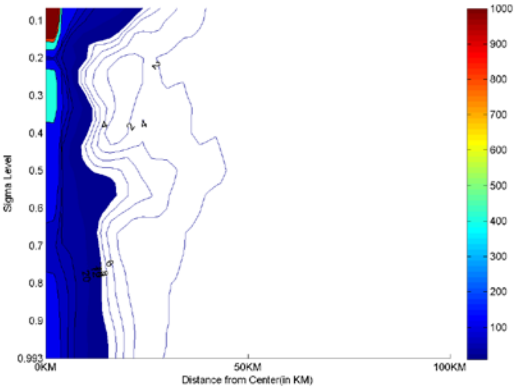

Fig. 4 Simulated vertical distribution (model sigma levels) of the azimuthal mean of the inertial stability as a function of radius from the surface center.

6. Summary

The WRF simulation of the formation of Typhoon Ketsana (2003) is further analyzed after the earlier study of Lu et al. (2012). While Lu et al. focused on the role of MCSs in the formation of the Typhoon, this study considers the physical and dynamical processes associated with the warm core generation, as well as contribution from the convective-scale CVAs. Preliminary results indicate that the last MCS during the TC formation is in close vicinity of the surface low pressure center, and its associated heating almost directly transforms to the warm-core structure of the TC. It is argued with the theory of the response of a balanced vortex to diabatic heating (Hack and Schubert 1986; Vigh and Schubert 2009) that the heating from this last MCS is relatively effective (compared with earlier MCS development) in overcoming the inner-core high inertial stability to generate the necessary transverse circulation, and increase the static stability there for facilitating the pathway to a steady state of the vortex.

On the other hand, both positive vorticity anomalies of the CVAs and negative vorticity anomalies associated with downdrafts are identified in the WRF simulation, and they persist during the TC formation. A dynamical explanation of the surface vortex formation is being investigation on the self-aggregation of the CVAs and how the effect from the negative vorticity anomalies is reduced during the up-scale energy cascade process.

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