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A MODEL STUDY ON TROPICAL CYCLONE STRUCTURAL CHANGES IN RESPONSE TO AMBIENT MOISTURE VARIATIONS

Yue Ying and Qinghong Zhang*
Peking University, Beijing, China

1. INTRODUCTION

The structural changes of a tropical cyclone (TC) during its life cycle have received increasing attention from researchers these years. Some early studies showed that structural parameters (intensity, size and strength) could vary among TCs, and the intensity and size are only weakly related (Merrill 1984; Weatherford and Gray 1988). Weatherford and Gray (1988) proposed that the inner-core intensity changes through internal dynamics, while the outer-core wind strength and TC size are more susceptible to environmental influences.

More recent experiments have evaluated the relationship between TC size and its moisture condition (Wang 2009; Hill and Lackmann 2009). They found that TCs in moister environment generate more outer rainbands, and the latent heat released in outer rainbands contributes to the horizontal expansion of TC wind field. Fudeyasu and Wang (2011) confirmed these results by their balance dynamics diagnoses.

The aforementioned numerical experiments used idealized TC vortices with axi-symmetric structure. However, in real atmosphere, TCs often display asymmetric structure in vertically sheared environment (Lonfat et al. 2004). A real TC case with the presence of vertical wind shear (VWS) was simulated in this study, and some sensitivity tests were performed to evaluate the impact of moisture perturbation on TC structure in this case.

2. EXPERIMENTAL DESIGN

A typical Northwest Pacific typhoon, TC Talim 2005, was chosen for the real-case simulation in this paper. Figure 1 displays the evolution of its size and intensity. The Weather Research and Forecasting model (WRF) was employed to perform the simulation. The model was setup with 4 km horizontal grid spacing and 26 vertical layers. The moist convection was simulated explicitly with WSM6 microphysics scheme.

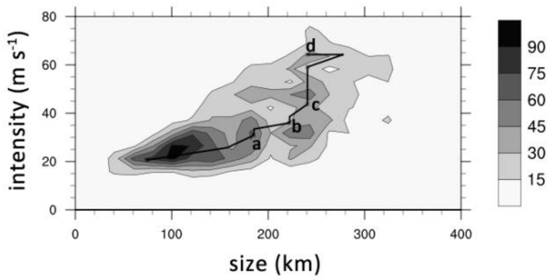

Figure 1 Number of occurrence (shadings) of Northwest Pacific TCs in an intensity-size diagram, derived from 6-hourly JTWC best track data from 2003 to 2009. The black line displays evolution of size and intensity of TC Talim 2005, showing a size-growth period (a-b as 0:00~12:00, 8/29) and an intensification period (c-d as 0:00~12:00, 8/30).

Exp.	Description
CTRL	Control experiment
Q-	Subtract Δq
Q+	Add Δq
QN-	Subtract Δq from the northern sector
QS-	Subtract Δq from the southern sector
QN+	Add Δq from the northern sector
QS+	Add Δq from the southern sector

Table 1 Modification of water vapor mixing ratio (Δq=2 g kg^{-1}, the modification took place from surface to 3.5 km, within the 300~600 km annular region).

Corresponding author address: Qinghong Zhang, Dept. of Atmospheric and Oceanic Sciences, Peking University, Beijing 100871, China; email: qzhang@pku.edu.cn.

A bogus Rankine vortex were inserted into the model at 0:00 8/28 and spun up for 24 hours before the modification of water vapor was applied at 0:00 8/29 (point a in Fig.1). This is to eliminate influences from the initially unbalanced bogus vortex. The modifications of each experiment are explained in Table 1. Now we evaluate the results of simulations with different moisture perturbations. We hereafter denote 0:00 8/29 as t=0h.

3. RESULTS AND INTERPRETATION

3.1 Moisture's feedback on ambient flow

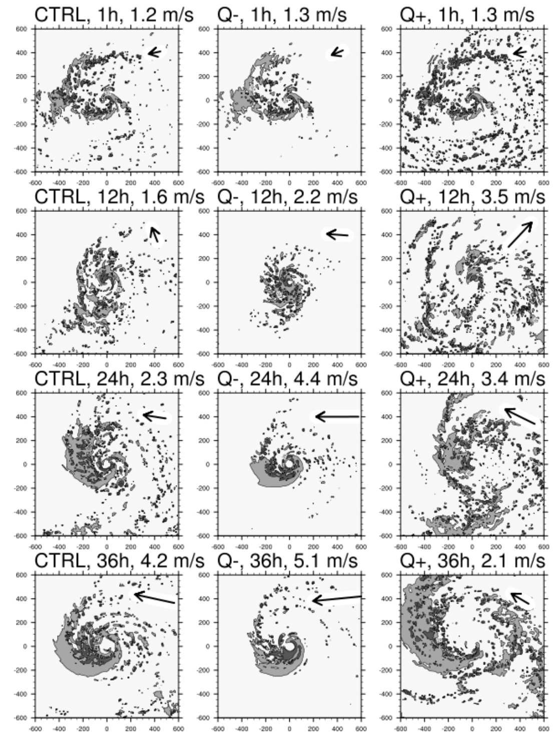

Figure 2 Radar reflectivity (shadings, light gray=20~40 dBZ, dark gray=40~60 dBZ) at 3 km height, and vertical wind shear showed in vector. CTRL, Q- and Q+ runs (from left to right) at t=1, 12, 24 and 36h (to top to bottom) are shown.

The increased moisture (Q+) yields more rainband convection in TC circulation, causing TC to have broader horizontal extent (Fig. 2). Before quantifying the contribution by rainband diabatic heating to TC structural change, it is necessary to first look at the ambient flow of each run, since changes in storm-relative flow also leads to structural changes (Wang and Holland 1996). The vertical wind shear is defined as 9km and 3km wind difference averaged over the 200~600km annular region. Figure 2 shows that, in Q+, the direction of vertical wind shear vector is different compared to CTRL at t=12h. Such difference may contribute to changes in the final TC rainband structure.

3.2 Sensitivity of structural parameters

In this study, we define TC inner- and outer-core as the r=0~100km and r=100~300km regions, respectively. TC intensity is defined as the maximum wind speed at z=1km, TC size as the radius of gale force wind (17 m s^{-1}) and strength as the averaged angular momentum. Figure 3 displays the evolution of these structural parameters.

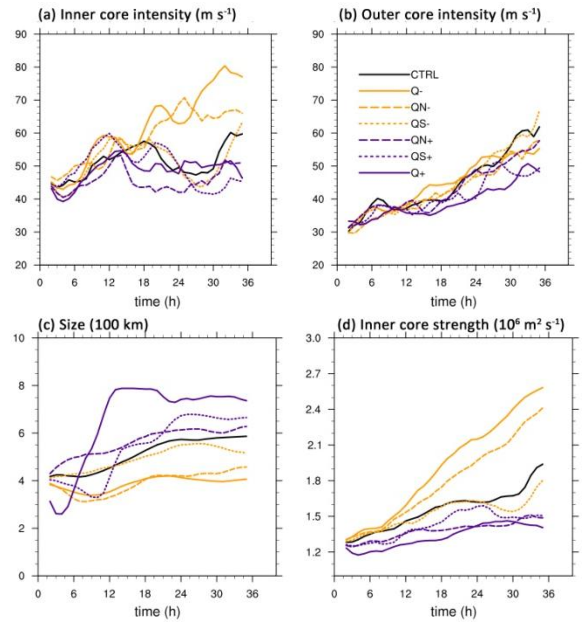

Figure 3 Evolution of TC structural parameters for each run: (a) inner core intensity, (b) outer core intensity, (c) size and (d) inner core strength.

TCs in drier environment (Q-) intensify faster than CTRL (Fig. 3a), and they have smaller sizes (Fig. 3c) and stronger inner core strength (Fig. 3d). TCs in moister environment (Q+), however, intensify slower and have weak but broadened wind field. Subtracting the same amount of moisture from different locations (QN- and QS-) did not produce the same result. From the trajectory analysis (Fig. 4), we deduce that air in the southern sector travels a longer distance before wrapping into TC core, thus moisture in the south has less influence on TC rainband convection. In our case, rainband convection is more sensitive to moisture from upstream side of the rainbands (from the north).

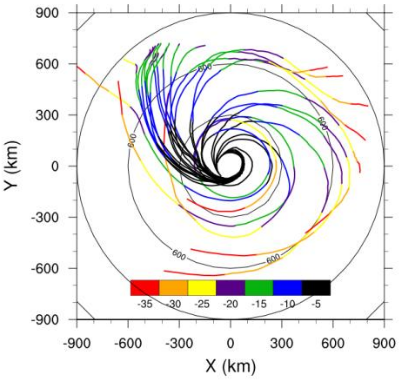

Figure 4 Backward trajectories at z=1km level seeded along r=100km radius (the outer boundary of inner core). The colors denote the time (hour) of backward integration.

3.3 Propagation of outer rainbands

The secondary circulation is altered by the presence of rainband diabatic heating in outer core region (Fig. 5). With extra diabatic heating in outer core region, more upward motion is induced (Q+, QN+ and QS+ runs) outside the primary eyewall and inner rainbands. These updrafts transport low-level angular momentum to the mid-level, favoring the formation of a secondary wind maxima in outer rainbands. They also limit the radial inflow of moist air into the inner core region.

Due to the blocking of low- to mid-level inflow by outer rainbands, convection in outer core did not propagate radially inward and TC inner core spin-up is suppressed (see Q+, QN+ and QS+ runs in Fig. 6). With fewer outer rainband heating (Q- and QN- runs), convection generated outside the primary eyewall propagates radially inward faster than CTRL. TC inner core also strengthens rapidly because of the radially inward advection of absolute angular momentum.

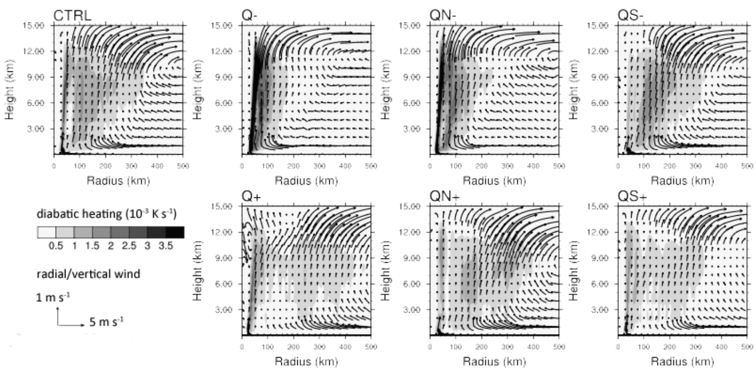

Figure 5 Secondary circulation (radial and vertical velocity in vectors) and azimuthal mean diabatic heating rate (shadings) averaged over the intensification period for each run.

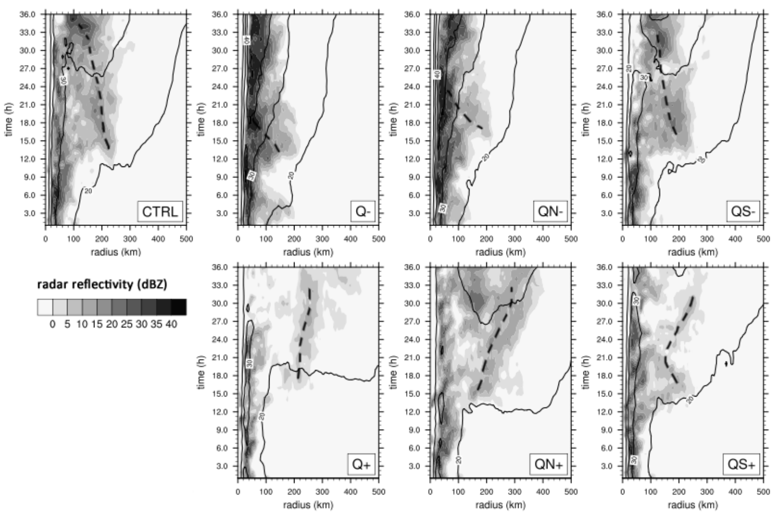

Figure 6 Radial-time Hovmöller diagram of the azimuthal mean radar reflectivity (shadings) and tangential wind (contours for 20, 30 and 40 m s^{-1}) at 1 km height. Thick dashed lines indicate the propagation of convection in outer core region.

4. SUMMARY

Combining our results with findings from idealized simulations in previous studies (Wang 2009; Hill and Lackmann 2009), we summarize the responses of TC vortex structure to ambient moisture variations as schematic diagrams in Fig. 7. In idealized TCs, the ambient flow is not sheared and TCs develop symmetric structures. Moister environment yields TCs with expanded core, often associated with the breakdown of eyewall (Fig. 7a). In drier environment, TCs will contract due to enhanced secondary circulation, and grow smaller in size with less outer rainband convection (Fig. 7b). TCs in drier environment intensify faster and have shorter life cycle than those in moister environment. In sheared environment, TCs develop asymmetric outer rainbands, and only the moisture from upstream side of TC rainbands exerts most impact on TC structure. Provided sufficient moisture supply (Fig. 7c), the outer rainbands will grow stronger, latent heat released in outer rainbands induces upward motion and reduces the radial inward advection of absolute angular momentum, which weakens the inner core intensity. On the contrary, drier upstream inflow to the outer rainbands (Fig. 7d) inhibits convection and yields small TCs with strong inner core intensity and strength.

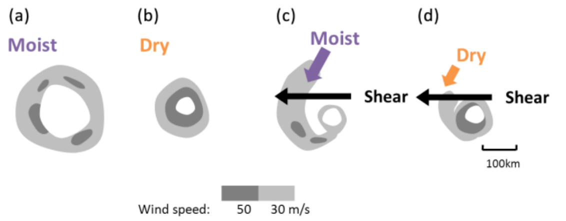

Figure 7 Schematic diagram showing TC Talim's wind field changes under varying moisture perturbations.

Acknowledgments

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