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Cloud-Resolving Studies of West Pacific Tropical Cyclones

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LONG-TERM GOALS

Improve the prediction of tropical cyclone (TC) genesis and its subsequent track, intensity and intensity change; and provide a better understanding of the fundamental dynamical and physical processes taking place in TCs from its genesis to typhoon and landfalling stages, including the inner-core clouds/precipitation and catastrophic winds.

OBJECTIVES

(i) Study the predictability of TCs occurring over West Pacific using the Weather Research and Forecast (WRF) with the finest grid resolution of 1 – 2 km; (ii) examine the multiscale dynamical processes leading to TC genesis and rapid deepening; (iii) explore the roles of different physical processes, including the air-sea interaction and cloud microphysics, in determining changes in TC intensity, inner-core structures and the formation of spiral rainbands, and (iv) provide a theoretical understanding of different (e.g., vortex-Rossby, inertial-gravity, and mixed-Rossby-gravity) wave motions in TCs.

APPROACH

Both the Penn State/NCAR mesoscale model (i.e., MM5) and the WRF model have been used as a research tool. This project has been conducted by three of my Ph. D. students, Drs. Wallace Hogsett (graduated in 2010), Wei Zhong (graduated in 2009), and Liqing Tian (graduated in 2009). In addition, the PI has a) co-supervised one Ph. D. student, Mr. Weijun Wen, with Chinese scientists; b) collaborated with Prof. Ming-Jen Yang of Taiwan's National Central University, and c) collaborated with Profs. Liguang Wu and Yong-Qing Wang of the Nanjing University of Information Science and Technology on the Chinese-funded projects related to West Pacific TCs.

WORK COMPLETED

We developed (i) a piecewise potential vorticity (PV) inversion algorithm and then applied it to hurricane inner-core anomalies (Kieu and Zhang 2010); examined (ii) the structural changes and terrain-induced asymmetry during the landfall of Typhoon Nari (2001) (Yang, Zhang and Huang 2010); and performed two case studies with different genesis processes: (iii) Genesis of Typhoon

Chanchu (2006) from a westerly wind burst associated with the MJO and role of deep convection in tropical transition (Hogsett and Zhang 2010a,b); (iv) Genesis of Typhoon Nari (2001) from a mesoscale convective system (MCS) (Zhang et al. 2010).

RESULTS

(i) *A piecewise PV inversion algorithm and its application to hurricane inner-core anomalies*. We developed a piecewise PV inversion algorithm for an arbitrary number of PV pieces, and then studied the nonlinear responses to various types and magnitudes of axisymmetric PV anomalies (PVAs) in hurricane vortices. Results show that the balanced flows corresponding to the PVAs in the eyewall appears to account for a substantial portion of the warm core and the minimum pressure in the eye. However, the lower-level PVA in the eye inversion layer is more effective in contributing to the hurricane intensity than that at the upper levels. We also show that the radius of the balanced response of PVAs is more sensitive to the mean vortex intensity than the vertical penetration. Similar behaviors are also observed for the quasi-balanced secondary circulations. That is, given a diabatic heating profile in the eyewall, the weaker background vortex or the weaker PVAs, the stronger the secondary circulations will result.

It is found that the development of an outer eyewall (or spiral rainbands) could be inimical to the inner eyewall in several ways by (a) adding an anticyclonic flow inside to offset the cyclonic rotation of the inner eyewall, (b) enhancing a ring of a lower pressure zone underneath to broaden the inner-core lower pressure region, (c) inducing an inward (outward) radial flow outside (inside) in the PBL (upper-level) to block the energy supply to (outflow of) the inner eyewall, and (d) generating subsidence between the two eyewalls to suppress the connective development in the inner eyewall (see Fig. 1).

(ii) *On the structural changes and terrain-induced asymmetry during the landfall of Typhoon Nari (2001).* In this study, a series of model-output diagnoses using the cloud-resolving simulations of Typhoon Nari (2001) with or without Taiwan topography is performed to gain insight into the landfalling characteristics of the storm as it moves across Taiwan Island. Results show that tangential winds weaken, whereas the low-level inflows and midlevel outflows increase, after landfall due to the increased friction and terrain blocking. Meanwhile, the eyewall updrafts exhibit more cellular and wave structures and tend to tilt more outward with height over the high topography. However, Nari's primary and secondary circulations are on average stronger in the presence of topography than those without it. It is found that radii of the maximum winds and the eyewall updrafts could contract even after landfall in a fashion similar to those prior to landfall, with more pronounced contraction occurring in the eyewall where more terrain retardation and blocking are present. In particular, the high topography allows the elevated low equivalent potential temperature (θ_e) air in the rugged boundary layer to intrude into the inner-core region, causing the breakdown of the eyewall. It is concluded that the interaction of Nari's circulations with the elevated low-θ_e air, combined with topographical effects, accounts for most of the asymmetrical structures after landfall.

(iii) *Roles of deep convection in tropical transition of Typhoon Chanchu (2006) from westerly wind burst (WWB) associated with the MJO*. We have studied the equatorial formation of Typhoon Chanchau (2006) using both observations and an 11-day 2-km resolution simulation. Results show that the MJO, together with a convectively coupled Kelvin wave, provides the necessary low-level convergence and rotation for the development of the pre-Chanchu disturbance. The incipient vortex evolves slowly westward, like a mixed Rossby-gravity wave, on the northern flank of the WWB,

exhibits a vertically westward-tilted circulation structure, and eventually moves northward off of the equator.

It is found that the tilted WWB vortex at early stages is characterized by an elevated cold-cored layer (about 200-hPa thick) below and a weak warm column above with large vertical wind shear across the layer, which extends over a horizontal distance of about 450 km between the vortex's 400- and 900-hPa centers (see Fig. 2). During the final two days of the genesis process, the upper-level warm column increases in depth and intensity as a result of the absorption of convectively generated vortices, including a mesoscale convective vortex, causing more rapid amplification of cyclonic vorticity in the middle than the lower troposphere. The commencement of sustained intensification of Chanchu occurs when the upper-level warm column is vertically aligned with the surface-based warm-core vortex. We conclude that the roles of deep convection are to a) generate cyclonic vorticity and then store it mostly in the midtroposphere; b) moisten the low- and midlevels; c) enhance the northward displacement of the WWB vortex; and d) reduce the vertical tilt of the WWB vortex.

(iv) *Genesis of Typhoon Nari (2001) from a mesoscale convective system*. In this study, the origin and genesis of Typhoon Nari (2001) as well as its early erratic looping track are examined using the large-scale analysis, satellite observations and a 4-day nested-grid, cloud-resolving simulation with the finest grid size of 1.33 km. Observational analysis reveals that Nari could be traced more than 5 days back to a diurnally varying MCS with growing cyclonic vorticity and relative humidity in the lower half of the troposphere, and it evolved over a warm ocean surface under the influence of a subtropical high, an eastward-traveling midlatitude disturbance, an initially approaching and later departing Typhoon Danas to the east, and the Kuroshio current nearby.

Results show that (a) continuous deep convection stretches the low-level vorticity and moistens a deep mesoscale column that are both favorable for genesis; (b) the passage of a midlevel trough enhances local cyclonic vorticity and pressure falls, thereby facilitating the re-organization of deep convection; (c) convective asymmetry induces a smaller-sized vortex circulation from the pre-existing mesovortex; (d) the vortex-vortex interaction with Typhoon Danas leads to the looping track of the storm; and (e) the midlevel convergent sheared flows associated with the subtropical high and Danas account for the generation of upright eyewall convection and upright radius of the maximum wind.

IMPACT/APPLICATIONS

Our results suggest that (i) TC genesis under different environments could occur with different mechanisms, such as the WWB, MCSs, merging vortices, and the PV fluxes in the ITCZ; (ii) TC genesis over the West Pacific appears to be more complicated than that over the Atlantic basin due to the presence of the MJO, the Taiwan and Philippine islands, monsoon troughs, and the Kuroshia; and (iii) The piecewise PV inversion algorithm for an arbitrary number of PV pieces is very useful for isolating the impact of different features or processes on the intensity and structures of TCs.

RELATED PROJECTS

This project is closely related to that funded by NSF on the landfalling characteristics of hurricanes and the genesis of TCs, by NASA on the simulation of Hurricane Bonnie (1998), and by NSF of China on TC research.

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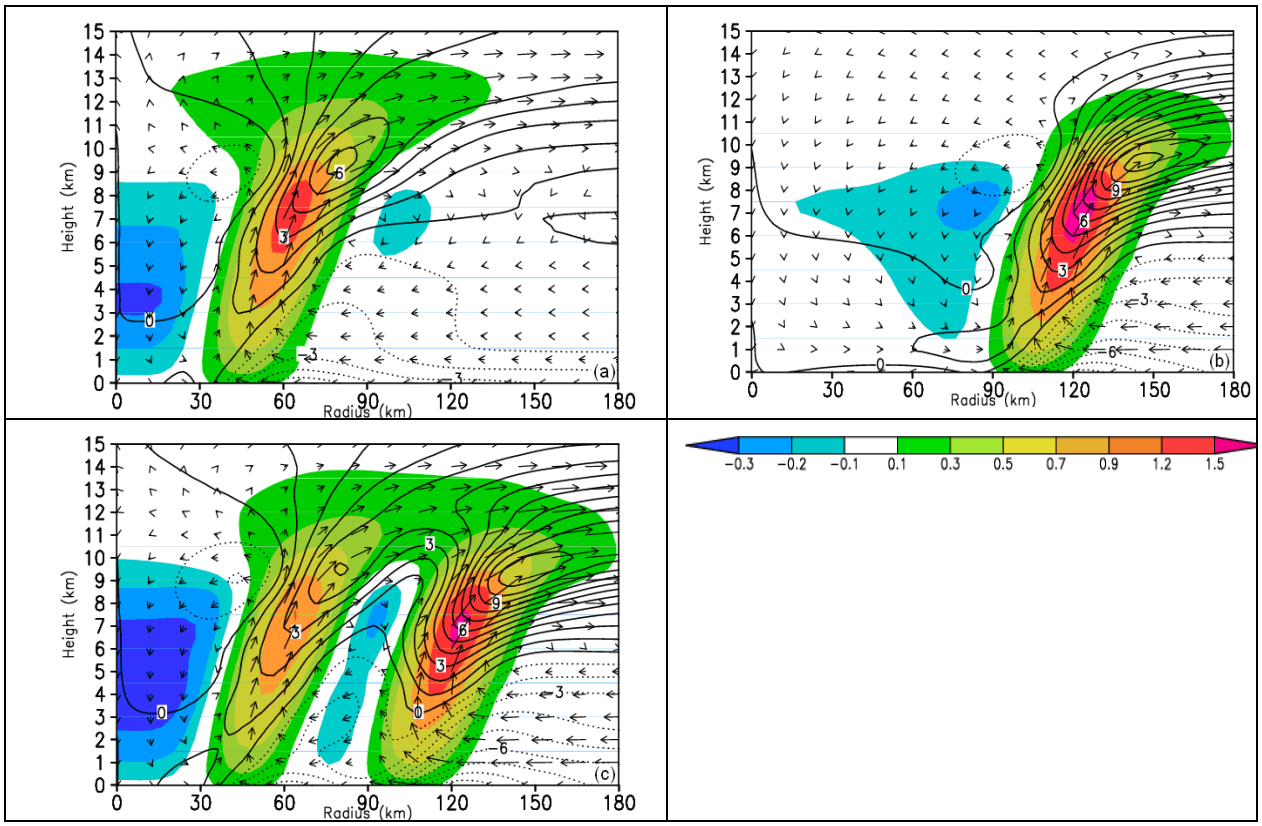

Figure 1. Radius-height cross sections of the quasi-balanced vertical motion (shaded at intervals of 0.3 m s^{-1}) and radial flows (contoured at intervals of 0.5 m s-1) associated with diabatic heating in (a) the inner eyewall; (b) the outer eyewall; and (c) the double eyewalls.

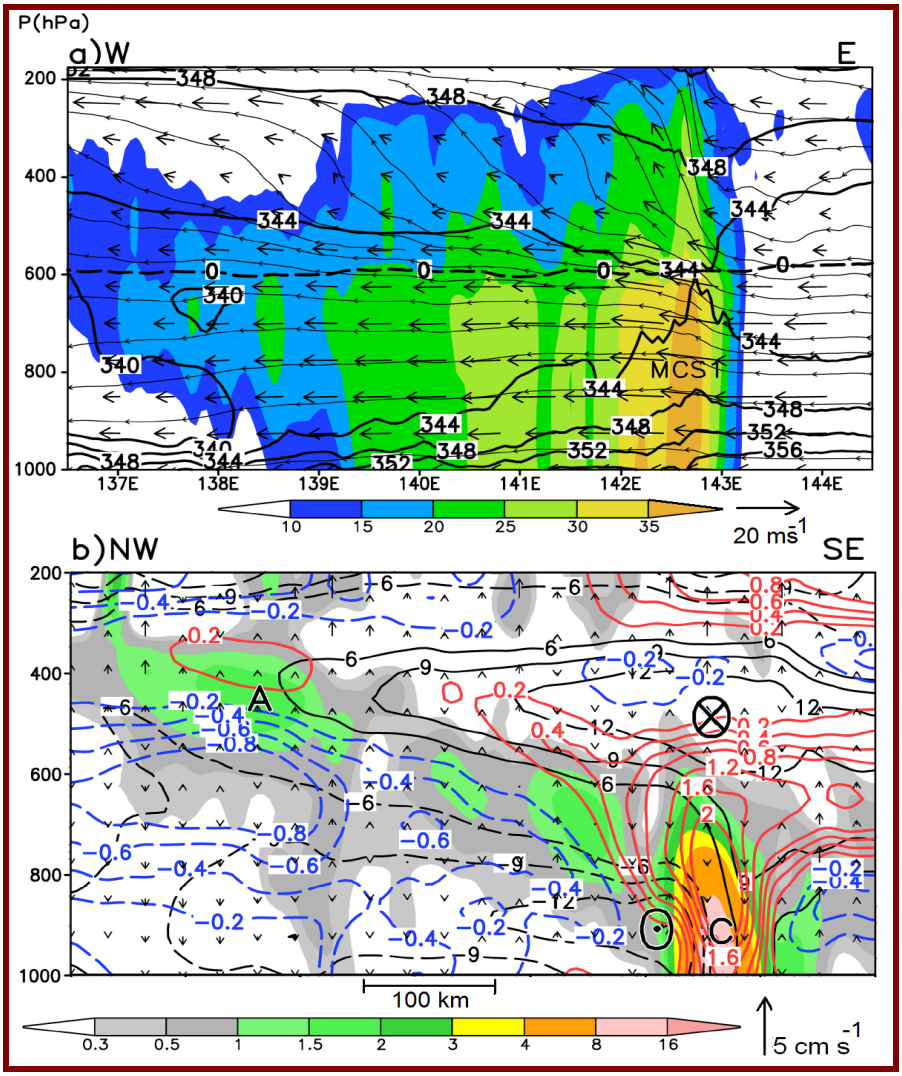

Figure 2. (a) West-east vertical cross section of radar reflectivity (shaded, dBZ), equivalent potential temperature (at intervals of 4 K), superimposed with the melting level (heavy dashed line) and in-plane flow vectors and streamlines (vertical motion multiplied by a factor of 10). (b) Northwest-southeast vertical cross section of the relative vorticity (shaded, 10^{-4} s^{-1}), the cross-plane wind speed (contoured, ± 3, 6, 9, 12, and 15 m s^{-1}) into (out of) the vertical plane with their maximum magnitude marked by a cross (dot) symbol, superimposed with deviation temperatures (heavy contours, ± 0.2, 0.4, 0.6, 0.8, 1.2, 1.6 and 2.0 °C) and vertical motion vectors. They are taken from the 144-h simulation.