Cloud-Resolving Simulations of West Pacific Tropical Cyclones

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LONG-TERM GOALS

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

OBJECTIVES

(i) Study the predictability of tropical cyclones occurring over West Pacific using both the Weather Research and Forecast (WRF) model and Navy's Coupled Ocean Atmosphere Prediction System (COAMPS) with the finest grid resolution of 1 – 2 km; (ii) examine the larger-scale environments that are favorable for, and the mesoscale processes leading to tropical cyclogenesis; (iii) explore the roles of internal dynamics and different physical processes in determining changes in hurricane intensity, inner-core structures and the formation of spiral rainbands, and (iv) provide a theoretical understanding of propagating waves in tropical cyclones.

APPROACH

The Penn State/NCAR mesoscale model (i.e., MM5) has been used in the past, and the WRF and COAMPS models are being used from now on as a research tool. More physics options will be incorporated into the COAMPS model to determine to what extent it can reproduce tropical cyclogenesis, and its subsequent track and intensity, as compared to the MM5 and WRF. This project has been conducted by a Ph. D. student, Mr. Wallace Hogsett, who is co-supervised by the PI and Dr. Chi-Sann Liou of the Naval Research Laboratory at Monterey (NRLM). Prof. Ming-Jen Yang, a visitor from Taiwan's National Central University, Dr. Liqing Tian, a visitor from the Institute of Atmospheric Physics of the Chinese Academy of Sciences, and Ms. Sue Chen of NRLM also play important roles in this project. In addition, the PI has co-supervised a Ph. D. student with a Chinese student to develop a new theory for understanding the development and propagation of mixed vortex-Rossby-gravity waves in tropical cyclones.

WORK COMPLETED

(i) Hurricane energy budgets to gain insight into energy conversion and generation in hurricanes using a cloud-resolving study of Hurricane Bonnie (1998); (ii) A 7-day cloud-resolving simulation of Super-Typhoon Chanchu (2006) using the WRF model with the finest grid size of 2 km and later with the

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COAMPS to study the effects of air-sea interaction, vertical shear and local topography on the track and intensity of the storm. A memorandum needs be signed before the most recent version of COAMPS could be released to the PI; (iii) A cloud-resolving simulation of Typhoon Nari (2001) at landfall over Taiwan; and (iv) A new theory for the development of mixed vortex-Rossby-gravity waves in tropical cyclones to understand some unbalanced dynamics in intense hurricanes.

RESULTS

(i) *Hurricane energetics* (Hogsett and Zhang 2008). We have studied hurricane energetics using a cloud-resolving simulation of Hurricane Bonnie (1998) with the finest 4-km resolution at 15-min intervals. We observed the development of substantial fluctuations in the surface and lower-level winds in cocidence with the presence of intense vertical wind shear. The stronger the shear, the more significant fluctuations are in the low-level horizontal winds. We then found that the fluctuating winds are highly related to fluctuations in the energy conversion and production rates due to the propagation of wavenumber-1 vortex-Rossby waves (VRWs) associated with episodic convective activities occurring in the eyewall. That is, it is the deep convection that grows in the shear-favored downshear half of the eyewall and decays as it reaches the unfavorable upshear side of the storm, causing high-frequency intensity changes in surface winds. It is found that about 1.2~2.5% of latent energy from deep convection could be converted to kinetic energy at very short time scales.

Our energetic analysis also reveals well the formation of double eyewalls and the eyewall replacement during the mature stage of Bonnie, which occurs as the wavenumber-0 component of vertical motion grows in magnitude, and the higher order components decay. Fig. 1 shows that the eyewall replacement is closely associated with the propagation of convective elements in the eyewall. That is, as the vertical shear decays rapidly during this period, convective elements are able to propagate around the full annulus of the storm. For example, at 84.5 h, there is a single spiral rainband (A) whose leading edge is located at R = 50 km in the northern half of the storm where the peak kinetic enenrgy remains confined but at R = 60 km. As this rainband propagates cyclonically and outward, it facilitates the production of kinetic energy in the boundary layer. By 87 h, the convective element has made almost a half circle at R = 50 km (i.e., B). Meanwhile, the trailing convective band is active in producing kinetic energy, and now the kinetic energy maximum has filled more than 75% of the annulus at R = 100 km. By 88.5 h the spiral band has completed nearly a full circle (C) around the annulus of the storm and the peak kinetic energy has propagated outward and remains near R = 100 km, effectively forming a new axisymmetric radius of maximum kinetic energy at R = 100 km. In this way, the propagation of a single rainband in a weak-sheared environment could facilitate the formation of a new eyewall. That is, a partial eyewall at 85 h, R = 60 km, is replaced by an axisymmetric eyewall with R = 100 km by 88.5 h. Subsequent intensification after 90 h is related to the contraction of this new eyewall prior to landfall.
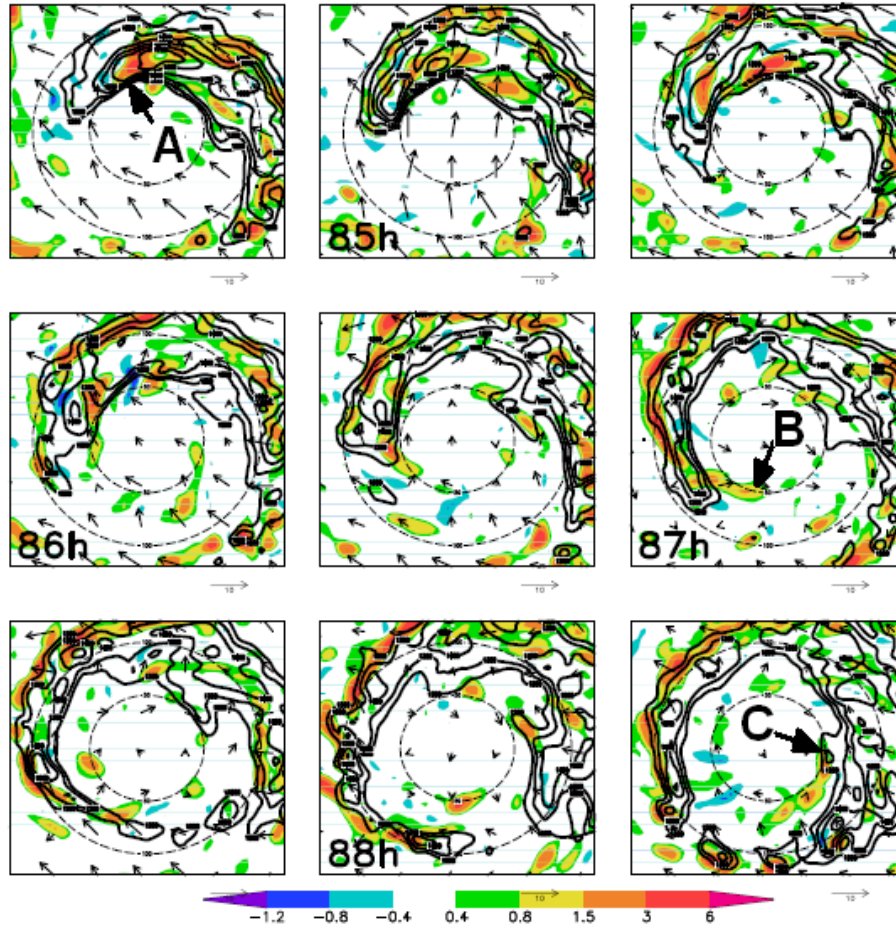
Fig. 1: Horizontal distribution of vertical motion (shaded) averaged within z = 6 – 10 km, from 84.5 – 88.5 h simulation plotted every 30 min. Solid contours are kinetic ennergy averaged within the z = 0 - 3 km layer and plotted at intervals of 1 J kg⁻¹. Horizontal asymmetric flow vectors at z = 1.5 km are superimposed. Dashed circles represent radius rings at R = 50 km and R = 100 km. A, B, and C denote the leading edge of a convective element.

(ii) *A 7-day cloud-resolving simulation of Super-typhoon Chanchu (2006)* with the finest grid size of 2 km – part of Mr. Hogsett's Ph. D. thesis. After verifying the 7-day simulation against available observations, the model simulation data is analyzed to examine the development of eyewall contraction, significant wave propagations, double eyewalls, vortex-frontal interaction, and air-sea interaction. During the eyewall contraction phase, the inner core convection exhibits an elliptical eyewall that propagates cyclonically with time. This feature can be described as a wavenumber-2 phenomenon after Fourier decomposition, as given in Fig. 2 showing that the major axis of the ellipse is characterized by negative (positive) anomalies of pressure (vertical motion) in the eyewall. The anomalies associated with the wavenumber-2 features are seen to extend above 500 hPa and exhibit maximum amplitude near the radius of maximum wind. The pressure and vertical motion features propagate together azimuthally with time.
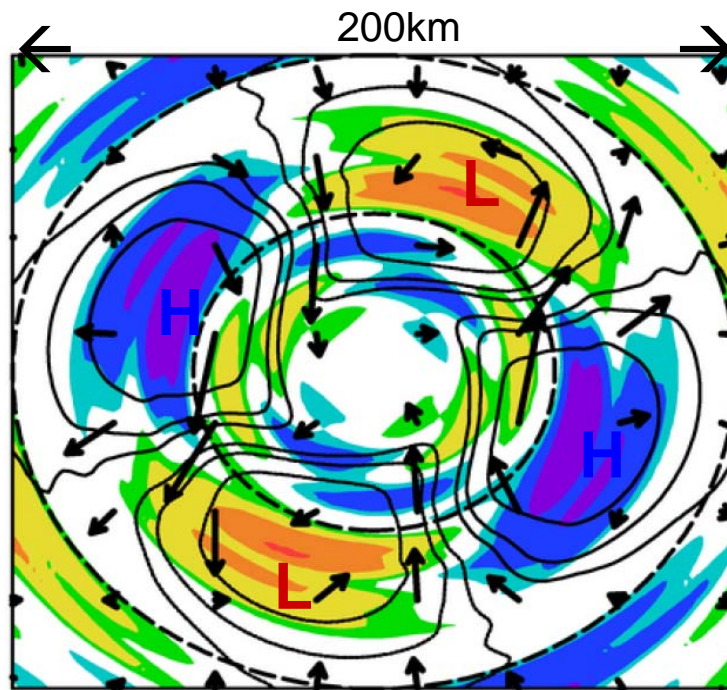
Fig. 2 Horizontal distribution of the wavenumber-2 geopotential height (contoured) and vertical motion (shaded) at 900 hPa from 48-h simulation of Super-Typhoon Chanchu (2006).

The horizontal flow field associated with the wavenumber-2 pressure perturbations can be characterized by cyclonic (anticyclonic) flow about the negative (positive) pressure perturbations. This flow pattern causes radial inflow (outflow) that leads (lags) the low pressure features and facilitates the outward spiraling appearance of the wavenumber-2 features. This is similar to the VRWs that lead to spiral rainbands by Montgomery and Kallenbach (1997), and more likely to the propagation of vortex-Rossby-gravity waves as discussed by Zhong, Zhang and Lu (2008) under (iv). The consequence of their interaction with the mean vortex remains unclear and is the focus of our future study.

(iii) *A cloud-resolving simulation of Typhoon Nari (2001) at landfall over Taiwan* (Yang, Zhang and Huang 2008). In this study, several 84-h cloud-resolving simulations of Typhoon Nari (2001) that produced torrential rainfall of more than 1400 mm over Taiwan, are carried out using a quadruply nested–grid mesoscale model with the finest grid size of 2 km. We found that the model reproduces reasonably well Nari's track, the sizes of the eye and eyewall, the spiral rainbands, the rapid pressure rise during landfall, and the nearly constant intensity after landfall as well as the local rainfall maxima associated with Taiwan's orography.

It is found from a series of sensitivity simulations that the impact of island terrain on Nari's intensity is nearly linear, with stronger storm intensity but less rainfall in lower-terrain runs. In contrast, changing the terrain heights produces nonlinear tracks with circular shapes and variable movements associated with different degrees of blocking effects. Parameter and diagnostic analyses reveal that the nonlinear track dependence on terrain heights results from the complex interactions between the environmental steering flow, Nari's intensity, and Taiwan's topography, whereas the terrain-induced damping effects balance the intensifying effects of latent heat release associated with the torrential rainfall in maintaining the near-constant storm intensity after landfall.

(iv) *A new theory for the development of mixed vortex-Rossby-gravity waves in tropical cyclones* (Zhong, Zhang and Lu 2008). Montgomery and Kallenbach (1997) developed a VRW theory using a *nondivergent* barotropic vorticity model. However, our analyses of several cases, as mentioned above, reveal the presence of significant divergent perturbations propagating in tropical cyclones. Thus, we are motivated to develop a theory for azimuthally propagating mixed vortex-Rossby-gravity waves by including both *rotational and divergent* components in a shallow-water equations model, as compared to that used by Montgomery and Kallenbach (1997). A cloud-resolving hurricane simulation is used to simplify the radial structure equation for linearized perturbations, and then transform it to Bessel's equation with constant coefficients. A cubic frequency equation is eventually obtained, yielding three groups of allowable waves in hurricanes.

We found that low-frequency VRWs and high-frequency gravity waves could coexist, but with separable dispersion characteristics, in the eye and outer regions of hurricanes, whereas mixed vortex-Rossby-gravity waves with inseparable dispersion and wave instability properties tend to occur in the eyewall. Results show that high-frequency gravity waves propagate at half of their typical speeds in the inner regions with more radial "standing" structures. Results also show that the intense rotational flows in the eyewall account for the development of the mixed-wave instability, and shorter mixed vortex-Rossby-gravity waves will grow faster than longer waves.

IMPACT/APPLICATIONS

Our results suggest that (i) hurricane intensity changes are closely related to the generation and propagation of VRWs and more likely mixed vortex-Rossby-gravity waves in the eyewall; and (ii) hurricane rainfall after landfall may be determined by the large-scale sheared flows and enhanced by the local topography.

RELATED PROJECTS

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

PUBLICATIONS

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11. Hogsett, W., and D.-L. Zhang, 2008: Numerical simulation of Hurricane Bonnie (1998). Part III: Energetics. *Mon. Wea. Rev.* [submitted, refereed]
12. Zhong, W., D.-L. Zhang, and H. Lu, 2008: A theory for mixed vortex Rossby- gravity waves in tropical cyclones. *J. Atmos. Sc*. [submitted, refereed]

HONORS/AWARDS/PRIZES

2006: NASA's Group Achievement Award.
2006:   Fellow, American Meteorological Society.