Prediction and Predictability of Tropical Cyclones over Oceanic and Coastal Regions and Advanced Assimilation of Radar and Satellite Data for the Navy Coupled Ocean-Atmosphere Mesoscale Prediction System

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LONG-TERM GOALS

This project addresses tropical cyclone (TC) structure and intensity prediction improvement problem by (a) developing and testing advanced data assimilation (DA) capabilities for use by the Navy's COAMPS model and other community mesoscale prediction systems; and (b) by studying the effects of DA and initial condition and model errors at the convective scales on the predictability of TCs, which will in turn provide guidance to optimal ensemble prediction system design and DA improvement.

OBJECTIVES

The project seeks to help fill some gaps of the Navy, DoD and NOAA's weather forecasting research and development. The research will accelerate our nation's capability to accurately predict hurricane intensity, thereby potentially reducing hurricane-related losses through better preparedness and response. Reduction in the uncertainty in track and intensity forecasting can directly translate into huge economic savings. The project will directly contribute to Navy's goal of reducing TC structure and intensity prediction error by 50% within a decade. The software developed has a direct path of transition to Navy's operations.

APPROACH

The ensemble Kalman filter (EnKF) will be the primary method used for data assimilation in this project. The EnKF system developed by this research group will be significantly enhanced to assimilate additional airborne, shipboard, as well as other types of ground-based Doppler weather radar data. Available dropsonde, driftsonde, satellite track wind, sea surface QuikScat wind, Doppler lidar wind, and routine observational data will be assimilated together. The effort will also involve the development of new observation operators for radar and satellite data. Cases from major field experiments will be used as the test cases. We will perform systematic predictability studies that emphasize the understanding of convective-scale errors and uncertainties in both the initial conditions and the prediction models themselves on the predictability of hurricane structure and intensity. Based

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successful simulations/predictions of tropical cyclones, diagnostic analyses on the physical processes involved will be carried out.

WORK COMPLETED

1. EnKF assimilaiton of coastal Doppler radar data and impact on prediction of Hurricane Ike (2008)

In this study, EnKF is used to assimilate radial velocity and reflectivity observations from two coastal WSR-88D radars for the analysis and forecast of Hurricane Ike (2008). The Advanced Regional Prediction System (ARPS) of the University of Oklahoma is used at a horizontal resolution of 4 km. The Lake Charles (KLCH) and Houston (KHGH) radar observations are used. The assimilations start from 0400 UTC September 13 with 10-minute cycles and end at 0600 UTC September 13. The forecast starts with ensemble mean analysis from 0600 UTC September 13 and ends at 0000 UTC September 14. The impact of assimilation radial velocity, reflectivity, or both on the structure, intensity and tracking forecasting of Ike is examined.

2. Initial investigation of predictability based on the forecast sensity of Hurricane Ike (2008) it initial condition and model microphysics perturbations

EnKF can help predictability studies by providing initial conditions that properly sample initial condition uncertainties. The development of hurricane track and intensity uncertainty results partly from the uncertainty in the initial conditions and partly from the uncertainty in the prediction model. The forecast uncertainty growth owing to initial condition uncertainties is compared with the uncertainty growth due to model physics uncertainties, especially in microphysics. We include the effect of physics uncertainty by using different microphysics parameterization schemes in the ensemble forecasts, initialized from Hurricane Ike’s (2008) EnKF analysis, and examine its relative impact of uncertainty growth.

3. A modeling and diagnostic study of Typhoon Morakot (2009)

Typhoon Morakot was an example of the rarely seen evolution of a monsoon gyre circulation into a very large tropical cyclone (TC) over the northwest Pacific Ocean (Lander 1994). It developed about 1300 km east of Taiwan in early August 2009, and adopted an almost due westerly track towards the island. The typhoon claimed a heavy toll in terms of lives lost and material damages over Taiwan and China, mainly due to flooding, landslides and debris flows. Although Morakot was only a moderate intensity typhoon at landfall, it produced extreme rainfall over southern parts of Taiwan, including observations of 1400 mm in 24 hours and three day storm totals of 2800 mm.

A series of simulations of Morakot were undertaken utilizing version 5.2 of the ARPS (Xue et al. 2003). The experiments presented in this report were conducted on a large 3009 x 2409 km grid at a resolution of 3 km, with 53 levels. Initial and boundary conditions were provided by the NCEP GFS analyses and forecasts. The model used a full physics package including the Lin microphysics scheme. The Taiwan Central Weather Bureau (CWB) provided Doppler radar data from their four radars, and surface observations. Geostationary and microwave satellite imagery was collected from the Naval Research Laboratory, Monterey. These data are used verification purpose in this study.

RESULTS

1. EnKF assimilaiton of coastal Doppler radar data and impact on prediction of Hurricane Ike (2008)

The composite reflectivity and horizontal wind vectors at the 3 km height from NoDA (without radar data assimilation), ExpVr (assimilating radial wind alone), ExpZ (assimilating reflectivity alone) and ExpAll (assimilating both radial wind and reflectivity) are presented in Fig. 1, together with the observed composite reflectivity (OBS). ExpAll and ExpZ have similar rainband structures and are closer to the observations than ExpVr at the end of the analysis cycles (Fig. 1d-e). During the 18-hour forecast, a clear-air hole without precipitation is always visible in the vortex center in NoDA (Fig. 1g, l and q). With the radar data assimilated, the vortex centers are filled with precipitations. The precipitation patterns are closer to the observations, reflecting more tightly wrapped vortex structure.

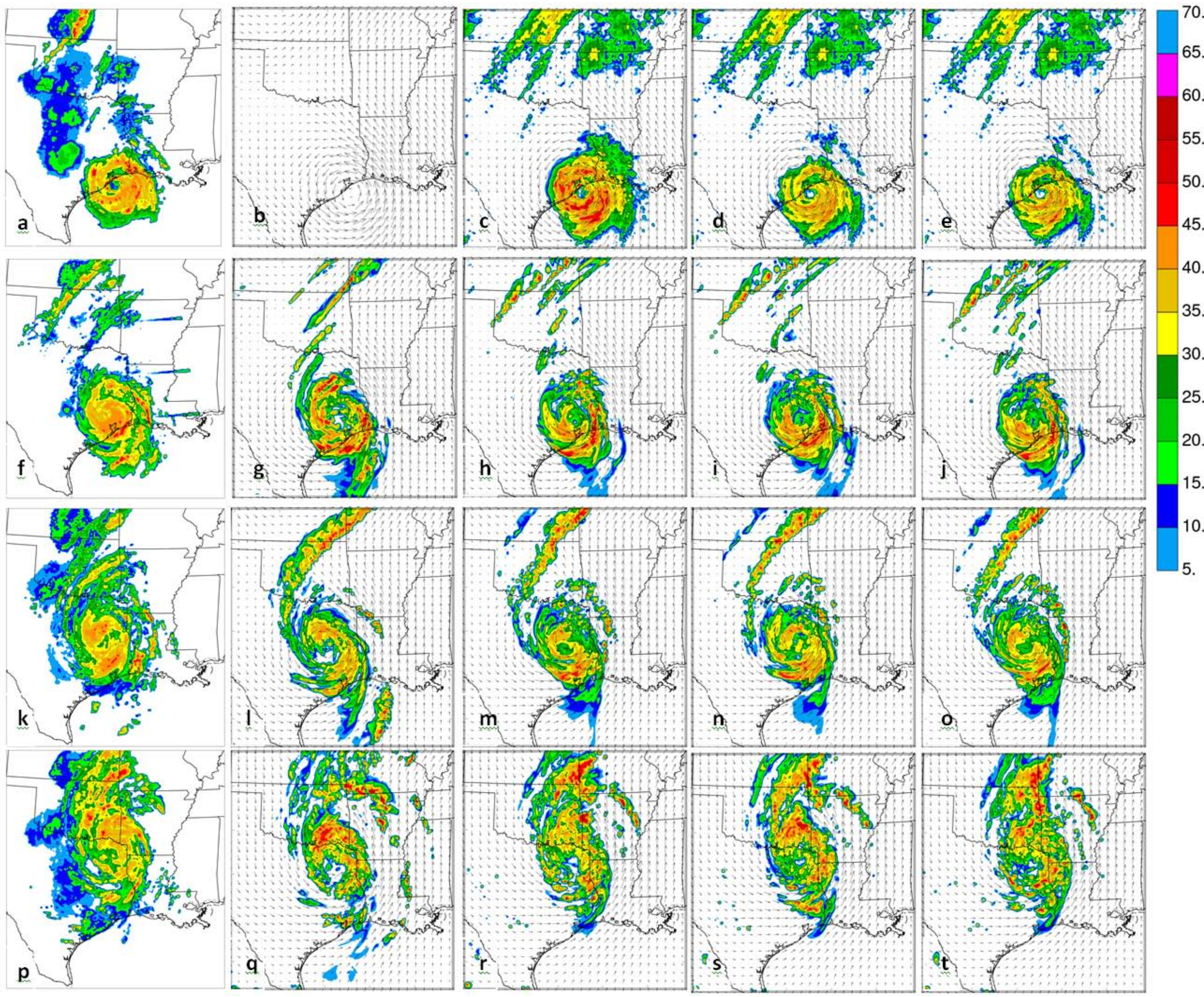

Fig. 1. Composite reflectivity (color shaded) and wind vectors at 3 km height analyzed and predicted by experiments (b, g, l and q) NoDA, (c, h, m and r) ExpVr, (d, i, n and s) ExpZ, and (e, j, o, t) ExpAll, as compared with (a, f, k and p) corresponding observations. The times shown are 0600, 1200, 1800 UTC, September 13 and 0000 UTC September 14, 2008.

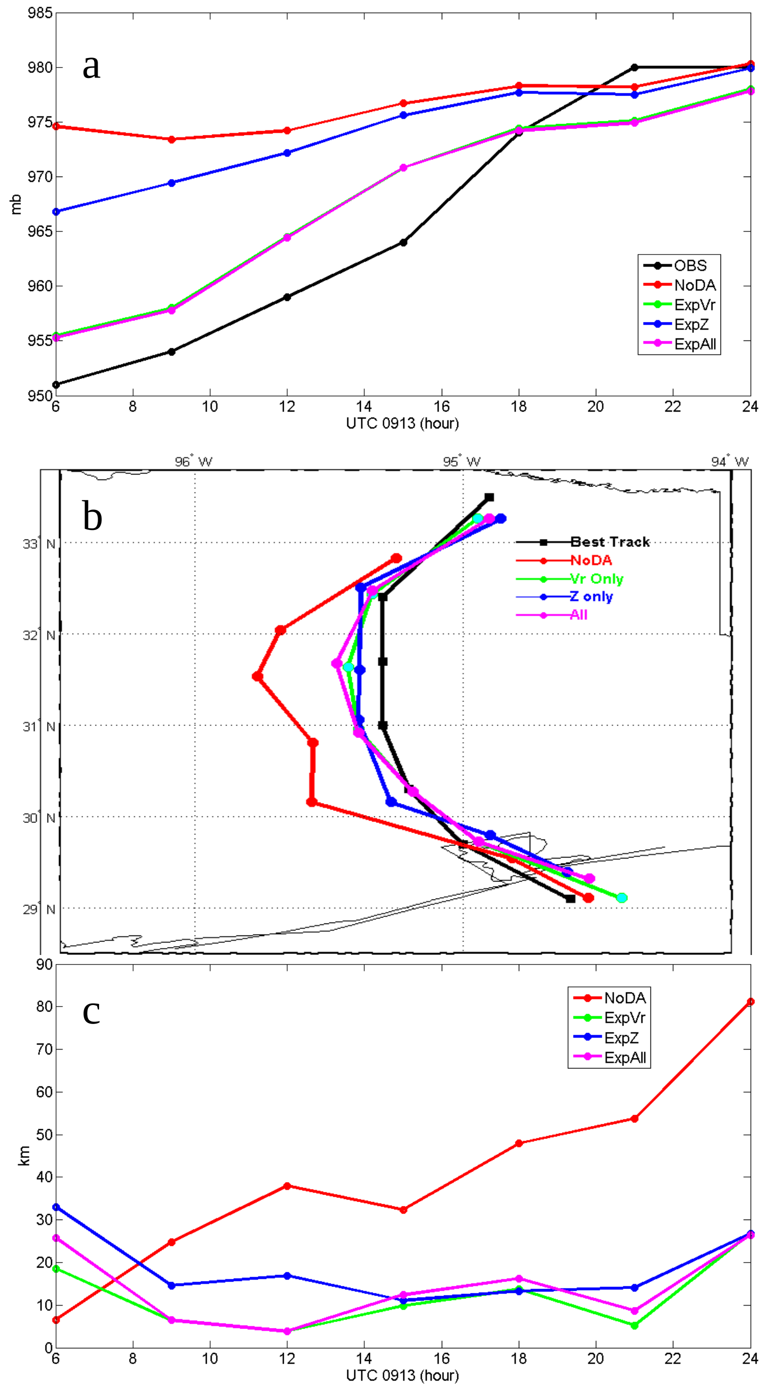

Fig. 2. (a) The predicted intensity for Hurricane Ike, plotted every three hours from 0600 UTC September 13 to 0000 UTC September 14. (b) The predicted track for Hurricane Ike, plotted every three hours from 0600 UTC September 13 to 0000 UTC September 14. (c) The predicted track error for Hurricane Ike, plotted every three hours from 0600 UTC September 13 to 0000 UTC September 14. OBS denotes the best track. NoDA denotes the no radar data assimilation simulation. ExpZ denotes EnKF experiments assimilating Z alone. ExpVr denotes EnKF experiments assimilating Vr alone. ExpAll denotes EnKF experiments assimilating both Vr and Z.

The intensity and track forecasts from the control simulation without radar data assimilation NoDA and EnKF are plotted in Fig. 2 against the best track. The track errors are also plotted. The assimilation of radar observations is found to significantly improve the intensity and track forecasts of Ike. The relative improvements over NoDA are 80% for assimilating Vr alone or both Vr and Z, and 55% for assimilating Z on intensity at 0600 UTC. Assimilating Vr alone also leads to a much larger improvement to the intensity forecast than Z alone. For track forecast, starting from 0600 UTC, NoDA takes a more west path than the best track and all the data assimilation experiments. All the mean track errors of three data assimilation experiments are smaller than 20 km, showing an evident improvement over NoDA with 40 km mean track error. Vr alone produces a slightly better forecast than Z alone. Assimilating both Vr and Z has similar results as assimilating Vr alone, indicating dominant role of Vr data when analyzed using EnKF.

Minimum seal level pressure (MSLP) from the best track data is also assimilated with radar observations with 60-minute interval. With the single MSLP observation analyzed, the increment field ($x_{\text{after analsyis}}$- $x_{\text{before analsyis}}$) of wind shows the strong cyclonic circulation around the MSLP observation (Fig. 3a), indicating the enhancement of the vortex by the MSLP observation. The covariance between the pressure observation and the model wind fields allows the MSLP observation to update the wind field properly, which reflects the benefit of multivariate analysis. The pressure increment is below -10 mb on the pressure observation position and increases outward. The increment of potential temperature is plotted in Fig. 3b. While the increment of potential temperature is not as well-shaped as pressure, there is still noticeable positive increment at the center of the vortex with the maximum of 5 K, suggesting the strengthening of the warm core structure by the assimilation of MSLP.

When MSLP is assimilated with reflectivity, the improvement is as large as 14-15 mb at the end of the analysis (not shown). The impact decreases with forecast but is still noticeable until the 12-hour forecast. The additional assimilation of MSLP with radar data also improves the track analysis. The improvement on the track forecast from MSLP is always over 50% in the first 9-hour forecast when MSLP is assimilated with reflectivity.

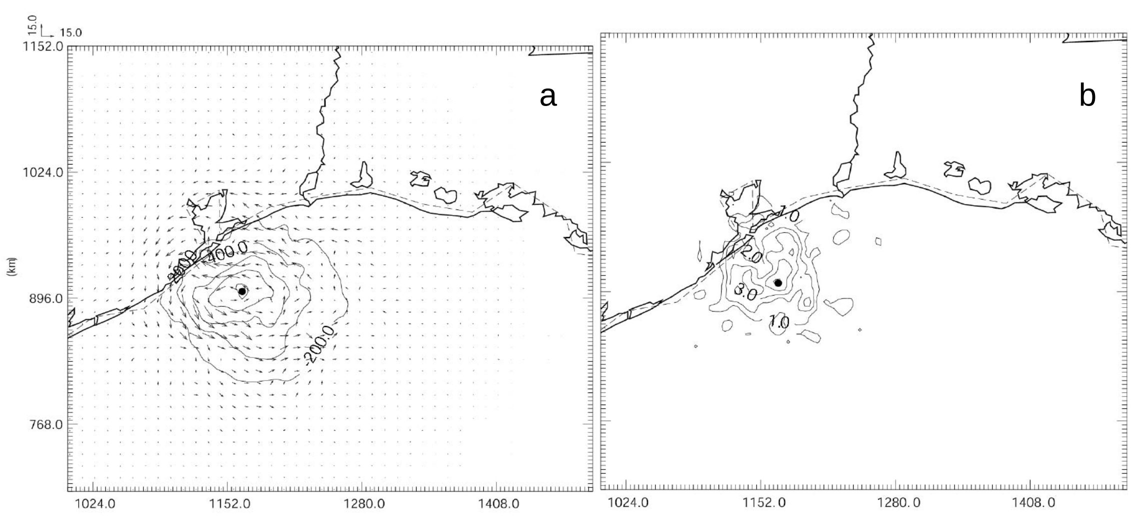

Fig. 3. Increment fields from assimilating MSLP at z=1km for (a) horizontal wind component and pressure (every 200 mb), and (b) potential temperature (every 1 K) at 0500 UTC 0913 of ExpZMSL. The black dot denotes the position of the MSLP.

2. Initial investigation of predictability based on the forecast sensity of Hurricane Ike (2008) it initial condition and model microphysics perturbations

Three 4-member ensemble forecasts are conducted, with initial perturbations or microphysical parameterization perturbations or both. When the initial condition perturbations and the microphysical schemes perturbations are combined together in Exp4FULL, the intensity spread is larger than Exp4PERT, with initial perturbations only, and Exp4PHYS, with microphysical parameterization perturbations only, after 1200 UTC (Fig. 4). The growth rate of intensity spread in Exp4FULL is close to Exp4PHYS, demonstrating the dominate role of microphysical schemes perturbations on intensity uncertainty growth. For most of the forecast times, the spread of Exp4FULL is always smaller than the linear combination of the spread of Exp4PERT and Exp4PHYS due to the nonlinear effect.

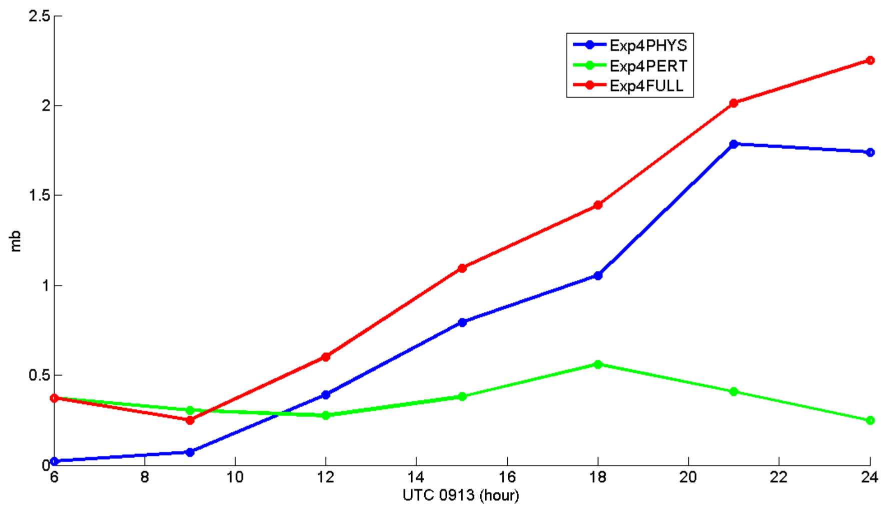

Fig. 4. The spread of intensity forecasts for Exp4PHYS (blue, microphysical parameterization perturbations only), Exp4PERT (green, initial condition perturbations only) and Exp4FULL (red, both microphysical parameterization and initial condition perturbations).

3. A modeling and diagnostic study of Typhoon Morakot (2009)

The evolution of the track, structure and intensity of Morakot was complex during the landfall phase over Taiwan. Despite this, ARPS runs were able to reproduce the observed track and intensity changes well, as can be seen in Fig. 4, where the tracks produced by the 3km ARPS runs are plotted with the best track produced the Taiwan Central Weather Bureau (CWB), along with time series of central pressure and maximum sustained winds (MSW). It is evident that landfall had little impact upon the intensity or the intensity trend of the cyclone, contrary to expectations for a landfalling TC over such rugged terrain.

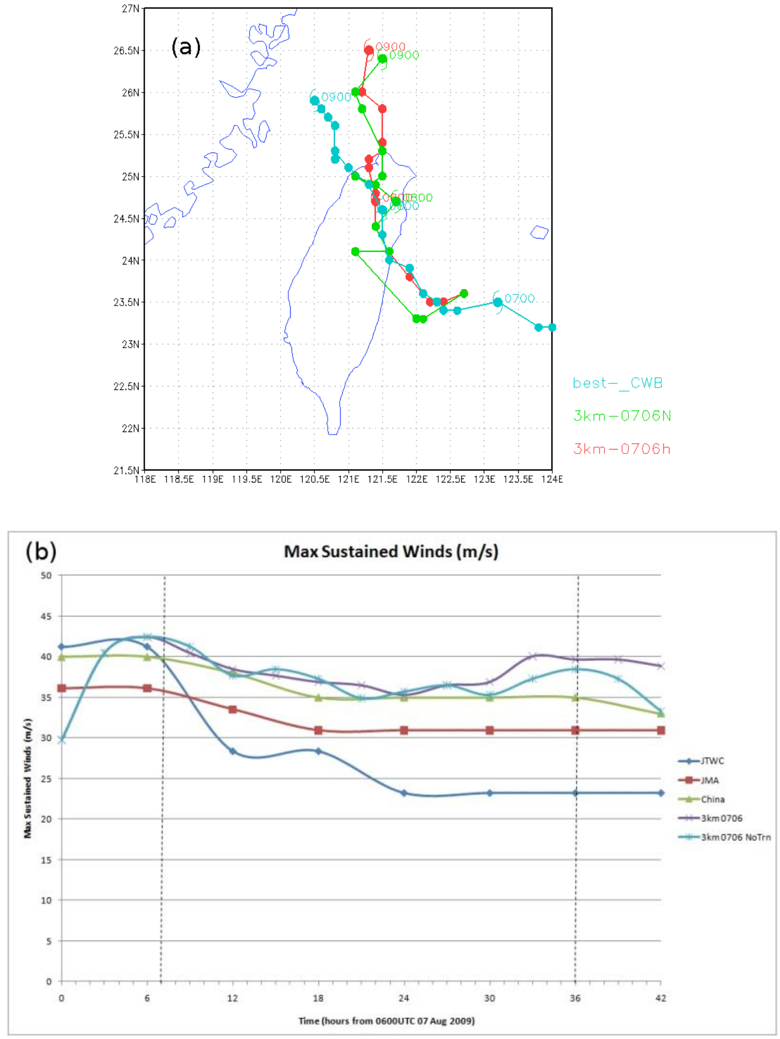

Fig.4. (a) Tracks of ARPS 3km resolution model runs initialized at 0600UTC 7 August 2009, with and without Taiwan terrain, along with the best-track from the Taiwan Central Weather Bureau (CWB). Positions are three hourly, and the label format is ddhh UTC. (b) Time series of intensity, in terms of maximum sustained winds. Best track intensities from CWB were not available, values are shown for Joint Typhoon Warning Center (JTWC), Japan Meteorological Agency (JMA), and China Meteorological Administration (CMA). Vertical dashed lines show approximate times of landfall and movement back over water.

A snapshot of the general evolution of Morakot's structure during the landfall phase over Taiwan is shown in Fig. 5. The original low level center and initial inner eyewall, with a radius of approximately 60 km, had weakened and decayed as it approached Taiwan. Meanwhile, a much larger vorticity annulus remained in place, with an average radius of about 160 km. This feature was particularly pronounced around the southern semi-circle just prior to landfall, where it was associated with deep convection and low level convergence between southwesterly monsoon flow and the typhoon circulation, and this was captured in the model composite reflectivity seen in Fig. 5b. These features were evident in geostationary and microwave satellite imagery, and in radar data from Taiwan (Fig. 5c and 5d). The southern semi-circle of the vorticity annulus remained almost stationary near the southern tip of the island during the landfall phase. This band, and its associated deep convection, appeared to play a crucial role in the mesoscale evolution of the typhoon during and after landfall over Taiwan, acting as a forcing for Vortex Rossby Waves (VRWs), which became the dominant mesoscale structure of the storm.

Previous studies have emphasized the importance of VRWs to the evolution of the structure and intensity of tropical cyclones. The present case was different from previous studies due to much greater size of Morakot, and the lack of a classical eyewall feature in the pre-existing vortex.

Following the methodology of earlier observational (Corbosiero et al. 2006) and modeling studies (Wang 2002; Wu et al. 2009), the vorticity field and model reflectivity were decomposed into azimuthal wavenumbers using a Fast Fourier Transform, in order to identify low wavenumber asymmetries in the low level flow. Wavenumber one, two and three asymmetries are clearly evident in the vorticity field (not shown), and these coincide with similar anomalies in reflectivity. Calculation of the phase speed of these waves shows that it is about 75% of the azimuthal wind speed, in good agreement with the theoretical value obtained from the dispersion relationship derived by Montgomery and Kallenbach (1997). The structure of the waves closely resembled those found by Wang (2002) in his idealized TC model, showing the propensity to slope downwind with height in the azimuthal direction in the low levels, and outward in the radial direction. In summary, it is highly likely that the waves are VRWs, rather than another wave type such as inertia-gravity waves.

There was very little difference in structure or track evident between ARPS runs conducted with full Taiwan terrain (TRN) and no terrain (NT). Tracks were virtually identical, and even in the low level wind fields there were few major differences. Interestingly, the NT runs displayed the same tendency to produce new low level centers over western Taiwan in similar fashion to the TRN runs. Previous studies of landfalling typhoons over Taiwan have attributed the development of these new low level centers to the effects of the terrain (e.g., Lin et al. 2005). However, the results in the case of Morakot suggest that the terrain had little impact, and the developing low level centers were a response to up-motion forced by the low to mid-level VRWs. Intensity trends were also very similar between the two cases.

VRW activity as a whole was also very similar between TRN and NT runs. By inspection, individual VRWs had their origins in the convection associated vorticity annulus to the south of the center, and generally survived to complete at least one cyclonic orbit of the center. Thus, the hypothesis that the effects of the flow over the terrain can act to excite VRWs does not seem to be supported in this case, probably because the typhoon was large compared to the horizontal extent of Taiwan and its terrain. Wang (2002) used a local PV and eddy kinetic energy budget analysis to show that diabatic heating in deep convection is the primary potential vorticity (PV) source for the VRWs, and further than nonlinear processes associated with the wavenumber one waves are a significant source of PV for wavenumber 2 and higher waves. Work is underway to investigate whether similar results hold for Morakot, and to further establish the relationship between the VRWs and deep convection in these large, moderate intensity TCs.

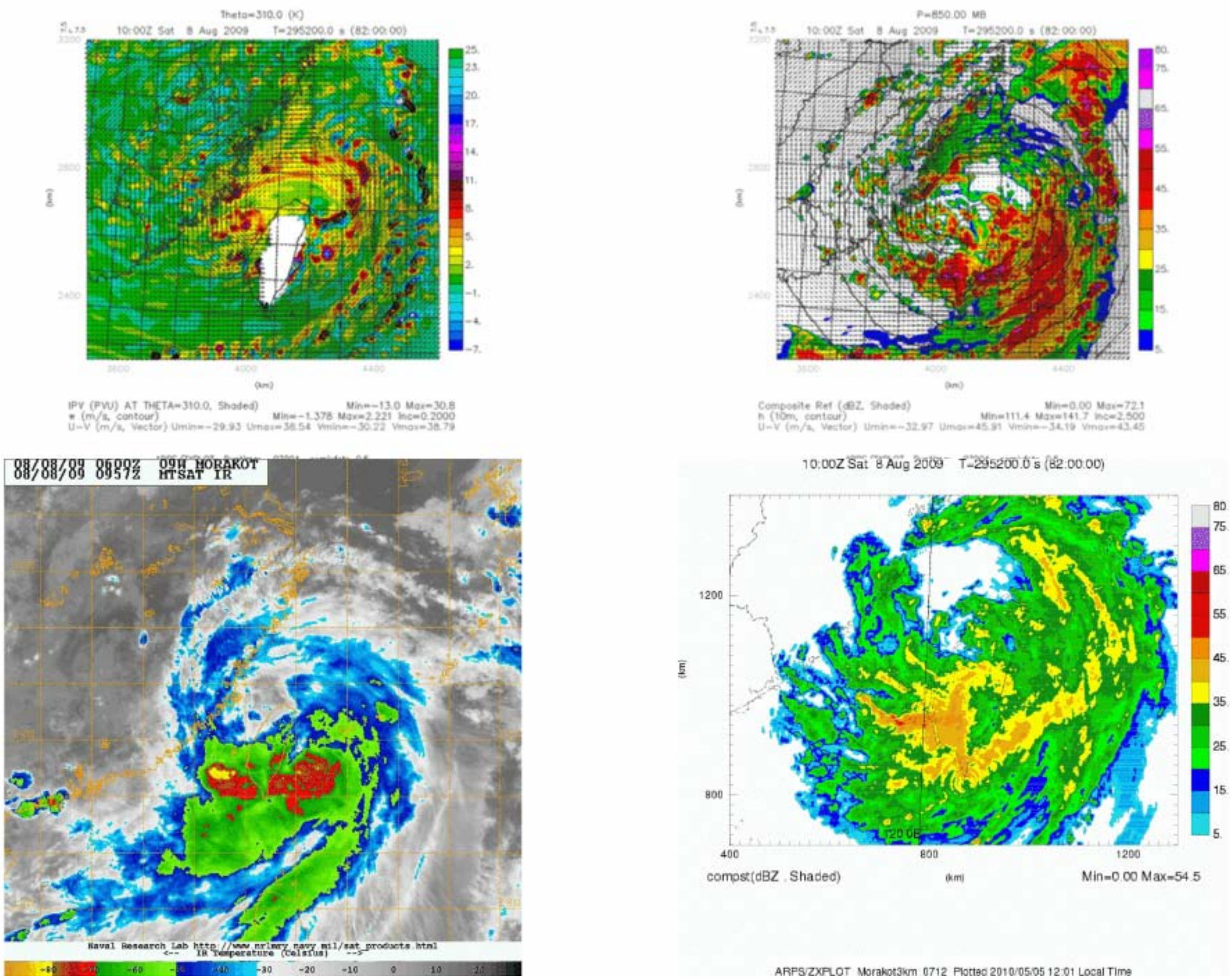

Fig.5. (a, top left) Vertical component of relative vorticity and (b, top right) composite reflectivity from 3 km ARPS model run, (c, lower left) enhanced infrared imagery from MTSAT and (d, lower right) composite radar imagery from Taiwan radars. All fields are valid at 1000 UTC 8 August 2009.

The VRWs were associated with the repeated development of convective bands on the western flank of the cyclone. As found in previous numerical studies of tropical cyclones in a vertically sheared environment (e.g., Braun et al. 2006), the convective response was suppressed while the VRWs were in the upshear part of the cyclone, and became associated with up-motion and convection as they rotated towards the downshear part of the system. Prior to landfall, with TC moving generally west, VRWs and bands on western flank of TC moved southwards in an Earth relative sense. However, later when the cyclone adopted a northerly track, this tended to cancel the southerly motion of the waves rotating around the center, and in response these become almost stationary (Earth relative), and this appeared to be a major factor leading to the extraordinary rainfall observed over Taiwan.

IMPACT/APPLICATIONS

Through collaborations with scientits (Drs. Allen Zhao, Yi Jin, Hao Jin and Melenda Peng) at Naval Research Lab at Moneterey, ensemble Kalman filter data assimilaiton capabilities for radar data will be implemented within NRL's EnKF DA system that has been interfaced with NAVDAS system. Physical understanding gained on the structure of TCS will help us improve observing and prediction systems for TCs.

TRANSITIONS

Certain advanced capabilities will be transferred into Navy's EnKF DA system. Further simulation experiments will also be performed with the COAMPS model.

RELATED PROJECTS

This project is complemetary to our recently funded ONR project "Advanced Multi-Moment Microphysics for Precipitation and Tropical Cyclone Forecast Improvement within COAMPS" (N00014-10-1-0775) led by the same PI.

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