6A.7 TROPICAL CYCLONE FORMATION AND STRUCTURE STUDIES USING A MOIST ADJOINT MODEL

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1. Motivation

The motivation of this study is two-fold. The first one is that as is well known to modelers, validation of some simulated parameters by observations does not mean that the corrected physical processes have been realized in the numerical model. For example, ability of a model to simulate the intensification profile of a tropical cyclone (TC) does not guarantee that all the correct physics responsible for intensification are reproduced numerically, a situation that is illustrated for Typhoon Robyn (1993) in the following section.

Moreover, much remained to be studied and clarified on the physics of TC formation and structure change. Just to name a few issues such as role of mesoscale and convective-scale system in TC formation (Lee et al. 2008). How each episode of deep convection during the early stage of development of a TC is contributing to deepening of surface pressure and strengthening of low-level vorticity? What are the heat sources of warm core formation in TCs? What are the physical mechanisms for size change? In order to investigate these issues, adjoint sensitivity is used as a diagnostic tool to indicate the essential processes for different stages of TC development, and may also suggest intrinsic problems within the numerical models. Utility of adjoint sensitivity for model diagnosis is limited by its mathematical formalism as well as other factors, which are briefly discussed in this paper.

2. Simulation of Typhoon Robyn (1993)

Cheung and Elsberry (2006) performed simulations of the formation processes of Typhoon Robyn (1993) using the PSU/NCAR mesoscale model (MM5) and compared with observations taken in the Tropical Cyclone Motion field experiment (TCM-93). The simulations started from 1200 UTC 31 July until 0000 UTC 3 August It was found from a series of sensitivity tests that the best results came from the experiment with a 27-km resolution domain (which was nested in a 81-km mother domain) and applying the Betts-Miller cumulus parameterization. The several deep convection episodes associated with three mesoscale convective systems (MCSs) during Typhoon Robyn's formation (Fig. 1) were roughly reproduced in the simulation and the simulated intensification profile was also close to that observed. However, although the simulation in a 9-km resolution inner domain resolved a lot more convective-scale details than in the coarser grids, the degree of intensification was much less than that observed and similar results were obtained for various model configurations as well as physical parameterizations. Therefore, based on these results a natural question to ask is that what the most essential physical processes are in numerical simulations that can reproduce well the formation process and structure change of TCs, and are there any effective diagnostic tools?

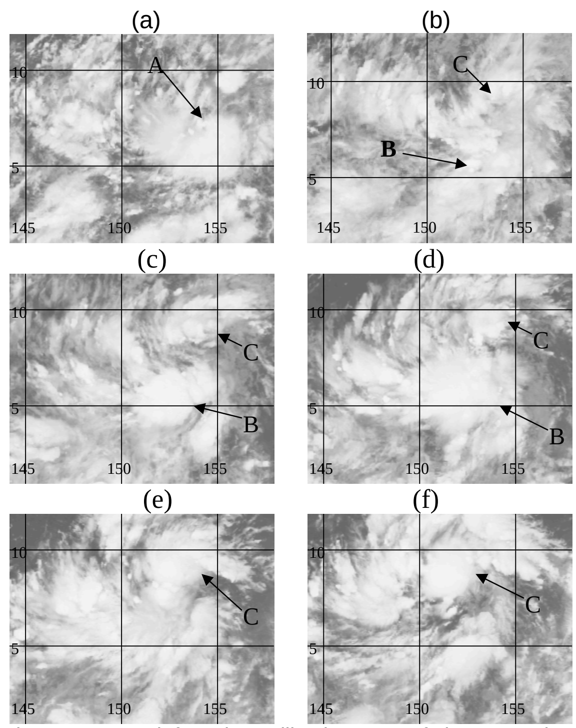

Fig. 1 GMS-5 infrared satellite imagery of the pre-Robyn disturbance at (a) 0030, (b) 0630, (c) 1030, (d) 1330, (e) 1730 and (f) 2130 UTC on 1 August 1993. Letters A, B, and C indicate three mesoscale convective system developments [adapted from Cheung and Elsberry (2006)].

A MM5 simulation of Typhoon Robyn with higher resolution domains is performed recently that consists of a 45-km resolution coarse domain and 15-km fine domain, with Kain-Fritsch cumulus parameterization being utilized in both. The intensification of Typhoon Robyn during the 60-h simulation in this new simulation is also close to that observed (Fig. 2) and as expected due to the higher resolution compared with previous runs more convection with finer scales are simulated. In general, the three episodes of deep convection associated with MCSs A, B and C shown in Fig. 1 is well simulated in terms of both timing and

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spatial distribution. The simulated early convection associated with MCSs A and B also concentrates at lower latitudes of 5-6^{o}N but vertical velocities of these early convective episodes are usually under 1 m s^{-1} and cloud development is at most up to the mid troposphere, which is not quite consistent with the observed lowest blackbody temperatures of less than 200 K (about -73 ^{o}C) associated with convection in that year.

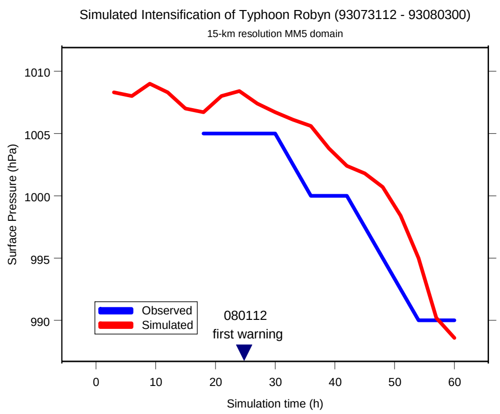

Fig. 2 Observed and simulated minimum sea-level pressure (hPa) of Typhoon Robyn during the 60-h period starting 1200 UTC 31 July 1993.

The strongest convection in the simulation occurs at around 1800 UTC 1 August that is located at the northern part of the developing vortex (Fig. 3), and this should be associated with the MCS C right after the vortex was declared tropical depression. Vertical velocities associated with this convection are over 1 m s^{-1} and last for several hours, which is consistent with the observed life time of MCS C. This convection leads to intensification of the surface vortex at around simulation time of 30 h in Fig. 2. Another simulated episode of convection with vertical velocities over 2 m s^{-1} at about 0600 UTC 2 August then leads to a rapid intensification phase of the cyclone.

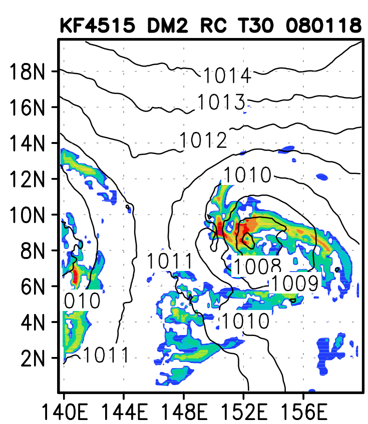

Fig. 3 Simulated sea-level pressure (contour, hPa) and 3-h accumulated convective rain (shaded, mm) valid at 1800 UTC 1 August 1993.

Examination of the cloud water mixing ratio indicates that the height of these simulated convection episodes is up to 200-300 hPa (Fig. 4), and comparison with the vertical temperature profiles in the vicinity shows that the simulated cloud-top temperature should be warmer than 200 K (-73 ^{o}C). However, observed blackbody temperatures at the same time depict some lowest temperatures of less than 190 K (-83 ^{o}C), which implies that the average deepness of convection in the simulation is underestimated. Sensitivity experiments is further performed with higher model top layer but probably because there is no additional observations to initialize the model upper layers except the global analyses, improvement in the deepness of convection is not significant.

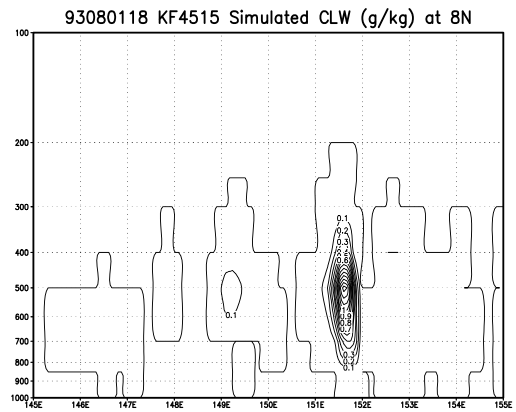

Fig. 4 Vertical cross section of simulated cloud water mixing ratio (g kg^{-1}) at 1800 UTC 1 August 1993.

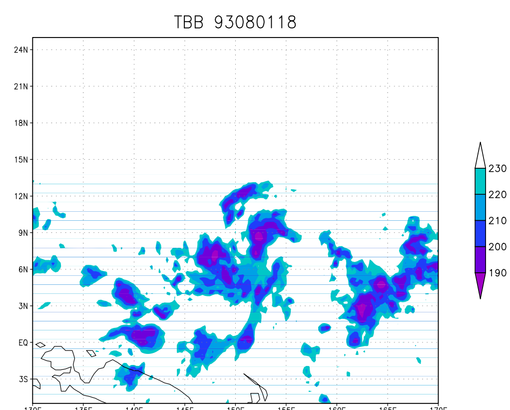

Fig. 5 Observed blackbody temperature (T_{BB}) lower than 230K (about -43 ^{o}C) at 1800 UTC 1 August 1993.

This leads to the question that although the intensification of Typhoon Robyn seems to be well realized in the MM5 model, there are still obvious deficiencies in the simulation such as ability of the model to initialize convection and degree of the simulated convection. The important issue for modelers and forecasters is that these deficiencies do not degrade a particular simulation but may be affecting substantially other TC formation cases (e.g., those with a single episode of deep convection) or TC structure change simulations. How can these effects be diagnosed systematically?

3. TC Structure studies using an adjoint model

The concept of adjoint model and its application in four-dimensional data assimilation has been well introduced in the literature (e.g., Errico 1997; Kleist and Morgan 2005; Wu et al. 2007) and is not repeated here. Practically, simulations from a nonlinear full-physics model such as MM5 are stored as basic states during its forward integration. Then these basic states are used as initial and boundary conditions of an associated adjoint model that is integrated backward in time, and its state variables are the so-called adjoint sensitivities ($\partial J/\partial x$) of a pre-selected forecast aspect J with respect to the other variables x's in the original nonlinear model. The adjoint model is mathematically a tangent linear version of the original model that involves linearized dynamics and part of the physics. Validity of this tangent linear model (TLM) as compared with outputs from the nonlinear model imposes an intrinsic limit to the duration of integration using the TLM. An early application of adjoint sensitivities for diagnosing extratropical cyclone development can be found in Langland et al. (1995).

4. Issues involved

There are several basic issues that have to be considered in applying adjoint sensitivity as a diagnostic tool for TC formation and structure studies, which are discussed in the following:

(1) The first one is the validity of linearity when utilizing the TLM in backward integration. For example, Wu et al. (2007) found that a period of 36 h is valid in applying the MM5 adjoint modeling system (Zou et al. 1997) in diagnosing TC motion, which is a timeframe when synoptic steering flow that influences TC motion is usually quite steady. However, sometimes TC formation processes may take up to 50 h (Lee et al. 2008) and it is desirable to diagnose contribution from convective systems up to two days ahead, but may be limited by deviation of TLM simulations from the nonlinear model.

(2) Secondly, not all physics are linearized in the TLM and this imposes limitation for diagnosing some physical processes based on adjoiint sensitivities. For example, the dry MM5 adjoint modeling system as described in Zou et al. 1997 may be adequate for TC motion study because influences from moist processes do not dominate TC motion, but cannot identify the appropriate sensitivities when moist convection is essential to the system development under investigation.

(3) Generation of adjoint sensitivities involves enormous computational resources due to the requirement of storage of outputs from the nonlinear model and extra effort in carrying out the backward TLM integration especially when high resolution grids are used to diagnose mesoscale systems. Another interesting issue is interpretation of results when adjoint sensitivities are generated for the same TC case from adjoint models with different resolutions. Are there methodologies of ranking sensitivities with different scales?

5. Future work

Some preliminary results that apply the MM5 adjoint modeling system on the formation process of Typhoon Robyn will be presented in the conference. In light of the issues discussed in the last section and the fact that thermodynamics processes are essential for the purposes in this study, an adjoint modeling system that has incorporated moist physics in the TLM such as the COAMPS adjoint model (Amerault 2005) and WRF 4D-Var system (Huang et al. 2007) will be used for generating sensitivity fields and developing diagnosis strategies for TC formation and structure change.

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