Understanding Impacts of Outflow on Tropical Cyclone Formation and Rapid Intensity and Structure Changes with Data Assimilation and High-resolution Numerical Simulations

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LONG-TERM GOALS

Understanding the processes that contribute to tropical cyclone (TC) formation, intensity and structure changes is essential for improving the predictability of TCs. Previous studies have focused mostly on the low- to mid-level processes leading to TC formation and rapid intensity and structure changes. The influence of upper-level atmospheric processes, especially the evolution of the outflow layer has not received much attention until recently. Therefore, the long-term goal of the proposed work is to improve our understanding and prediction of the TC outflow layer, its evolution, and its relation to TC formation and intensity and structure changes.

OBJECTIVES

Using advanced data assimilation methods and state-of-the-art numerical models, the objective of this project is to comprehensively investigate several key issues that are identified in relation to TC outflow dynamics, processes, and evolution: 1) How does the outflow layer evolve during the genesis and rapid intensification (RI) of a TC? What is its relationship to TC rapid intensification (RI) and structure changes? 2) How does TC outflow interact with inner-core convection and updrafts during RI? 3) How does TC outflow interact with environmental flows, especially large-scale troughs and ridges? How do these interactions impact TC RI and rapid decay (RD)? 4) To what extent can assimilation of satellite and radar data improve the predictability of TC outflow and related TC structure changes, RI and RD?

APPROACH

In order to achieve the research objectives of this proposal, we propose to conduct high-resolution numerical simulations by assimilating satellite, radar, and in-situ observations into the Weather
Research and Forecasting (WRF) model and/or the Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS®) model using advanced data assimilation methods (e.g., the ensemble Kalman filter, or EnKF; four-dimensional variational technique or 4DVAR) to obtain the best possible high-resolution analysis and numerical simulations. Specifically, available in-situ observations, as well as satellite and radar data from recent field programs (e.g., ONR TCS08, NASA HS3, ONR TCI-14) will be assimilated. In addition, leveraged by the results from the proposed questions and high-resolution data assimilation, we will evaluate the Naval Research Laboratory (NRL)’s new generation global model, the Navy Global Environmental Model (NAVGEM), for its ability to predict atmospheric conditions in the outflow layer.

The people involved in this project in FY14 include the PI (Prof. Zhaoxia Pu), one of her graduate students, and a postdoctoral researcher.

**WORK IN PROGRESS**

Work has been ongoing in the following areas:

- Investigating the effect of the accurate representation of atmospheric conditions, especially upper-level atmospheric processes on the prediction of TC genesis with the assimilation of radar and satellite data.
- Examining the role of upper-atmospheric warming in TC genesis and rapid intensification.

**RESULTS**

(1) Impact of model top altitude on satellite data assimilation and numerical simulations of TC genesis

In order to investigate the effects of the accurate representation of upper-level atmospheric processes on the predictability of TC genesis, we conducted a series of data assimilation and numerical simulation experiments for Typhoon Nuri (2008). Specifically, we examined the impact of model top altitude on satellite data assimilation as well as its impact on the numerical simulation of the genesis and rapid intensification of Typhoon Nuri. NASA Atmospheric Infrared Sounder (AIRS)-derived temperature profiles were assimilated into the WRF model with several different configurations (see Table 1). The simulation period covered 0000 UTC 16 to 0000 UTC 18 August 2008, around the observed time of Nuri’s genesis at 18 UTC 16 Aug 2008. Figures 2 and 3 show AIRS data coverage and vertical distribution.

Results indicate that assimilation of AIRS-derived temperature profiles results in more accurate prediction of Nuri in terms of its genesis, rapid intensification and track (Figure 3). Without the AIRS data assimilation, the model fails to predict Nuri’s genesis. With the AIRS data assimilation, the WRF model successfully predicts Nuri’s genesis. More importantly, increasing the altitude of the model top allows more data to be assimilated into the model and has a positive impact on the simulation (Figure 3). Further diagnosis was conducted to examine the impact of data assimilation, and it was found that the upper-level warming contributes to Nuri’s genesis. Assimilation of AIRS data enhances the representation of upper-level warming and circulation (Figure 4), notably in the regions above 400 hPa, including the outflow layer.

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Table 1: Experiment configurations

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Model top altitude</th>
<th>Data assimilated</th>
</tr>
</thead>
<tbody>
<tr>
<td>NODA</td>
<td>50 hPa</td>
<td>None (cold start from NCEP FNL)</td>
</tr>
<tr>
<td>CTRL</td>
<td>50 hPa</td>
<td>NCEP BUFR (conventional observations)</td>
</tr>
<tr>
<td>AIRS_BUFR_L</td>
<td>50 hPa</td>
<td>AIRS-derived temperature profiles NCEP BURF</td>
</tr>
<tr>
<td>AIRS_BURF_H</td>
<td>15 hPa</td>
<td>AIRS-derived temperature profiles NCEP BURF</td>
</tr>
</tbody>
</table>

Figure 1: Location of model domains and AIRS data coverage at 0400 UTC 16 August 2008.
Figure 2: Variation in the number of observations with pressure level.
Figure 3: Impact of AIRS data assimilation on numerical simulations of Typhoon Nuri as revealed by (a) time series of minimum central sea level pressure (simulations vs. best track; top panel) and (b) track errors (bottom panel).

Figure 4: Temperature (shaded) and wind vectors at 300 hPa at 00 UTC 18 Aug 2008.

The overall results from this study show that using a high model top results in better assimilation of the satellite data and improved representation of the outflow layer, thus enhancing the forecasting of TC genesis and RI.

(2) Impact of radar data assimilation on TC genesis and implications of the effects of upper-level atmospheric conditions
Initial conditions have substantial impacts on the numerical prediction of TC genesis. Conventional observations are usually rather sparse in terms of both temporal and spatial resolutions over the ocean, where TC genesis commonly occurs. Remotely sensed observations from satellite and radar have become important data sources. Previous studies have demonstrated that assimilating satellite observations into numerical weather prediction models can have positive impacts on TC genesis forecasts, mainly due to improvement in the simulation of TC genesis environmental conditions. In past years, airborne Doppler radar has demonstrated its advantage of its mobility in sampling detailed TC structural features near the TC core and associated major convective systems. Previous studies have also indicated that assimilating these Doppler radar observations near the TC core region into numerical models could improve the numerical simulation and prediction of mature TCs. Despite much previous effort in data assimilation, research on the assimilation of airborne observations (especially radar data) is rarely conducted for TC genesis cases. The Office of Naval Research–sponsored Tropical Cyclone Structure 2008 field experiment (ONR TCS-08) provided useful observations to examine the impact of data assimilation on predicting TC genesis.

Continuing our previous effort, the WRF model and its four-dimensional variational (4DVAR) data assimilation system (Huang et al. 2009, MWR) are employed to examine the impact of airborne Doppler radar observations on predicting the genesis of Typhoon Nuri (2008). The ELDORA airborne radar data, collected during the TCS-08 field program, are used for data assimilation experiments. Two assimilation methods are evaluated and compared, namely, the direct assimilation of radar-measured radial velocity and the assimilation of three-dimensional wind analysis derived from the radar radial velocity.

Results from this work show that:

- The 4DVAR radar data assimilation significantly improves the numerical simulations of Nuri’s genesis. Simulations with radar data assimilation predict Nuri’s genesis, while the control experiment [Ctrl, without radar data assimilation, cold start from NCEP final analysis (FNL) initial and boundary conditions] fails to predict Nuri’s genesis. The simulations with radar data assimilation also produce realistic rainfall structures and reasonable environmental flows before, during, and after Nuri’s genesis.

- Among various ways to assimilate radar radial velocities, direct assimilation of radar radial velocity leads to better intensity forecasts, as it enhances the development of convective systems and improves the inner core structure of Nuri, whereas assimilation of the radar-retrieved wind analysis is more beneficial to tracking forecasts, as it results in improved environmental flows. The assimilation of both radar-retrieved wind and radial velocity can lead to better intensity and track forecasts, if radial velocity observations are assimilated first and retrieved winds are then assimilated in the same data assimilation window.

- Experiments with and without radar data assimilation lead to developing and nondeveloping TC genesis in numerical simulations. The improved initial conditions and forecasts from the data assimilation imply that the enhanced midlevel vortex and moisture conditions are favorable for the development of deep convection into the center of the pouch and eventually contribute to Nuri’s genesis. In addition, the improved simulations of the convection and associated environmental conditions produce enhanced upper-level warming in the core and lead to the drop in the minimum central sea level pressure (MSLP).
Overall, this study demonstrates the benefits of radar radial velocity data assimilation in the simulation of Nuri’s genesis. First, the ELDORA airborne radar provides sufficient high-resolution observations for representing and predicting the convective system in the pre-Nuri disturbance. Second, because such a convective system shows rapid temporal variations, the 4DVAR system is able to take advantage of assimilating the observations at multiple times in order to accommodate the rapid changes. For these two reasons, detailed conditions associated with the convective system are imposed by 4D-VAR into the model to make it produce more accurate predictions of the convective system, which eventually improves the forecasts of Nuri’s genesis.

![Figure 5: East-west vertical cross-sections of the temperature anomaly (shaded contour) and the relative humidity (black contour lines) across Nuri’s center at 1800 UTC 16 Aug 2008 from the experiments (1) Ctrl, without radar data assimilation (left), and (2) with radar data assimilation (right). The results clearly demonstrate that radar data assimilation enhances the convective system, resulting in strong upper-level warming during Nuri’s genesis.](image)

(3) Participating in ONR TCI-14 field program

During the 2014 hurricane season, ONR, along with the NASA HS3 science team, has conducted a hurricane field program (TCI-14) over the Atlantic Ocean, with the goal of examining the role of the outflow layer in TC rapid intensification. In accordance with the recent field program, research effort has been moving toward hurricane cases during the TCI-14 field program. The PI and students have been collecting the available observations from the field program. The next step will be assimilating these observations to address the key questions mentioned in the objectives of this project. In addition, the collaboration with NRL scientists will lead to an evaluation of the performance of NEVGEM during the TCI-14 field experiment.

IMPACT/APPLICATIONS

Assimilation of satellite and radar observations improves the representation of the outflow layer in numerical models and has positive impact on forecasting tropical cyclone formation and rapid intensification. In addition, better understanding of the role of the upper-level atmosphere will lead to improvement in our ability to predict TC formation, rapid intensification and intensity and structure changes.
PUBLICATIONS

(1) Peer-reviewed journal articles


(2) Conference papers and presentations


