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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Award Number: N000141310582

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 investigate several key issues related 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 the relationship of outflow layer to TC 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)? In order to address these key questions, accurate numerical simulations are necessary. Therefore, The major tasks of this study aim to answer following question: 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; and the 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 and TCI-15) 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 FY15 include the PI and two graduate students.

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, in situ and satellite data. Hurricane cases during TCI-14 and TCI-15 have been used.
- Evaluating the Navy Global Environmental Model (NAVGEM) for TC forecasts

RESULTS

(1) Impact of data assimilation on numerical simulations of hurricane rapid intensification and intensity changes

A data assimilation study was performed to assimilate satellite, radar, and in situ observations into the hurricane cases during TCI-14. The data impacts and the implications of the results for the role of upper-level atmospheric processes were examined.

Specifically, we performed data assimilation and high-resolution numerical simulations for two major hurricanes (Edouard and Gonzalo) during the TCI-14 field campaign. The hurricane Weather Research and Forecasting (HWRF) model and the NCEP Gridpoint Statistical Interpolation (GSI) data assimilation system were employed. The innermost model horizontal resolution was 3 km. A hybrid 3-dimensional variational (3DVAR) and ensemble Kalman filter (EnKF) data assimilation system for GSI (GSI hybrid system, hereafter) was used. Results from the assimilation of various observations are summarized as follows.

a) Dropsonding data: The dropsonding observations from NASA Global Hawk during ONR TCI-14 / NASA HS3 were assimilated into HWRF during 06 UTC to 18 UTC 15 September 2014, when Hurricane Edouard was in its mature phase. It was found that the assimilation of dropsondes had a slight positive impact on the HWRF intensity forecasts of Hurricane Edouard. Its impact on the track forecast was neutral.

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b) Tail Doppler radar (TDR) observations: In conjunction with the NOAA Hurricane Forecasting Improvement Program (HFIP) and previous efforts in radar data assimilation conducted by the PI’s group, the assimilation of TDR observations was focused on diagnosing the initial vortex spin-down problem in the HWRF model with the NCEP vortex initialization scheme and the operational GSI hybrid system. Using Hurricane Edouard as a case study, it was found that with the assimilation of TDR inner-core data using the GSI hybrid system, the HWRF forecast outperformed other experiments (either 3DVAR or no-TDR data assimilation) in terms of hurricane intensity forecast. But, it was still unable to overcome the spin-down problem. Since the current GSI hybrid system uses global ensemble forecasts to generate the background error covariance term, progress was made in testing the impact of using regional (HWRF, instead of the global model) ensemble forecasts on GSI hybrid system analysis and subsequent HWRF forecasts. It was found that the use of regional ensemble forecasts provided reasonable background error terms, thus improving the HWRF analysis and forecasts of the hurricane and also mitigating the vortex spin-down problem to some degree.

![Minimum Sea Level Pressure](image)

**Figure 1.** Time series of the minimum central sea level pressure (top) and maximum surface wind (bottom) during 18 UTC 15 to 06 UTC 17 Sep 2014 for Hurricane Edouard. The best track data (black line) are compared with the data from data assimilation experiments. The control (CNTRL) experiment (blue line) assimilated all conventional and satellite data from NCEP operations. The experiment ALL_AMV (green line) assimilated all available AMVs (up to the 100 hPa pressure level) with all data used in CNTRL. The experiment UPP_AMV (red line) is the same as ALL_AMVs except for it assimilated the AMVs from the 350 hPa pressure level and above (up to 100 hPa).

c) Atmospheric Motion Vector (AMVs): Enhanced AMVs, derived from multiple satellites, were produced by CIMSS, University of Wisconsin (Chris Velden, pers. comm). Before and during TCI-14, AMVs were proven to be good datasets for revealing outflows in a hurricane environment. We evaluated the impact of the enhanced AMVs on numerical analyses and prediction of hurricanes with HWRF and the GSI hybrid system. First, two types of AMV data products, with different quality control thresholds, were assimilated into the HWRF model for Hurricanes Edouard and Gonzalo (2014) during their rapid intensification and mature stages. It was found that the impact of AMVs on
hurricane intensity forecasts depended on the quality of the AMV data. Assimilation of high-quality but lower-coverage data led to slightly better intensity forecasts.

Various sensitivity studies have also been conducted. Results show positive impacts with the assimilation of AMVs on forecasts of Edouard and Gonzalo. However, the degree of the impacts depends on the horizontal and vertical coverage of the data and the configurations of the data assimilation system. Specifically, for Hurricane Edouard, among different configurations of AMV assimilation, assimilation of only the data at upper level (~350 hPa and above) can result in at least 60 ~70% of the total improvement in intensity forecasts in the first 24 h, relative to the improvements in the experiment that assimilated all AMV data at all available levels (Figure 1). This may imply the importance of accurate representation of upper-level atmospheric processes in hurricane intensity forecasts. In addition, the background error terms in the GSI hybrid system have an influence on the assimilation results. The use of high-resolution HWRF ensemble forecasting, instead of the global ensemble forecasts in generating the GSI hybrid background term, will enhance the assimilation of AMVs.

![Figure 2](image)

**Figure 2.** Time series of the minimum central sea level pressure (top) and maximum surface wind (bottom) during 06 UTC 15 to 06 UTC 18 Sep 2014 for Hurricane Edouard. The best track data (black line) are compared with those from data assimilation experiments. Data assimilation was performed during 06 UTC to 18 UTC 15 Sep 2014 for three cycles. The experiment Hybrid_NOTCV (blue line) assimilated all available conventional and satellite data used in NCEP operations. The experiment Hybrid_TCV (green line) assimilated TC Vital data, along with all data used in Hybrid_NOTCV.

**d) Assimilation of TC Vital data:** The TC Vital file, provided by the National Hurricane Center (NHC) in real time, contains significant information about hurricane intensity and structure, such as hurricane position, minimum center sea level pressure, maximum wind, radius of maximum wind, etc. In order to improve the initial vortex structure, we conducted experiments to assimilate TC Vital data into the GSI 3DVAR/EnKF hybrid system. The experiments emphasized the assimilation of hurricane position, minimum sea level pressure, maximum wind, and radius of maximum wind. Experiments with Hurricane Edouard have been encouraging, showing positive impacts of TC Vital data assimilation on improving forecasts (Figure 2).
With the results above, integrated data assimilation work with TCI-14 and TCI-15 observations and hurricane cases is ongoing. It is anticipated that the analysis and numerical simulations of the hurricanes, along with detailed diagnoses and evaluation, will lead to significant understanding of TC outflow and its role in TC rapid intensification and intensity changes. Work with the COAMPS model is also in preparation.

(2) Participating in ONR TCI-14 and TCI-15 field programs

During the 2014 and 2015 hurricane seasons, ONR, along with the NASA HS3 science team and NOAA SHOUT science team, has conducted hurricane field programs TCI-14 and TCI-15, respectively, over the Atlantic and eastern Pacific Oceans, with the goal of examining the role of the outflow layer in TC rapid intensification. The PI has participated in the planning meetings prior to and sometimes during the field programs. She and her students have also been collecting the available observations from the field programs and have been conducting data assimilation and numerical simulation studies to address the key questions mentioned in the objectives of this project. In addition, the collaboration with NRL scientists has led to an evaluation of the performance of NAVGEM during the 2014 hurricane season.

(3) Evaluating NAVGEM for TC forecasts

The performance of the Navy Global Environmental Model (NAVGEM) for TC forecasts was evaluated for all TC cases during the 2014 hurricane season for the Atlantic, eastern Pacific, and western Pacific basins. The track and intensity errors were characterized. The ability of NAVGEM to predict the trend of TC intensity changes was evaluated. Future evaluation is ongoing with additional cases for more robust conclusions. In addition, the adequacy of NAVGEM in representing the atmospheric conditions in the outflow layer during TC formation and RI is under evaluation.

IMPACT/APPLICATIONS

Assimilation of satellite and radar observations improves the representation of the outflow layer in numerical models and has a positive impact on forecasting TC formation and rapid intensification. 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. Evaluation of the performance of the NAVGEM global model has implications for future improvement of the modeling system.

PUBLICATIONS

(1) Peer-reviewed journal articles

• Thatcher, L., and Z. Pu, 2014: Characteristics of tropical cyclone genesis forecasts and underdispersion in high-resolution ensemble forecasting with a stochastic kinetic energy backscatter scheme. Tropical Cyclone Research and Review, 3 (4): 203-217


(2) Conference papers and presentations


