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Xuguang Wang, Lance Leslie, Jim Doyle

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School of Meteorology
University of Oklahoma
120 David Boren Blvd.
Norman, OK, 73072

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August 30, 2019

Defense Technical Information Center
8725 John J Kingman Road Ste 0944
Fort Belvoir, VA 22060-6218

Dear Sir,

Enclosed is the final technical report for award #N00014-14-1-0125.

Project Title: Understanding the impact of outflow on hurricane intensification through ensemble-based data assimilation and ensemble simulation with multiple models.

Thank you,

Cathi Parker

Cathi Parker
Sponsored Programs Coordinator
Office of Research Services
University of Oklahoma

201 Stephenson Parkway, Suite 3100, Norman, Oklahoma 73019
PHONE: (405) 325-4757 FAX: (405) 325-6029
EMAIL: ors@ou.edu WEBSITE: ors.ou.edu

Understanding the impact of outflow on hurricane intensification through ensemble-based data assimilation and ensemble simulation with multiple models

Principal Investigator and Technical Contact:
Dr. Xuguang Wang
School of Meteorology
University of Oklahoma,
120 David L. Boren Blvd., Norman, Oklahoma, OK 73072
Email: xuguang.wang@ou.edu
Tel: 405 325 3426

Co-Principal Investigator
Dr. Lance Leslie
School of Meteorology, University of Oklahoma,
120 David L. Boren Blvd., Norman, Oklahoma, OK 73072
Email: lmleslie@ou.edu
Tel: 405 325 0596

Collaborator
Dr. James Doyle
Naval Research Laboratory
Marine Meteorology Division, 7 Grace Hopper Ave.
Monterey, CA 93943-5502.
Email: doyle@nrlmry.navy.mil
Tel: (831) 656-4716

What were the major goals and objectives of the project?

Evolving outflow jet's dynamical and thermo-dynamical structure and location during the hurricane life cycle are increasingly believed to have profound impacts on storm intensity and structure. To advance the understanding of the influence of the outflow layer on TC intensification, high resolution, accurate observations that sample the outflow layer are needed. Flying at high altitudes, the WB57 aircraft sponsored by ONR's TCI program released HDSS dropsondes that sampled all the way from the outflow layer to the ocean surface. The primary goal of this project is to understand the impact of outflow on hurricane intensification through ensemble-based data assimilation.

What was accomplished towards achieving these goals?

1. **A comprehensive study of the impact of assimilating TCI and IFEX Field campaign observations, and CIMSS AMVs on the analysis and prediction of Patricia (2015)**

Diverse observations collected from Tropical Cyclone Intensity (TCI) and Intensity Forecasting Experiment (IFEX) field campaigns together with Atmospheric Motion Vectors (AMVs) from Cooperative Institute for Meteorological Satellite Studies (CIMSS) simultaneously depicted the three-dimensional (3D) structure of hurricane Patricia (2015). Therefore, experiments are conducted to understand the impacts of each of these observation types on Patricia analysis and prediction using the ensemble-variational data assimilation system. Results show that (1) assimilating the operational observations (OperH) slightly improves the structural analysis and forecast, but overestimates the TC movement speed than not assimilating any observations (NoDA). (2) Solely assimilating single-level wind observations from either CIMSS AMV (CIMSS_Only) or Stepped Frequency Microwave Radiometer (SFMR_Only) primarily improve the analyses near the observation levels. These improvements merely translate to forecast improvements. (3) Assimilating flight-level observations (FL_Only), which offer both dynamic and thermodynamic information, produces better inner-core structures and the improvements last longer in forecasts. (4) Assimilating 3D observations like tail doppler radar (TDR_Only) or TCI dropsonde observations (HDSS_Only) can produce even better structural analyses than the aforementioned experiments, and the structural improvements are better maintained during forecasts. (5) HDSS_Only outperforms TDR_Only with additionally better analyzed and predicted outflow thermodynamic inner-core structures. (6) Combining all observations complementarily improves all aspects of the TC structure in both the analysis and forecast. Unlike the structural improvements which last the entire forecast, the intensity forecast improvement is usually found for the first several hours and for the timing of peak intensity. Detailed results are reported in peer reviewed papers Doyle et al. 2017 and Lu and Wang 2019.

2. **Impact of assimilating upper-level dropsonde observations collected during the TCI field campaign on the prediction of intensity and structure of Hurricane Patricia (2015)**

The dropsondes released during the Tropical Cyclone Intensity (TCI) field campaign provide high-resolution kinematic and thermodynamic measurements of tropical cyclones sampling all the way from the upper-level outflow to the ocean surface. In addition to comprehensive study of its overall impact as discussed in section 1. Additional study is performed to investigate the impact of specifically the ***upper-level*** TCI dropsondes on analyses and prediction of Hurricane Patricia (2015) during its rapid intensification (RI) phase using an ensemble-variational data assimilation system. In the baseline experiment (BASE), both kinematic and thermodynamic observations of TCI dropsondes at all levels except the upper levels are assimilated. The upper-level wind and thermodynamic observations are assimilated in additional experiments to investigate their respective impacts.

Compared to BASE, assimilating TCI upper-level wind observations improves the accuracy of outflow analyses verified against independent Atmospheric Motion Vector (AMV) observations. It also strengthens the tangential and radial wind near the upper-level eyewall. The inertial stability within the upper-level eyewall is enhanced, and the maximum outflow is more aligned towards the inner core. Additionally, the analyses including the upper-level thermodynamic observations produce a warmer and dryer core at high levels.

Assimilating both upper-level kinematic and thermodynamic observations also improves the RI forecast. Compared to BASE, assimilating the upper-level wind induces more upright and inward-located eyewall convection, resulting in more latent heat release closer to the warm core. This process leads to stronger inner core warming. Additionally, the initial warmer upper-level inner core produced by assimilating TCI thermodynamic observations also intensifies the convection and latent heat release within the eyewall, thus further contributing to the improved intensity forecasts. The detailed results are documented in peer reviewed papers Feng and Wang 2019.

3. Statistical analysis to undersand outflow impact on rapid intensification rate

In addition to the data assimilation and modeling studies, we also performed statistical analysis to further understand the impact of outflow layer on the RI rates and compare the impact of outflow layer with other environmental factors. The statistical analysis facilitated interpretation of the results in the modeling and data assimilation studies. The Northwest Pacific tropical cyclone (TC) intensification is classified into rapid intensification (RI), normal intensification (NI), and slow intensification (SI) categories. The initial location and intensity, the preceding intensity change, the moving direction, the occurrence month, and the intensification duration time are all found to differ for RI cases compared with NI and SI cases. The dependence of RI, NI and SI on environmental conditions are further examined statistically by using the intensification rates of named TCs, for the 21-year period 1995-2015, obtained from JTWC best track data, and the environmental conditions derived from the ERA-Interim reanalysis data and FNMOC high resolution global ocean analysis data. It was found that deep-layer and upper-mid vertical wind shear (VWS), upper-level outflow, sea surface temperature (SST) and ocean heat content (OHC) are statistically different among RI, NI and SI both before and during intensification. RI is enhanced by weaker and decreasing VWS, warmer oceans, and stronger and increasing outflow. In contrast, SI typically occurs with larger and increasing VWS, cooler oceans, and weaker, static outflow. The impacts of low-level VWS and net moisture inflow are only significantly different between RI and SI, and between NI and SI, but not between RI and NI. Another key finding is that increased upper-level outflow and decreased VWS are important precursors, and hence are possible predictors, of RI onset. The direction of upper-level outflow affects TC intensification, with NW and NE outflow being more favorable for TC RI than SE and SW outflow. The detailed results are documented in peer reviewed papers Lyu, Wang and Leslie 2019.

What opportunities for training and professional development did the project provide?

These project support two part time postdocs and one part time student. This project provides them opportunity to participate a major scientific field experiment, the TCI field campaign, to work with the assimilation of these data sets, and to use the data and models to improve their understanding of the kinematic and thermodynamic processes that are responsible for RI. It provided much needed education and training in the increasingly important areas of advanced data assimilation, high-resolution ensemble simulation, NWP and hurricane dynamics. The PI advised student and the postdocs on various aspects of the project on regular basis.

How were the results disseminated to communities of interest?

The research results are disseminated through peer-reviewed publications and conference presentations

Feng, J. and X. Wang, 2019: Impact of assimilating upper-level dropsonde observations collected during the TCI field campaign on the prediction of intensity and structure of Hurricane Patricia (2015), *Mon. Wea. Rev.*, 147, 3069-3089.

Lu, X. and X. Wang, 2019: Improving Hurricane Analyses and Predictions with IFEX, TCI Field Campaign Observations and CIMSS AMVs Using the Advanced Hybrid Data Assimilation system for HWRF. Part II: Observation Impacts on the Analyses and Predictions of Patricia (2015). *Mon. Wea. Rev.*, accepted with revision.

Lyu, X., X. Wang and L. M. Leslie, 2019: The Dependence of Northwest Pacific Tropical Cyclone Intensification Rates on Environmental Factors, *Advances in Meteorology (invited contribution)*, accepted with revision.

Feng, J. and X. Wang, 2018: Impact of Assimilating Outflow Layer Dropsonde Observations Collected during the TCI Field Campaign on the Prediction of Intensity and Structure of Hurricane Patricia (2015). 33rd Conference on Hurricanes and Tropical Meteorology, April 16-20, Ponte Vedra, FL.

Lyu, X. and X. Wang, 2018: The Impact of HDOB and CIMSS AMV Observation Assimilation on the Analysis of Inner Core and Outflow Structures and the Prediction of Rapid Intensification of Hurricane Matthew (2016). 33rd Conference on Hurricanes and Tropical Meteorology, April 16-20, Ponte Vedra, FL.

Lu, X. and X. Wang, 2018: Impact of Assimilating TCI and IFEX Field Campaign Observations on the Prediction of Hurricane Patricia (2015) with Improved Model Physics. 33rd Conference on Hurricanes and Tropical Meteorology, April 16-20, Ponte Vedra, FL.

Products

Feng, J. and X. Wang, 2019: Impact of assimilating upper-level dropsonde observations collected during the TCI field campaign on the prediction of intensity and structure of Hurricane Patricia (2015), *Mon. Wea. Rev.*, 147, 3069-3089.

Lu, X. and X. Wang, 2019: Improving Hurricane Analyses and Predictions with

IFEX, TCI Field Campaign Observations and CIMSS AMVs Using the Advanced Hybrid Data Assimilation system for HWRF. Part II: Observation Impacts on the Analyses and Predictions of Patricia (2015). *Mon. Wea. Rev.,* accepted with revision.

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