13A.6

IMPROVING HIGH-RESOLUTION TROPICAL CYCLONE PREDICTION USING A GSI-BASED, CYCLED, DUAL RESOLUTION HYBRID ENSEMBLE-VARIATIONAL DATA ASSIMILATION SYSTEM FOR HWRF: SYSTEM DESCRIPTION AND EXPERIMENT RESULTS

Xu Lu* and Xuguang Wang

School of Meteorology, University of Oklahoma

1. Introduction

Improving predictions, especially for intensity forecasts of Tropical Cyclones (TC), remains a challenge. There are many factors contributing to the slow improvements in storm intensity forecast. Some of them could be attributed to: a) the deficient data assimilation (DA) method; b) the limitations of the NWP models; and c) the inefficient usage of inner-core observations (Rogers, 2006).

An accurate estimation of the background error covariance and efficient utilization of inner core observations are important for providing initial conditions in TC forecasts. Starting from 2013, the operational HWRF DA system has implemented a GSI-based hybrid 3DEnVar DA method (Wang et al. 2013) to assimilate inner-core Tail Doppler Radar (TDR) observations (Tallapragada et al., 2013). A GFS (Global Forecast System) ensemble is ingested in this implementation to provide the flow-dependent background error covariance (Tong et al., 2015). However, the coarser resolution GFS ensemble is not able to resolve the TC core structures accurately for the higher resolution HWRF model. Therefore, a hybrid EnKF–Variational data assimilation system with a self-consistent HWRF EnKF ensemble was developed for HWRF based on the operational GSI in our previous study (Lu and Wang et al., 2015). Lu and Wang et al. (2015) showed that this hybrid system was able to correct both wind and mass fields in a dynamically and thermodynamically coherent fashion. The hybrid system ingesting self-consistent HWRF EnKF ensemble was found to improve both the analyzed TC structures and forecasts relative to GSI-3DVar and the hybrid system ingesting GFS ensemble.

However, Lu and Wang et al. (2015) only explored the system over a small period of the TC lifetime which was covered by TDR data. Therefore in this study, a hybrid DA system that has the capability to cycle continuously for the entire life of a TC is developed. In order to solve the non-overlap domain issue brought by the cycling ensemble forecasts in the storm following model, a directed moving nest strategy is developed and applied.

The grid resolution is one of the limitations of NWP models. Without a high enough grid resolution, it is difficult for the models to resolve the convective scale features (Zhang et al., 2011). Unfortunately, there are usually not enough computing resources for the operational centers to run ensembles at a very high resolution. Therefore, in this study a dual resolution hybrid data assimilation (DA) system is developed for the operational Hurricane Weather Research and Forecasting model (HWRF; Tallapragada et al., 2014), One goal of this study is to explore the impact of introducing a high resolution control analysis and forecast through dual resolution hybrid DA for TC analysis and prediction.

Satellites provide the majority of observation over the open ocean. However, effective utilization of cloud contaminated satellite observation in DA remains a challenge. Therefore, observations that directly sample the inner core of TCs are still limited. To partly solve this issue, vortex relocation and initialization methods which derive vortex position and structure base on very limited vortex information were applied in early studies (Kurihara et al., 1993, 1995). In the meantime, elegant data assimilation methods can effectively extrapolate observation information without relying the assumptions typically used in vortex initialization. Would vortex initialization and relocation still be necessary in a fully cycled DA system? What is the impact of applying vortex initialization and relocation on top of the data assimilation? These questions are addressed in this study by comparing the performances of different combinations of vortex relocation and initialization with data assimilation.

The operational HWRF assimilate the TDR data 6-hourly due to the operational requirement. However, the 6-hour time window using a 3DEnVar may lack the temporal flow-dependent features of the background error covariance even if the FGAT method is applied. This might be an issue for high resolution inner core observation assimilation especially when the storms are rapidly changing, such as going through Rapid Intensification (RI) and eyewall replacement. Therefore, the hybrid DA system is further extended to a 4DEnVar. The impact of properly resolving the temporal variations of the error covariance for the assimilation of inner core observations is therefore studied.

2. Experiment Setup

---

* *Corresponding author address:* Xu Lu, University of Oklahoma, School of Meteorology, Norman, OK, 73072; e-mail: luxu@ou.edu

Table 1 Experiment Descriptions

Experiment name	Description
Hybrid	6-hourly continuous end to end cycling
	3DEnVar hybrid with FGAT
	Dual-resolution hybrid (3km control ingests 9km ensemble);
	New directed moving nest strategy adopted; domains move for first 3 hour integration and stay for the next 6-hour integration.
	Control background: vortex relocation and initialization for the control background when no TDR; vortex relocation only when TDR.
	Ensemble backgrounds: vortex relocation
Hybrid-279	Same as “Hybrid” except it is not dual-resolution hybrid. Both hybrid control and ensemble are done at 9km resolution.
Hybrid-norelo	Same as “Hybrid” except it does not do any vortex initialization or relocation on control and ensemble backgrounds.
Hybrid-noensrelo	Same as “Hybrid” except it does not do relocation for ensemble backgrounds.
Hybrid-4DTDR	Same as “Hybrid” except it uses 4DEnVar in the TDR-involved cycles.

In this study, the DA were conducted in continuously cycling mode every 6 hour from September 11th 18 UTC to September 19th 18 UTC using HWRF model for hurricane Edouard (2014). All operational observations including conventional in-situ data, satellite wind, tcvital, satellite radiances, and tail Doppler radar observations were assimilated. A nominal horizontal grid spacing of 0.18/0.06/0.02 degrees (approximately 27/9/3 km) for the outer/middle/inner domains was used. Physical and dynamic schemes are set following the 2014 operational HWRF (Tallapragada et al., 2014). Experiments are described as in table 1.

3. Results

3.1 Impact of dual resolution

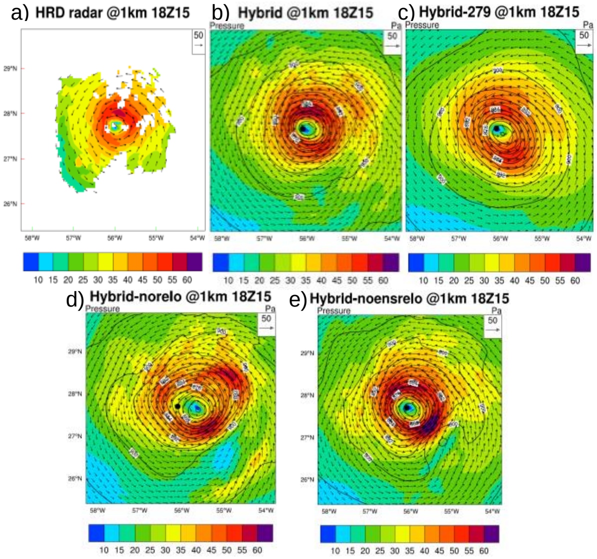


Fig. 1 Wind (shaded and vector) and pressure (contour) at 1km height for a) HRD radar wind composite, b) Hybrid, c) Hybrid-279, d) Hybrid-norelo, and e) Hybris-Hybrid-noensrelo. Black dot is the best track position from NHC.

Fig. 1 shows the simulated horizontal structure of Edouard (2014) for different experiments and the corresponding observation verification valid at 18 UTC, Sep. 15th, 2014 after assimilating the second TDR mission. Fig. 1 a) ~ c) shows the impact of dual resolution over coarser single resolution hybrid DA. Compared to “Hybrid-279” (Fig.1c), “Hybrid” (Fig. 1b) fits the HRD composite (Fig. 1a) much better. Specifically, “Hybrid” can capture the wind maximum in the north section presented in the HRD composite. In addition, the location and fine structures analyzed by “Hybrid” were better than “Hybrid-279”.

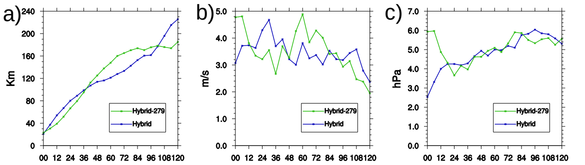


Fig. 2 a) Track , b) Vmax and c) MSLP Mean Error statistics for Hybrid (dark blue) and Hybrid-279 (green) experiments during 32 cycles of Edouard.

Fig. 2 shows the absolute mean errors of track (Fig. 2a), mean sea level pressure (MSLP, Fig. 2b) and 10-m maximum wind (Vmax, Fig. 2c) forecasts for “Hybrid” (blue) and “Hybrid-279” (green) corresponding to the 32 DA cycles conducted for Edouard (2014). “Hybrid” improved the MSLP and Vmax forecast for the first 12-18 hours compared to “Hybrid-279”. Together, the analyzed structures and the forecasts suggested the advantages of using dual resolution over coarser single resolution hybrid DA.

3.2 Impact of vortex initialization and ensemble relocation

Fig. 1 a), b), d) and e) show the impact of applying the vortex relocation for ensemble background and the vortex initialization and relocation for the control background. Without doing any relocation or vortex initialization in “Hybrid-norelo” (Fig. 1d), the wind structure disagrees with the HRD (Fig. 1a) composite and there exists a larger location error for the analysis. Only doing the vortex initialization for the control background in “Hybrid-noensrelo” (Fig. 1e), the location error is reduced but the wind maximum is spuriously large and is located in the south rather than the north, which is still not consistent with the observation. In comparison, with both vortex initialization and relocation, “Hybrid” (Fig. 1b) is able to correct the location and capture the wind maximum much more consistently with HRD wind composite.

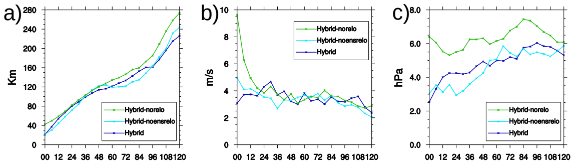


Fig. 3 a) Track , b) Vmax and c) MSLP Mean Error statistics for Hybrid (dark blue solid), Hybrid-279 (orange), Hybrid-norelo (green) and Hybrid-noensrelo (light blue) experiments during 32 cycles of Edouard.

Fig. 3 shows the corresponding absolute mean errors for “Hybrid” (dark blue), “Hybrid-norelo” (green) and “Hybrid-noensrelo” (light blue). Without any relocation and vortex initialization in both ensemble and control background, the forecasts produced by “Hybrid-norelo” performed the worst. If only doing relocation and vortex initialization for the control background without the relocation for the ensemble, the forecasts by “Hybrid-noensrelo” is improved over “Hybrid-norelo”, but still worse than the “Hybrid” especially for MSLP and Vmax forecasts at early lead times. Together with the structure analyses, both vortex initialization and relocation are preferred in this continuously cycled, self-consistent, dual-resolution hybrid DA system for HWRF.

3.3 Impact of 4DEnVar for vortex scale observation

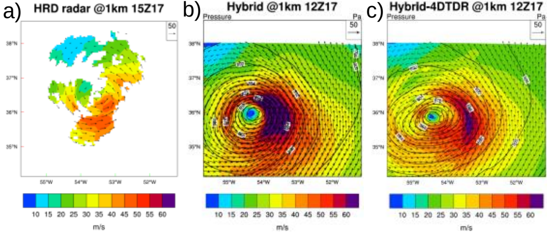
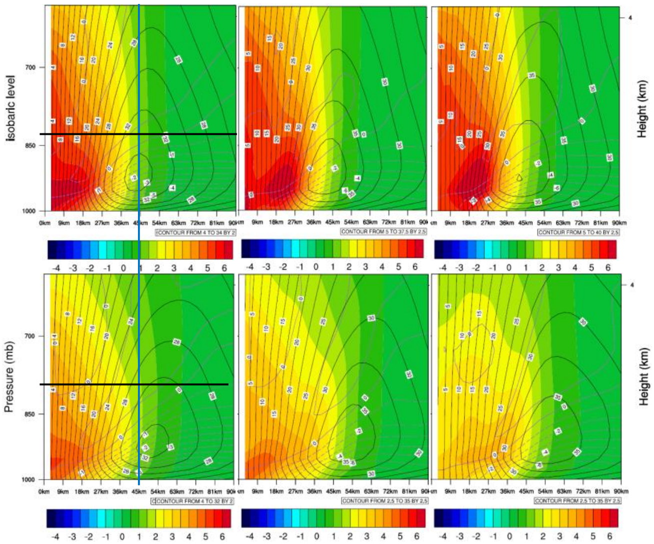


Fig. 4 Wind (shaded and vector) and pressure (contour) at 1km height for a) HRD radar wind composite, b) Hybrid, c) Hybrid-279, d) Hybrid-norelo, and e) Hybris-Hybrid-noensrelo. Black dot is the best track position from NHC.

Fig. 4 shows the analyzed horizontal structure after assimilating the 4th TDR mission from different experiments (valid at 12 UTC on Sep. 17th, 2014). During this time period, the storm was going through an eyewall replacement process while the temporal coverage of TDR data was very brief. The 3DEnVar analysis from “Hybrid” (Fig. 4b) showed a spuriously strong wind maximum in the east side of the storm center. . In comparison, the 4DEnVar analysis from “Hybrid-4DTDR” (Fig. 4c) greatly reduced the wind maximum and fit the HRD much better. Together with the forecast errors (Not shown), they indicated that for the assimilation of inner core TDR data, 4DEnVar which has the capability to resolve the temporal evolution of the error covariances were more preferred than 3DEnVar.



3.4 Alleviation of “spin-down” issue

Fig. 5 Averaged azimuth mean Inertial Stability (Shaded), Radial wind (Grey contour) and Tangential wind (Black contour) during all Intensifying Stage (Vmax change > 10kt/12h) for a)~c) Hybrid-4DTDR and d)~f) Operational HWRF. a),d) 00h; b),e) 06h; and c),f) 12h. The black lines indicate the inflow layer depths and the blue lines indicate the RMW differences between the models.

Comparisons of the performances between our system and the operational HWRF reveals large improvements in the intensity forecasts by the new system. Analyses on the individual cases indicated that the improvement is primarily due to the alleviation of “spin-down” issues during the intensification period of Edouard until it reached the maximum intensity. The reasons for the alleviation are found as shown in Fig. 5.

Fig. 5 shows the azimuth mean of inertial stability (shaded), radial wind (grey contour) and tangential wind (black contour) for the analyses and 12-hour forecasts during the entire intensifying stage (Rogers et al., 2013) of Edouard for both “Hybrid-4DTDR” and the operational HWRF. The analysis from “Hybrid-4DTDR” had a stronger inertial stability, smaller radius of maximum wind, stronger tangential wind and shallower inflow layer in comparison with the operational HWRF. According to early studies (Holland and Merrill, 1984), the stronger inertial stability indicates the stronger resistance to radial inflow. The resistance facilitates updraft in the eyewall, which results in a stronger secondary circulation. This process therefore leads to storm intensification. On the contrary, the weaker analysis from the operational HWRF does not help the intensification immediately.

4. Conclusions

The newly extended GSI-based, Continuously cycled, Dual Resolution Hybrid Ensemble-Variational Data Assimilation System for HWRF is successfully implemented. The system included the self-consistent HWRF EnKF ensemble and directed moving nest strategy. The system is extended to improve intensity predictions for high resolution TC forecasting with inner core observations.

Experiments were designed to address various scientific questions. This study found that:
a) The dual resolution hybrid improved upon the coarser, single resolution hybrid;
b) Vortex initialization and relocation in the control and relocation of the ensemble background improved the forecasts;
c) Using 4DEnVar DA in the TDR-involved cycles improved the intensity forecasts for early lead times compared to 3DEnVar DA;
d) The hybrid system improved intensity forecasts relative to operational HWRF during the intensification period due to the alleviation of the “spin-down” issue because the hybrid better analyzed the structures of an intensifying storm.

Acknowledgements:
This work was supported by grants NA12NWS4680012, NA14NWS4830008 and NA14NWS4680021 from the National Ocean and Atmosphere Administration (NOAA) Hurricane Forecast Improvement Project (HFIP) project and the ONR grant N00014-14-1-0125. The experiments were performed on the NOAA supercomputer Jet.

References:

Rogers, R. and coauthors, 2006: The intensity forecasting experiment: A NOAA multiyear field program for improving tropical cyclone intensity forecasts. *Bull. Amer. Meteor. Soc.*, **87**(11), 1523–1537.

——, Reasor, P., & Lorsolo, S. (2013). Airborne Doppler Observations of the Inner-Core Structural Differences between Intensifying and Steady-State Tropical Cyclones. *Mon. Wea. Rev.*, **141**(9), 2970–2991.

Gao, J., Xue, M., 2008: An Efficient Dual-Resolution Approach for Ensemble Data Assimilation and Tests with Simulated Doppler Radar Data*. Mon. Wea. Rev.*, **136**(3), 945–963.

Holland, G. J., and R. T. Merrill, 1984: On the dynamics of tropical cyclone structure changes. *Quart. J. Roy. Meteor. Soc.*, **110**, 723–745.

Kurihara, Y., M. A. Bender, R. J. Ross, 1993: An initialization scheme of hurricane models by vortex specification. *Mon. Wea. Rev*., **121**, 2030–2045.

——,——,R. E. Tuleya, R. J. Ross, 1995: Improvements in the GFDL hurricane prediction system. *Mon. Wea. Rev.,* **123**, 2791–2801.

Lei, T., Wang, X., 2015: A comparison of the GSI-based single resolution and dual resolution hybrid data assimilation for GFS forecasts..To be submitted.

Lu, X., X. Wang, Y. Li, M. Tong, X. Ma, 2015: GSI-based ensemble-variational hybrid data assimilation for HWRF for hurricane initialization and prediction: Experiments with airborne radar observations. *Quart. J. Roy. Meteor. Soc.*, submitted.

Tallapragada, V. and coauthors, 2013: Hurricane Weather Research and Forecasting (HWRF) Model: 2013 Scientific Documentation. [Available online at http://www.dtcenter.org/HurrWRF/users/docs/scientific_documents/HWRFv3.5a_ScientificDoc.pdf]

——, and coauthors, 2014: Hurricane Weather Research and Forecasting (HWRF) Model: 2014 Scientific Documentation. [Available online at http://www.dtcenter.org/HurrWRF/users/docs/scientific_documents/HWRFv3.6a_ScientificDoc.pdf]

Tong M, Tallapragada V, Liu E, Kieu C, Kwon I, Wang W, Liu Q. 2015. Impact of Assimilating Aircraft Reconnaissance Observations on Tropical Cyclone Initialization and Prediction using Operational HWRF and GSI Ensemble-Variation Hybrid Data Assimilation. *Mon. Wea. Rev.* submitted.

Zhang, F., Weng, Y., Gamache, J. F., Marks, F. D, 2011: Performance of convection-permitting hurricane initialization and prediction during 2008-2010 with ensemble data assimilation of inner-core airborne Doppler radar observations. *Geophys. Res. Lett.,* **38**(15), 2–7.