Final Report of the Project with the Developmental Testbed Center

Studies of Hurricane Initialization in Short-term Intensity Forecasts

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With the support of this project in 2011, Qingnong Xiao (University of South Florida) visited Developmental Testbed Center (DTC) for one and half months working on the Doppler radar data assimilation using Gridpoint Statistical Interpolation (GSI, Wu et al. 2002) for Hurricane Earl (2010). In addition, an USF Ph.D student, Esa-Matti Tustula also visited DTC for one month for the work. Drs. Kuo, Huang and Nance (DTC) provided insightful visions and valuable discussions that facilitate a smooth startup of the important research topic of hurricane initialization using Doppler radar data. Pam Johnson and Laurie Carson (DTC) provided logistical support and computer setup for our visiting.

During the project, we investigated the short-term forecasts of hurricane intensity and intensity change in relation to the vortex structures by incorporating Doppler radar data assimilation in the WRF inner domain with the resolution of 4km. Hurricane initialization using the advanced data assimilation system, GSI, is the key procedure for this investigation. With the help of DTC staff (Drs. Ming Hu and Chunhua Zhou) and NCEP/EMC staff (Dr. Mingjing Tong), the investigators (Qingnong Xiao and Esa-Matti Tustula from University of South Florida) learned the GSI data assimilation with PrepBUFR and Doppler radar data assimilation capabilities, and conducted a series of data assimilation experiments to study hurricane behavior with data thinning (Super-obbing) and background error covariance tuning. The results are preliminary, but encouraging. Assimilation of the observed information in the vortex region deserves more scientific research and technical development.

The GSI is an advanced data assimilation system, which is currently used for the NOAA/NCEP's operational Global Forecast System (GFS) and North American Mesoscale Model (NAM). It is also the data assimilation system for the Hurricane Weather Research and Forecasting (HWRF) model. GSI has provided the WRF research and operational communities with state-of-the-art, efficient data assimilation capabilities. GSI is supported by both DTC and NCEP/EMC. We employed the DTC testbeds of GSI (Wu et al. 2002) and Advanced Hurricane research WRF (AHW, Davis et al. 2009; Xiao et al. 2009a; b), and conducted hurricane initialization experiments with airborne Doppler radar data for Hurricane Earl (2010). The capability of Doppler radar data assimilation in GSI was first assessed in our experiments. Based on the techniques of Doppler radar data assimilation in WRF variational (WRF-Var) data assimilation (Barker et al. 2004; Skamarock et al. 2008), we tested Doppler radar data thinning and different length scales of background error covariance in assimilation technique with GSI data assimilation system and found some interesting results.

1. Doppler radar data assimilation capability in GSI

Doppler radar has the capability to scan large volumes of the atmosphere at high spatial and temporal resolutions. Because of radar data quality problems and the huge volumes of radar data, however, how to properly incorporate radar data in GSI, need to be investigated. The Doppler radar data was first preprocessed at NCEP and converted to the NCEP PrebBUFR format. Due to the high spatial and temporal resolution of radar data, the amount of radar data is huge, which make it impossible to assimilate all of radar observations (from consideration of data correlations and computation cost). For airborne Doppler radar, the position of radar base is moving, which poses an additional challenge not present with most other types of data. The super-obbing technique is applied at NCEP (Purser et al. 2000; Parrish 2005) for thinning and combining radar radial velocity data.

The GSI data assimilation system was developed by Wu et al. (2002), which is a grid point version of the NCEP Spectral Statistical Interpolation (Parrish and Derber 1992) based on a 3D variational (3DVAR) algorithm. The cost function includes two terms and is defined by

$$J = \frac{1}{2}\mathbf{x}^T\mathbf{B}^{-1}\mathbf{x} + \frac{1}{2}(H\mathbf{x} - \mathbf{y}_o)^T\mathbf{R}^{-1}(H\mathbf{x} - \mathbf{y}_o), \qquad (1)$$

where $\mathbf{x}$ is the vector of analytical increments, $\mathbf{B}$ is the background error covariance matrix, $\mathbf{y}_o$ is the observation vector, $\mathbf{R}$ is the observation covariance matrix, and H is the observation operator which brings the model state to observation state. In Eq (1) the first term on the right hand side is usually called the background term and the second one is the observational term. The background term affects how the observational information spreads in space and overcomes underdetermined-ness problem associated with limited number of observations. Cross-correlations among the analysis variables can be and are often built into the analysis through the background error covariance in the background term too. The dimension of $\mathbf{B}$ matrix is however too large to calculate, store or manipulate explicitly, and is modeled using a recursive filter (Purser et al. 2003a; 2003b) in GSI. Variable transformation and preconditioning are also performed (Wu et al. 2002). The filter cut-off scales used by the recursive filter will impact analysis result, and will be examined in the study.

To assimilate Doppler radar velocity, the observation operator for the radar radial velocity is incorporated into GSI. Following Sun and Crook (1998) and Xiao et al. (2005), the radial velocity operator is defined by

$$V_r = u\cos\gamma\cos\theta + v\cos\gamma\sin\theta + w\sin\gamma, \qquad (2)$$

where (u,v,w) are the wind components, θ and γ are the azimuth and elevation angles. Supposing there are N radar observations in a given domain and a super-obbing wind vector is represented by $\mathbf{x} = (u,v,w)^T$ at super-obbing centroid of the domain, the projection of the radial velocity field in the observation space is a vector defined by

$$\mathbf{y} = (V_{r1}, V_{r2}, \ldots, V_{rN})^T = H\mathbf{x}, \qquad (3)$$

where

$$H = \begin{bmatrix} \cos\gamma_1 \cos\theta_1 & \cos\gamma_1 \sin\theta_1 & \sin\gamma_1 \\ \cos\gamma_2 \cos\theta_2 & \cos\gamma_2 \sin\theta_2 & \sin\gamma_2 \\ \ldots & \ldots & \ldots \\ \cos\gamma_N \cos\theta_N & \cos\gamma_N \sin\theta_N & \sin\gamma_N \end{bmatrix}. \tag{4}$$

To reduce the dimension of the observation in the given domain, a Gram-Schmidt algorithm is applied to decompose H,

$$H = G\hat{H}, \tag{5}$$

where G and $\hat{H}$ are N x 3 and 3 x 3 matrices, respectively. G is defined so that $G^T R^{-1} G = \hat{R}^{-1}$ is diagonal. R is the observation error covariance matrix and $\hat{R}$ is super-obs error covariance matrix. The super-obs in this given domain can be expressed by

$$\hat{\mathbf{y}} = \hat{R} G^T \hat{R}^{-1} \mathbf{y} = \hat{H}\mathbf{x}. \tag{6}$$

Thus, the super-obs reduces N pieces of information to 3. The detailed description of forming super-obs can be found in Purser et al. (2000) and Parrish (2005). Clearly, the size of the given domain for super-obbing (called super-obs grid resolution hereafter) decides the dimension of the observation space N. The super-obs grid resolution will impact the quality of the super-obs, which will be investigated using the numerical experiments.

2. Hurricane Earl (2010) and its Doppler radar observations

Earl (2010) originated from a strong tropical wave that acquired sufficient convective organization. By 1200 UTC 29 August 2010, Earl became a hurricane, when centered about 220 n mi east of the northern Leeward Island (Fig. 1). It experienced rapid intensification on 30 August and reached a Category 4 hurricane by 1800 UTC 30 August (Figs. 2a, b). Earl remained a 115-kt hurricane for the next 24 hours, and weakened to a Category 3 hurricane by 1 September. The hurricane's best track positions are show in Fig. 1 and its maximum surface wind (MSW) and central sea-level pressure (CSLP) are shown in Figs. 2a and b.

Hurricane Earl (2010) was the 5th named storm in 2010. All three governmental agencies, NOAA, NASA and NSF had field experiments towards this hurricane. The three fields experiments are called NOAA/IFEX, NASA/GRIP and NSF/PREDICT. Two NOAA's P3 flights (N42RF and N43RF), NASA DC-8 and the Air Force C-130 flew to the hurricane from 29 August 2010 in the morning and afternoon, respectively. Fig. 3 shows the airborne Doppler radar observations (composite winds) at around 1200 UTC 29, 0000 and 1200 UTC 30, and 0000 UTC 31 August 2010. At 1200 UTC 29 August, Earl became a hurricane, centered about 220 n mi east of the northern Leeward Islands. Its vortex circulation is clear from the Doppler radar wind composite with the maximum wind in the northeastern quadrant (Fig. 3a). From 0000 UTC 30 to 0000 UTC 31 August (Figs. 3 b, c and d), the hurricane vortex underwent a rapid intensification with the development of an inner-core asymmetric structure. The radius of maximum wind of the vortex was evidently shrunk during the time, when Earl experienced rapid intensification.

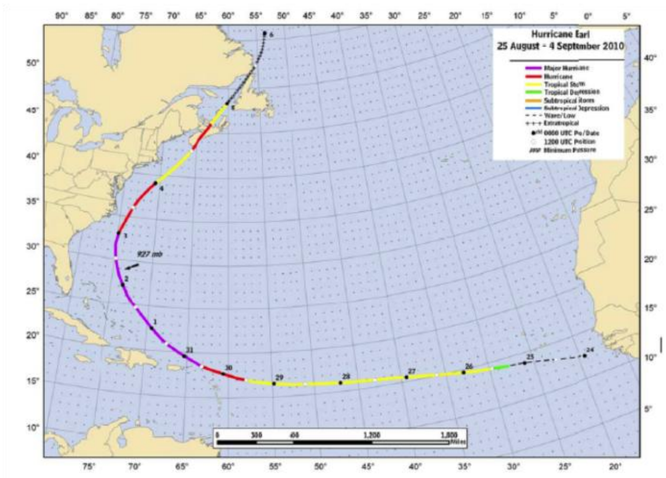

Fig. 1: Best track positions for Hurricane Earl from 25 August to 4 September 2010.

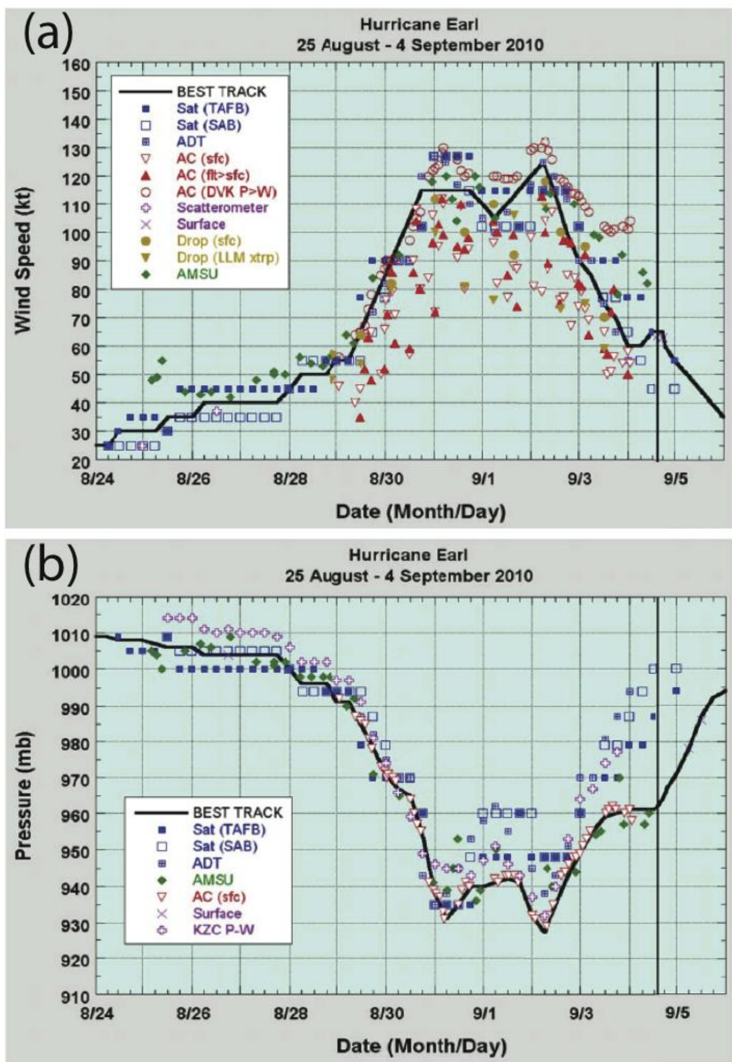

Fig. 2: Hurricane Earl's (2010) best track (a) maximum surface winds (MSWs), and (b) central sea-level pressures (CSLPs) from 25 August to 4 September 2010

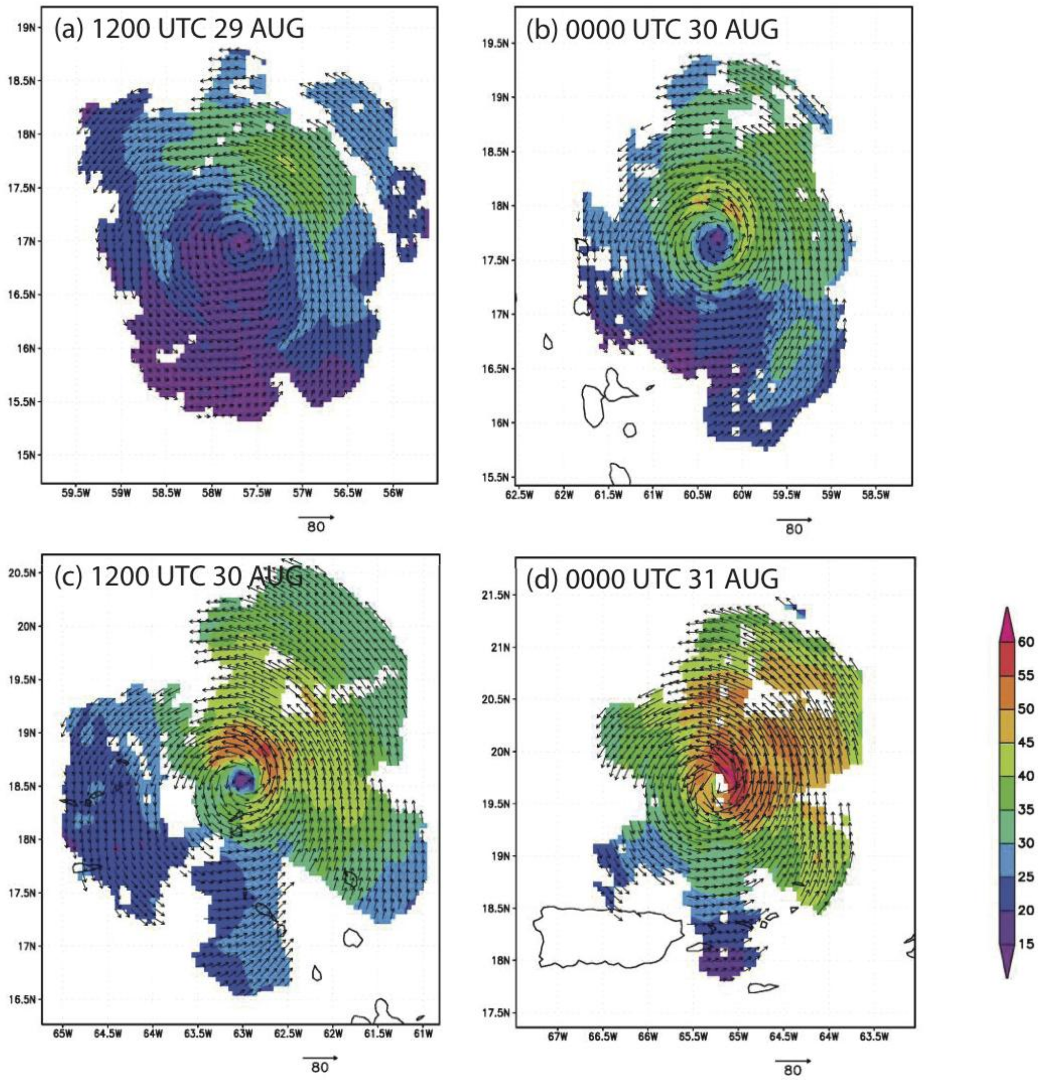

Fig. 3: Composite of airborne Doppler radar winds at 2-km altitude from NOAA/P3, NASA/DC-8 and Air force/C-130, centered at approximately (a) 0000 UTC 29, (b) 0000 UTC 30, (c) 12000 UTC 30 and (d) 0000 UTC 31 August 2010. (The color shading is for wind speed, and scale is on the lower right.)

Because of the field experiments conducted by tri-agencies, 12 dataset of the airborne Doppler radar data were collected and processed. In this study, we will conduct data assimilation experiments for Earl (2010) to assess the impact of Doppler radar winds in hurricane vortex initialization and subsequent forecast. As an initial test, the dataset at 1200 UTC 29 August is used in our data assimilation experiment. The GSI data assimilation with the radar data assimilation capability is applied to this study.

3. Experimental design

The numerical model used in this study is the Advanced-research Hurricane WRF (AHW), a derivative of ARW version 3 (Skamarock et al. 2008). It is a compressible, three-dimensional, non-hydrostatic model using terrain-following coordinates and its governing equations are written in flux-form. The Runge-Kutta third-order time scheme is employed and fifth- and third-order advection schemes are chosen for the horizontal and vertical directions, respectively.

We configured AHW model with three domains, two-way nested with Domain 3 following the hurricane track. The resolutions of the three domains are 36-km with 175 x 130 grids, 12-km with 286 x 244 grids and 4-km with 202 x 202 grids, respectively (Fig. 4). Doppler radar data assimilation is conducted in Domain 3 (4 km resolution). After initialization with Doppler radar data, the innermost domain (Domain 3) follows the hurricane track by the minimum geo-potential height at 500 hPa and was repositioned every 15 min.

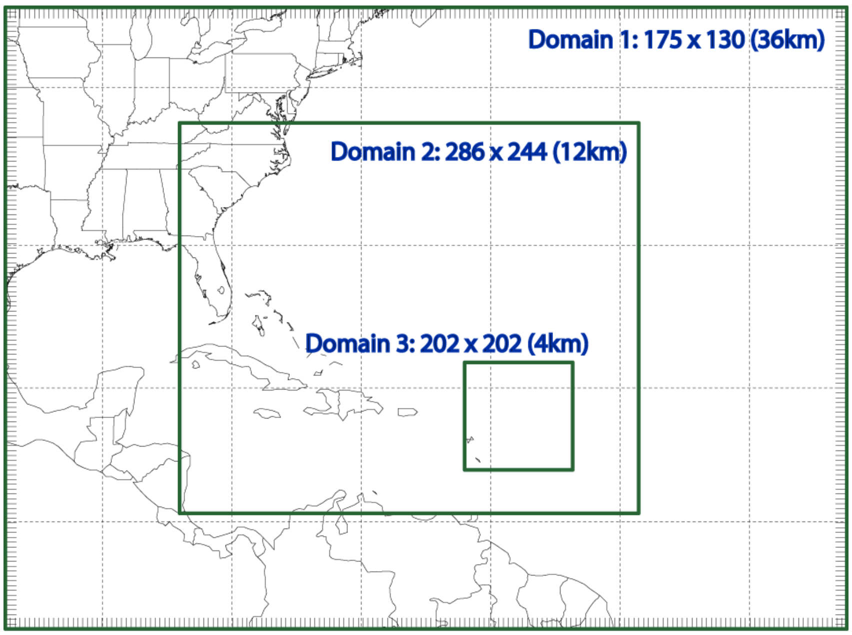

Fig. 4: Domain configuration of all experiments in this study. Domains 1 and 2 are fixed, but Domain 3 is a moving-nested domain that follows the hurricane track every 15 minutes.

The following parameterizations were activated for all three domains: WSM-6 microphysics scheme (Hong and Lim 2006); Yonsei University (YSU) boundary layer parameterization which accounts for local and non-local mixing (Hong et al. 2006); Dudhia shortwave parameterization (Dudhia 1989); and Rapid Radiative Transfer Model (RRTM) longwave parameterization (Mlawer et al. 1997). Because Domain 3 is with 4-km resolution, we didn't include any cumulus parameterization in this innermost domain. However, the new Kain-Fritch cumulus parameterization (Kain 2004) that includes deep and shallow convections was applied in the two outer domains (Domains 1 and 2).

This study was to assess the impact of Doppler radar data on the hurricane vortex initialization and subsequent forecasts. The NCEP data assimilation system, GSI was used to conduct the experiments. The FNL analysis with a spatial resolution of 1^o x 1^o was used to produce the first-guess for all data assimilation. Four sets of experiments were conducted:

CTRL - the control run which used the NCEP/GFS analysis as the initial condition;
PrepBUFR - the experiment which assimilated the conventional GTS data (PrepBUFR format) in all domains;
RadarDA1 - the same as PrepBUFR, but the GTS data plus airborne radar wind data are assimilated in Domain 3;
RadarDA2 – the same as the experiment RadarDA1, but with the radar data thinned;
RadarDA3 - the same as the experiment RadarDA2, but with the length scales of background error covariance tuned.

With the designed experiments, it is obvious that we try to answer the following four questions: 1) Does GSI assimilation of PrepBUFR data again in fine scales add benefits to hurricane forecasting? 2) How does the airborne Doppler radar data improve hurricane vortex initialization and what is the impact on the forecast? 3) Should we need to perform thinning of the airborne Doppler radar data to improve the results? 4) With GSI data assimilation cut-off length scale tuned, does it improve the vortex initialization and forecast? We will analyze the experimental results and provide answers to these questions in the following sections.

4. Numerical results

a. Analysis downscaling: Interpolation vs. re-assimilation of PrepBUFR data at fine scales

It is a long-time dispute on how to perform downscaling of NCEP/FNL analysis to WRF initial conditions. Some argue that the NCEP/FNL analysis has already assimilated PrepBUFR data, and the WRF initial conditions can be simply interpolated from the analysis using WRF Preprocessing System (WPS). On the other hand, many researchers consider the issue of different analysis scales that FNL analysis is obtained in a low resolution through data assimilation. When the WRF analysis is conducted in fine scales, the PrepBUFR data should be assimilated again for better use of the observation data. In recent years, the multi-scale assimilation strategy has been proposed and proved its analysis is much improved with the strategy (Li et al 2011; Xie et al. 2011). In fine scales, the observations rejected in low-resolution assimilation process could be picked up and assimilated into analysis in fine scales. This is especially important for initialization of hurricanes and other mesoscale weather systems.

For Hurricane Earl (2010), the CTRL experiment that interpolates FNL analysis to WRF initial conditions produces larger bias in the hurricane track and intensity forecasts compared with the data assimilation experiment PrepBUFR (Fig. 5b vs. Fig. 5c). Even though the PrepBUFR data has been assimilated in FNL, the benefits are observed in the data assimilation experiment that assimilates the data again at fine scales. The hurricane track is deviated to the east in the CTRL experiment (Fig. 5a vs. Fig. 5b). On the contrary, the PrepBUFR experiment corrects the track bias and makes the track positions closer to the observed (Fig. 5a vs. Fig. 5c). However, the intensity forecast shows little improvement in this study.

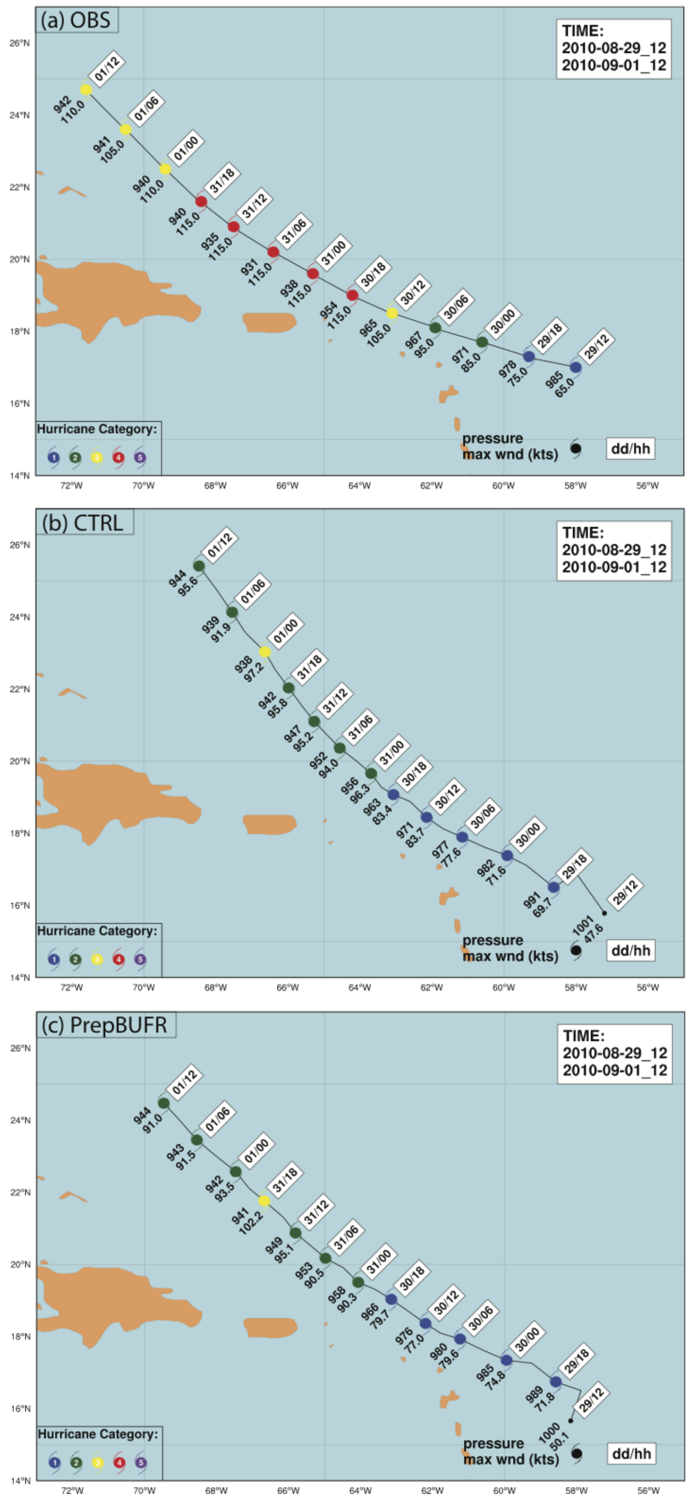

Fig. 5: Hurricane Earl from 1200 UTC 29 August till 1200 UTC 1 September 2010 from (a) best track OBS, (b) CTRL experiment, and (c) PrepBUFR experiment. The tracks are in solid line, with hurricane symbols at every 6 hours. The numbers of CSLP and MSW are on the left and the times are on the right of the hurricane symbols. Different color in hurricane symbols represents hurricane categories with labels on the left lower corner.

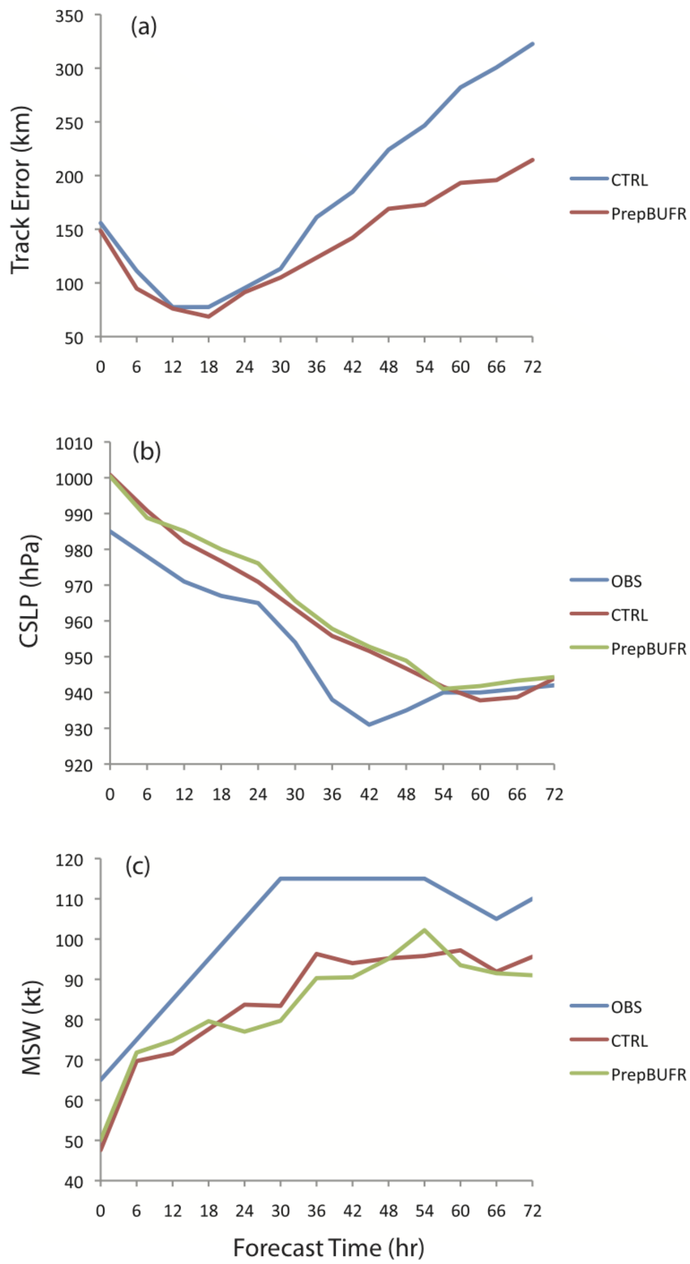

Fig. 6: Hurricane Earl's (2011) a) track error, b) central sea-level pressure (CSLP, hPa), and c) maximum surface wind (MSW, kt) from CTRL (red) and PrepBUFR (green) experiments

The variations of Hurricane Earl's (2010) track error and intensity forecasts by CTRL and PrepBUFR experiments are shown in Fig. 6a, b, and c. Fig. 6a indicates that the track error is reduced in PrepBUFR experiment. The improvement becomes more significant along with the time integration of the forecast. In the beginning 24 hours, the track errors in CTRL and PrepBUFR are close. However, the track error at 72 hour is reduced to over 100 km in PrepBUFR from CTRL. In Fig. 6b and c, we can see the intensity forecasts do not show significant difference. This is consistent with our previous studies (Xiao et al. 2006; 2009a; b), that hurricane intensity is mainly impacted by the vortex initialization. The PrepBUFR data are mostly in the hurricane environmental area. Enhancement with the data in the hurricane initial conditions does not change much in the hurricane intensity forecast. But it does change the hurricane track. Hurricane track is mainly impacted by the environmental circulation.

b. Vortex initialization with airborne Doppler radar data

i). Airborne Doppler radar data assimilation and the vortex structure of Earl (2010)

Airborne Doppler radar data are mainly in the hurricane vortex region. Assimilation of the data thus changes the vortex structure significantly. Usually the winds in the vortex region in the NCEP/FNL analysis are weak compared with the observed. The radial winds from airborne Doppler radar observations are sometimes 30 or 40 m/s higher than the background fields from FNL analysis. Therefore the analytical increments of winds in the hurricane vertex region are very large. Fig. 7 shows the analytical increments of winds from the experiments a) PrepBUFR, b) RadarDA1 and c) RadarDA2. The difference between the experiment PrepBUFR and the two radar data assimilation experiments (RadarDA1 and RadarDA2) is the airborne Doppler radar data in the assimilation procedure in RadarDA1 and RadarDA2. In RadarDA2, the airborne Doppler radar data are thinned, corresponding to the model resolution (4km), whereas RadarDA1 keeps the radar data in the original resolution.

As shown in Fig. 7, Doppler radar data assimilation imposes great influence on the vortex of Hurricane Earl (2010). In Fig, 7a, the analytical increments are small, which are below 5 m/s. On the contrary, airborne Doppler radar data assimilation significant increases the analytical increments in the vortex region, with the maximum increment that reaches 20 m/s. The maximum increments are in the northeastern quadrant, which is consistent with the observations (Fig. 3a). Compared Fig. 7b with c, the data thinning makes the analytical increments more smooth. Fig. 8c presents less small structures than Fig. 7b. It reflects the reduction of noise (or bias) by data, albeit some mesoscale or microscale structures in the data may be true. However, these small structures may produce gravity waves in modeling. Reducing analytical noises that are caused by redundant data in the data assimilation procedure is beneficial to a sound analysis and subsequent modeling.

Fig. 8 shows the wind analyses of Domain 3 in the experiments a) CTRL, b) PrepBUFR, c) RadarDA1 and d) RadarDA2. The vortex circulation is clear in all analyses. The background fields (CTRL) and the analyses from PrepBUFR experiment are somewhat similar. As shown in Fig. 8a and b, the maximum winds in CTRL and PrepBUFR experiments are less than 30 m/s, in the northeastern quadrant. Doppler radar data assimilation greatly enhances the vortex circulation. The maximum wind speed in the northeastern quadrant increases to over 40 m/s (Figs. 8 b and c). In the experiment RadarDA2, the airborne Doppler radar data are thinned to the resolution similar to model grids. Its wind analysis (Fig. 8d) compared with that in Fig. 8c, presents a more smooth circulation. Some small features that are easy to trigger gravity wave in model simulation are removed. We will show in the next section that data thinning produces positive impact on the hurricane intensity forecasting.

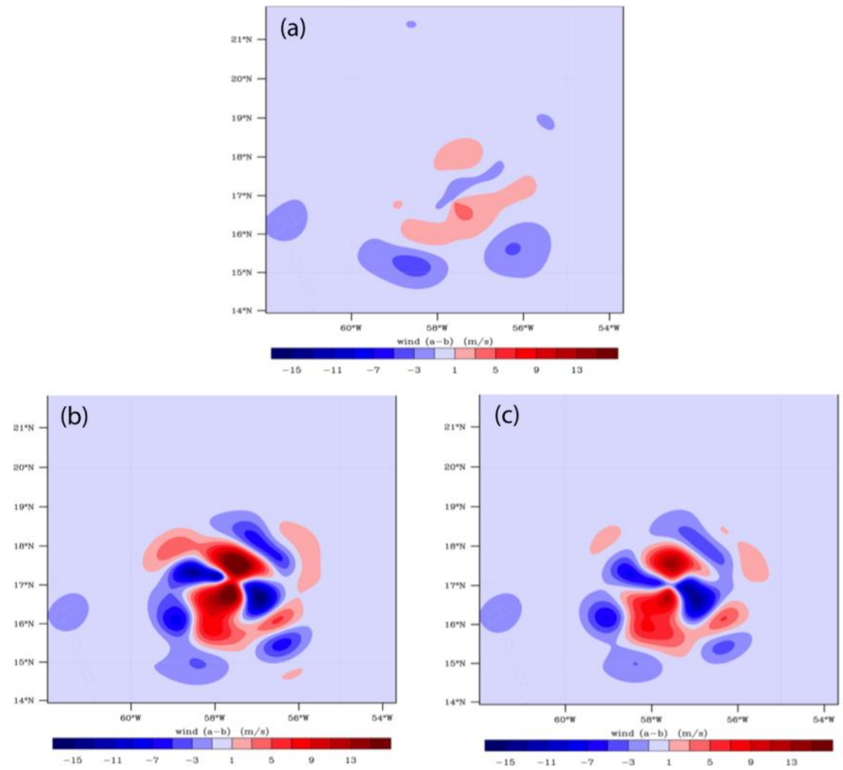

Fig. 7: Hurricane Earl's (2010) analytical increments of wind speed (unit: m/s) at the lowest level with airborne Doppler radar data assimilation at 1200 UTC 29 August 2010: a) PrepBUFR, b) RadarDA1, and c) RadarDA2

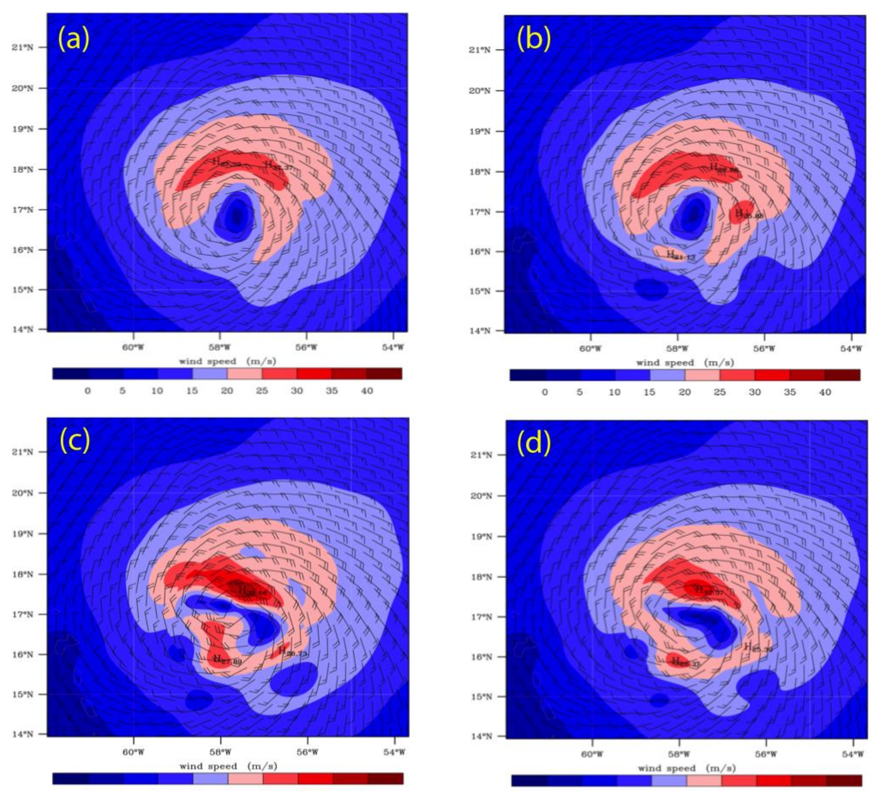

Fig. 8: Wind analyses at the lowest level (barb represents 5 m/s and the wind speed is in color scale) by the experiments a) CTRL, b) PrepBUFR, c) RadarDA1, and d) RadarDA2

ii). Tuning of background error covariance

GSI is the operational data assimilation system at NCEP. Accompanied with the GSI release at DTC, there is a default background error covariance matrix released. Before the background error covariance can be used in hurricane initialization with Doppler radar data, its correlation length scales should be tuned. The hurricane initialization is performed in a 4-km resolution domain, but the default background error covariance was calculated in a much lower resolution.

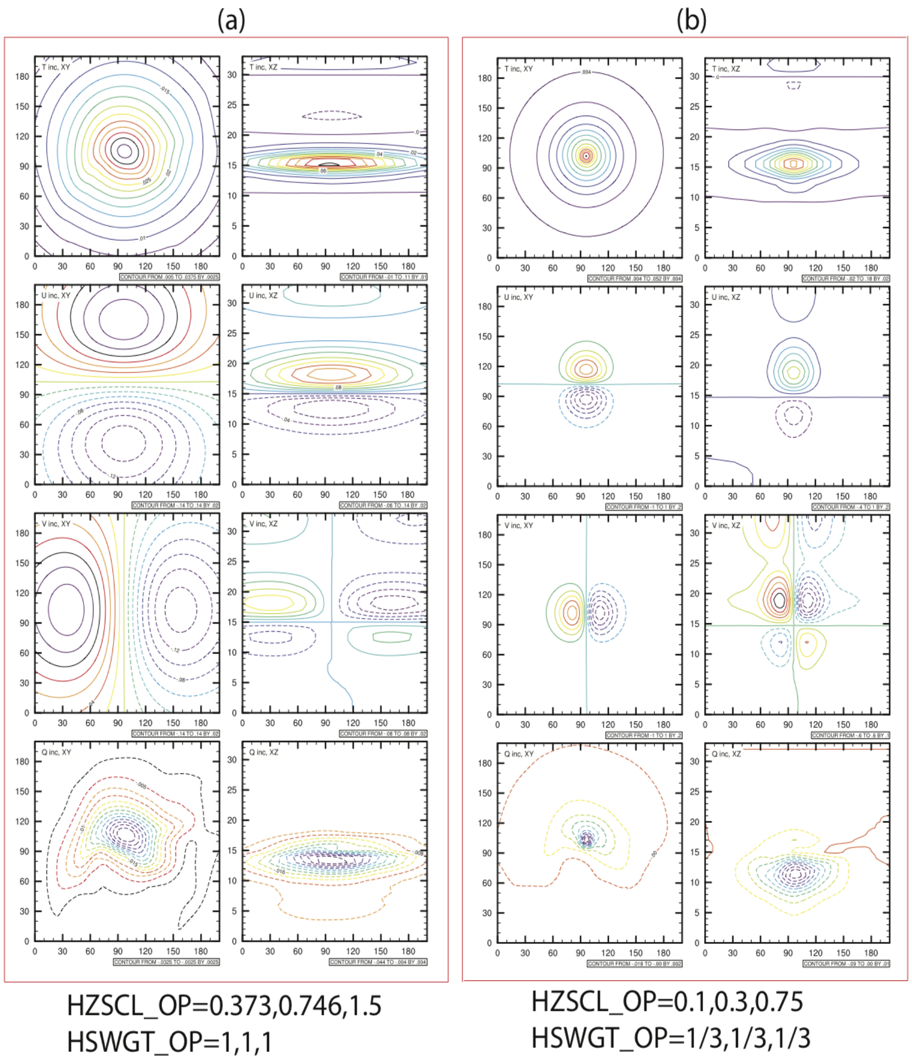

Fig. 9: Horizontal cross section (left column) and vertical cross section (right column) of analysis increment of T, U, V, and Q from a single T observation: a) horizontal lengthscale tuning factors (HZSCL_OP = 0.373, 0.746, 1.5) and weighting factors (HSWGT_OP = 1, 1, 1); b) HZSCL_OP = 0.1, 0.3, 0.75 and HSWGT_OP = 1/3, 1/3, 1/3.

Single observation test is usually conducted to examine how the background error covariance structure is. The background error covariance structure determines the propagation of observational information in the 3DVAR analysis. The correlation length scale is often tuned in real data assimilation. To perform single observation test with GSI, we put a single temperature observation at 500 hPa at the domain center, with an assigned innovation of 1 K and observation error of 1 K. Fig. 9 shows the GSI analytical increments of temperature, wind components, and moisture with two different lengthscale factors and weighting factors in the horizontal and vertical directions. Fig. 9a uses the default lengthscale and weighting factors recommended by DTC. It can be seen that the propagation of the observational information reaches a too large distance. Significant analytical increments are over the whole domain and greatly impact the analyses at the lateral boundaries of the domain. The incremental structures of the single observation test are not sound in the vertical too. The vertical extend of the background error covariance does not match with its horizontal extend. It means that the analytical increments are not in balance. Fig. 9b shows the tuned background error covariance structure with horizontal lengthscale tuning factors (HZSCL_OP = 0.1, 0.3, 0.75) and weighting factors (HSWGT_OP = 1/3, 1/3, 1/3). Although we don't know what the exact tuning factors should be, the analytical increment structures are more appropriate for the innermost domain with horizontal resolution of 4km. The temperature length scale is the largest with a cut-off distance over 200 km. The correlation cut-off distance for winds is around 50 km. It is important that the analysis incremental response in the vertical is better balanced with its horizontal response, so the analysis increments have a much sound structure. Doppler radar data assimilation will be performed in the 4-k domain. With the tuned background error covariance, improved analyses from Doppler radar data assimilation are anticipated.

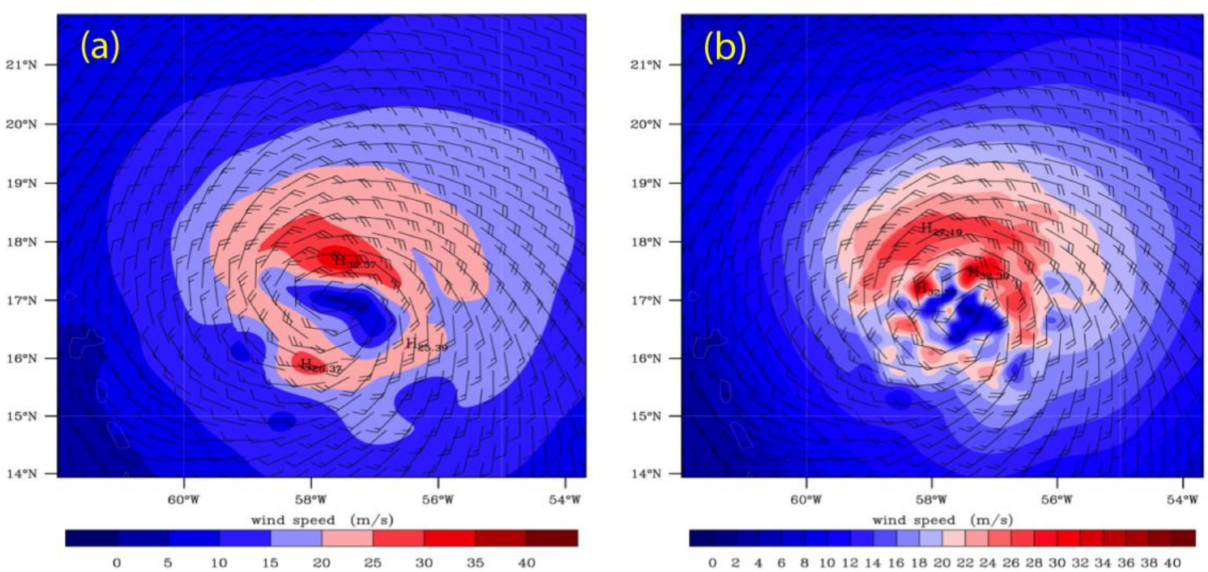

Fig. 10: Wind analyses at the lowest level (barb represents 5 m/s and the wind speed is in color scale) by the experiments a) RadarDA2, and d) RadarDA3

Comparing Figs. 10a and b, we can discern the change of wind analyses in Domain 3 before and after background error covariance tuning. The experiment RadarDA2 assimilated the thinned data with the DTC default background error covariance (Fig. 10a), whereas RadarDA3 assimilated the thinned data with the tuned background error covariance matrix (Fig. 10b). After the background error correlation cut-off lengthscale decreases, the vortex structure becomes more compact. The maximum wind speed is still in the northeastern quadrant. However, the radius of maximum wind is shrunken. Another feature observed in the experiment RadarDA3 after background error covariance tuning is that the wind speed in the southwestern quadrant is reduced. There is a large wind band in the southwestern quadrant in Fig. 10a. The magnitude of the wind band is greatly reduced after the lengthscale of the background error covariance is tuned.

c. Forecasts of Hurricane Earl (2010) initialized with Doppler radar data assimilation

Hurricane track is mostly influenced by the environment, instead of the inner structure of the vortex. Airborne Doppler radar data assimilation modifies the vortex structure. Its impact on hurricane track is not as significant as on intensity (Xiao et al. 2009b). Therefore we mainly discuss the intensity forecast of Hurricane Earl (2010) initialized with airborne Doppler radar data assimilation in this section.

The 72-h evolution of Hurricane Earl's (2010) maximum surface wind (MSW) and central sea-level pressure (CSLP) from the best track and the four experiments (CTRL, PrepBUFR, RadarDA2 and RadarDA3) are shown in Fig. 11. In general, merely assimilating PrepBUFR data does not improve the MSW and CSLP in the whole 72-h period. We noticed that assimilating airborne Doppler radar data without tuning of background error covariance slightly improves the intensity forecast. The assimilation experiment RadarDA3 improves the intensity forecast, especially the CSLP forecast, compared with the experiments CTRL and PrepBUGR, although the forecasted storm is still not as deep as observed. The improved MSW intensity forecast for Earl (2010) offered by assimilating airborne Doppler radar data lasts about 24 h. The improved CSLP intensity forecast can be observed from 12 h and is maintained between 12 h and 60 h. Overall, the improvement for CSLP is larger than for MSW, albeit the wind information from Doppler velocity is assimilated in the vortex initialization. The 72-h average forecast errors of MSW and CSLP for the experiments (CTRL, PrepBUFR and RadarDA3) are listed in Table 1.

Table 1: Hurricane Earl' (2010) 72-h average forecast errors of MSW (m/s) and CSLP (hPa) for the experiments (CTRL, PrepBUFR and RadarDA3)

	Average MSW error (m/s)	Average CSLP error (hPa)
CTRL	-10.7	8.9
PrepBUFE	-11.3	9.1
RadarDA3	-9.5	7.5

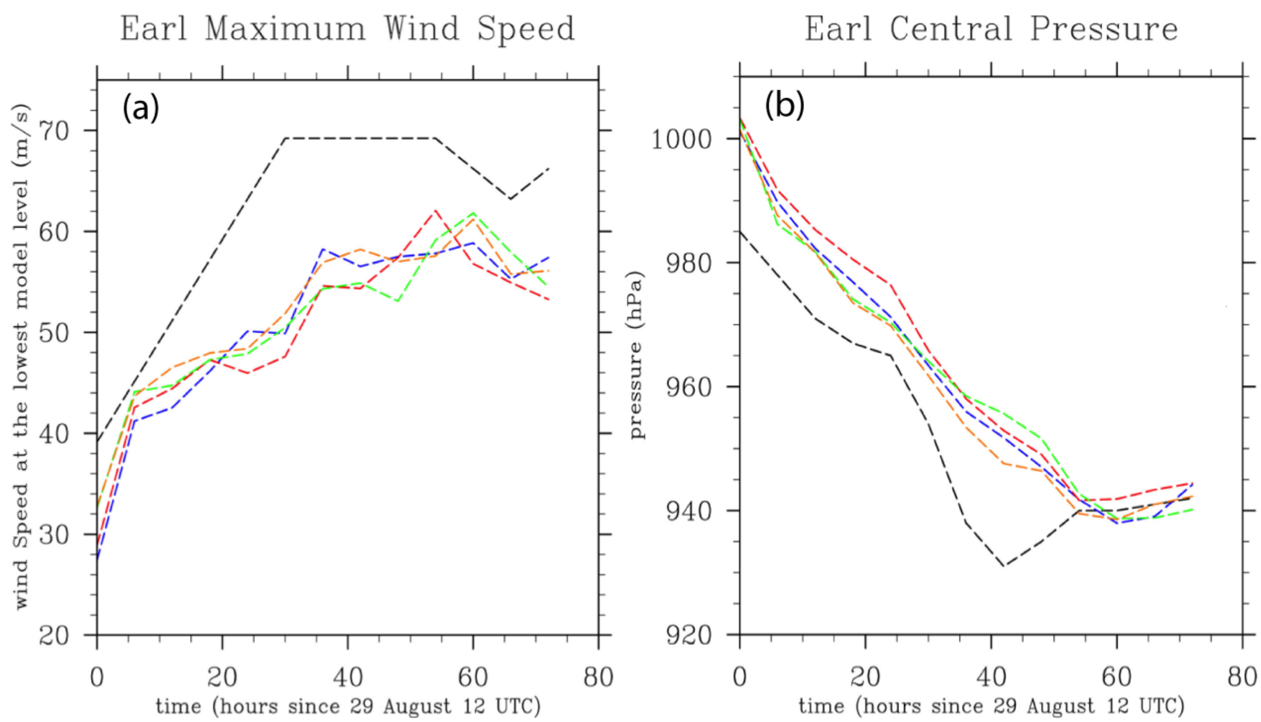

Fig. 11: Variations of Hurricane Earl's maximum surface wind (m/s) between 1200 UTC 29 August and 1200 UTC 1 September 2010, in which the black line represents the best track data, blue line from CTRL, redline from PrepBUFR, green line from RadarDA2, and brown line from RadarDA3

5. Summary and Conclusions

In order to have an accurate hurricane vortex structure in WRF initial conditions, observations in the vortex's inner core region should be used in the data assimilation procedure (Xiao et al. 2006; 2007; 2009b). Airborne Doppler radar data provide the hurricanes with detailed structure. During this project, we applied GSI, an advanced data assimilation system, in assimilation of Doppler radial winds for Hurricane Earl's (2010) vortex initialization. Several strategies, such as airborne Doppler radar data thinning (or super-obbing) and background error covariance tuning, were tested in this study. The major findings from this work as summarized in the following:

- Enhancement in the WRF initial conditions using conventional PrepBUFR data is necessary when the WRF model is in higher resolution than the background field. Numerical experiments in this study verified that the hurricane Earl's (2010) track was greatly improved after assimilating the PrepBUFE data with the GSI data assimilation in high-resolution. PrepBUFR data are mainly in the hurricane environment. Assimilation of the data enhanced the initial conditions of the hurricane environmental flow, thus the hurricane track is improved.

- GSI assimilation of the airborne Doppler radar data improves Hurricane Earl's (2010) vortex initialization. The vortex circulation structures are enhanced. As we know, hurricane intensity and intensity change are highly related to vortex structures. After improving hurricane vortex initialization capabilities with the Doppler data assimilation in GSI, the Doppler radar winds can be successfully assimilated into the vortex initialization, which provides detail and accuracy of the vortex structures in support of the subsequent hurricane intensity forecasting.

- Doppler radar data are in a very high density (resolution). For better use of the data, thinning or super-obbing strategy should be applied to the data. We tested that assimilation of the super-obs (thinning) data with the resolution corresponding to the model grids (4 km) produced a sound vortex initialization. Assimilating the thinned Doppler radar data avoids some spurious and redundant data, which could produce noise in the analysis and gravity waves in the subsequent model forecasting.

- Since hurricane vortex is in mesoscale, the background error covariance from the DTC release that is the statistics using FNL data should be tuned. The mesoscale background error covariance structure should be different from large scale or synoptic scale. With the single observation test, we could empirically select the background error covariance length scale factors and weighing factors according to the model domain and resolution. With the tuning, we obtained improved forecasts of hurricane intensity (maximum wind and central sea-level pressure) for Hurricane Earl (2010). Certainly, more objective tuning is needed in the future.

Application of hurricane vortex initialization using airborne Doppler radar data with the NCEP GSI data assimilation is in its infant stage. As our initial experiments, the results are encouraging. With regard of GSI's capability to assimilate Doppler radar data, there are obviously lots that need to be tested, improved and developed. We believe this is a right direction and more encouraging scientific results will be anticipated in the area.

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