THE EVALUATIONS OF HURRICANE BDA SCHEME WITH WRF 3DVAR

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1. Introduction

While numerical prediction of hurricane tracks has improved tremendously over the past several decades (Leslie and Holland 1995), there has been little appreciable improvement in hurricane intensity forecast skill over the ocean and at landfall. Similar to the fact that hurricane initial position is important for the track forecast, it is plausible that an appropriate initial vortex structure and intensity could contribute to the subsequent intensity forecast. Although there are many aspects of requirements to improve the forecast of hurricane intensity, providing accurate initial vortex is definitely one of the critical components. This is the task for the data assimilation community.

Over the past three years, the National Center for Atmospheric Research (NCAR) has been running the advanced research WRF (ARW) model in real-time simulations of landfalling hurricanes as part of the overall WRF development effort (Davis et al. 2007). The forecast verifications indicate that the poor initial conditions which are simply interpolated from GFDL or GFS analysis inhibit forecast accuracy for the first 36 hours or so in the ARW forecast. Since the WRF-Var data assimilation is mature, application of the system to hurricane initialization to produce an appropriate initial vortex is an interesting and important work. As the first step, BDA technique (Xaio et al. 2000; Zou and Xiao 2000; Xiao et al. 2006) is tested in this study.

BDA is a technique proposed by Zou and Xiao (2000) and Xiao et al. (2000), in which a synthetic vortex is assimilated by variational data assimilation scheme. During the optimization (minimization) procedure in the advanced varaitional data assimilation, the synthetic hurricane structures are gradually incorporated into the hurricane initial conditions. As the 3DVAR component of WRF-Var becomes mature, we will test the performance of BDA using 3DVAR in this study. The 4DVAR implementation using WRF-Var system and experimental results will be provided in the future.

There are several achievements in WRF-Var to conduct BDA. The technical details of bogus constructions, error specifications, and the BDA variational formulation are similar to our previous work with MM5 3DVAR (Xiao et al. 2006).

2. The BDA Scheme in WRF-Var

The 3DVAR component of WRF-Var inherits from MM5 3DVAR (Barker et al. 2004), and readers can be referred to Skamarock et al. (2005) for detail. The configuration of WRF-Var is based on the incremental formulation (Courtier et al. 1994), producing a multivariate incremental analysis in model space. The minimization is performed in preconditioned control variable space**.** The preconditioned control variables are streamfunction, unbalanced velocity potential, unbalanced temperature, pseudo relative humidity, and unbalanced surface pressure.

The BDA scheme in WRF-Var includes: 1) synthetic vortex construction and error specification, and 2) assimilation of the synthetic data. There are two components (symmetric and asymmetric) in the synthetic bogussing observations. The symmetric component is specified with the method of Ueno (1995) based on the best track information. The asymmetric component is extracted from background fields (analysis or previous forecast) and relocated to the observed position. We simply take the difference between background filed and its azimuth average around the hurricane center in the hurricane area as the hurricane asymmetric component. The relocation of the hurricane asymmetric component and addition to symmetric field create a set of bogus SLPs and wind profiles within the observed hurricane area. The errors for the bogus observations are assigned empirically. The detailed construction of the bogus observations and assignment of their errors refer to Xiao et al. (2006).

Assimilation of the synthetic bogussing data is treated similarly as other conventional observations. The initialization of hurricane is via minimization of a predefined cost function as

$$J(X) = J_b(X) + J_o(X) + J_p(X) + J_V(X)$$

where J_b is the background term and J_o is the regular observation term; details of the two terms in WRF-Var can refer to Skamarock et al. (2005). In order to include BDA capability, two additional terms, J_p and J_V, are added to the cost function:

$$J_P = \sum_{r \le R_B} [P(r) - P^{bogus}(r)]^T O_P^{-1} [P(r) - P^{bogus}(r)]$$

and

$$J_V = \sum_k \sum_{r \le R_B} [V(r,k) - V^{bogus}(r,k)]^T O_V^{-1} [V(r,k) - V^{bogus}(r,k)]$$

where $P(r)$ and $V(r,k)$ represent the SLP and wind fields (*u* and *v* components) of the model atmosphere, $P^{bogus}(r)$ and $V^{bogus}(r,k)$ are the bogus SLP and wind fields, O_P and O_V are diagonal error variance matrices for the bogus SLPs and wind fields, R_B is the radius of the bogus area, r is the radius from the hurricane center and k denotes the vertical layers of the bogus wind profile.

3. Cases and Experimental Design

Totally, twenty-one cases from seven hurricanes in the 2004 and 2005 seasons are chosen in our experiments (Table 1). They are Hurricanes Charley, Frances, Ivan, and Jeanne in 2004, and Katrina, Rita and Wilma in 2005. These hurricanes' activities are summarized in Figure 1. We select three cases for each hurricane before its landfall. The initial time for each case is provided in Table 1. Also listed in Table 1 are the hurricane categories, locations and intensities (CSLP and MSW) at the initial time of each experiment.

Numerical experiments were conducted using WRF-ARW with a single domain. An example of the domain set-up is shown in Figure 1, which is for the experiments for Katrina (2005). The domain size and model configurations are the same for all experiments. The grid-spacing of all experiments are set 12 km with 400 X 301 grid points. The domain center of each hurricane is different, but all three cases from the same hurricane have the same domain center (Table 1). There are 35 layers in the vertical and the pressure at model top is 50 hPa. Physics options used in the WRF-ARW for all experiments include: YSU PBL scheme, which is the new generation of Medium Range Forecast Model (MRF) PBL scheme described by Hong and Pan (1996); Kain-Fritsch cumulus scheme (Kain and Fritsch 1990; 1993); and WSM-3 microphysics scheme (Hong et al. 2004), which is a so-called simple-ice scheme wherein the cloud ice and cloud water are counted as the same category (Dudhia 1989). The WRF-ARW forecasts are executed for 72 hours started from the time indicated in Table 1.

Two sets of experiments are carried out; the difference is in hurricane initialization with the WRF 3DVAR. The first set of experiments (CT) uses GFS analysis as background and assimilates only the conventional observations from Global Telecommunications System (GTS). The second set of experiments (GB) is the same as CT, but hurricane vortex bogus observations are included in the assimilation. The parameters from the best-track report are used to construct the hurricane bogus data. For all 3DVAR experiments, the same background error covariance is used, which is calculated from statistics of one-month 24 minus 12 hour forecasts in September 2004 using NMC-method (Parish and Derber 1992).

Table 1: Categories, locations and intensities (CSLP and MSW) of the selected 21 hurricane cases in the 2004 and 2005 seasons (The initial time for each case and its experimental domain center are provided)

Hurricane Name	Domain Center	Initial Time (UTC)	Central Position	CSLP (hPa)	MSW (Kt,m/s)	Category
Charley	26N,76W	2004081100	15.6N,71.8W	999	55,29.7	TS
		2004081112	16.3N,75.4W	995	60,32.4	TS
		2004081200	17.4N,78.1W	992	65,35.1	1
Frances	23N,80W	2004090100	20.6N,66.4W	941	120,64.8	4
		2004090200	22.2N,71.4W	939	120,64.8	4
		2004090300	24.2N,75.0W	948	105,56.7	3
Ivan	24N,80W	2004091100	17.3N,76.5W	926	135,72.9	4
		2004091200	18.2N,79.6W	910	145,78.3	5
		2004091300	19.5N,82.8W	916	140,75.6	5
Jeanne	28N,76W	2004092100	27.4N,70.8W	982	75,40.5	1
		2004092300	25.7N,69.0W	966	85,45.9	2
		2004092400	26.0N,70.4W	966	70,37.8	1
Katrina	28N,84W	2005082500	26.0N,77.7W	1000	45,24.3	TS
		2005082600	25.9N,80.3W	983	70,37.8	1
		2005082700	24.6N,83.3W	959	90,48.6	2
Rita	27N,88W	2005092000	23.3N,77.2W	992	60,32.4	TS
		2005092100	24.1N,82.7W	967	95,51.3	2
		2005092200	24.5N,86.9W	897	150,81.0	5
Wilma	23N,83W	2005102000	17.9N,84.0W	892	135,72.9	4
		2005102100	19.1N,85.8W	924	130,70.2	4
		2005102200	20.6N,86.8W	930	120,64.8	4

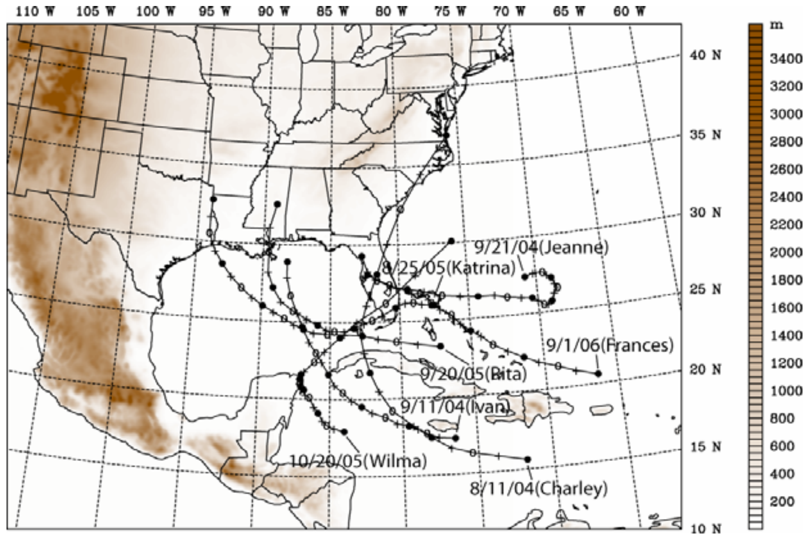

Figure 1: The best tracks of seven hurricanes (Charley, Frances, Ivan, Jeanne, Katrina, Rita and Wilma) in the 2004 and 2005 seasons. The hurricane positions are shown with "•" at 0000UTC, with "o" at 1200UTC, and with "+" at 0600 and 1800UTC. The shadings in the map are terrain height with scale on the right.

4. Statistical Verification of the Forecasts in Hurricane Track and Intensity

To examine the effects of BDA scheme on hurricane forecasts, we calculated the mean absolute errors of the forecasts in track and intensity for all 21 cases. Figure 2 shows the statistical verifications of the forecasts (position, central SLP, and maximum surface wind MSW) against the best track observations at 24, 48 and 72 h. It is indicated that errors of BDA experiments (GB) are smaller than that of control experiments (CT) for all the verification parameters (position, CSLP, and MSW). Over oceans, there are sparse observations; assimilating bogus data is able to improve the hurricane forecasting skill. Assimilating only conventional GTS data could not improve it effectively, especially on the hurricane intensity forecast. With BDA, the largest improvement is in the forecast of CSLP. The improvement in hurricane MSW is also significant. The track has the smallest improvement among the three verification parameters.

The forecast skill in hurricane track is reduced along with the increase of the forecast time. On the contrary, the skill of hurricane intensity forecast is gradually increased with the forecast time. This is a common phenomenon observed in all hurricane forecasts. As far as the impact of BDA is concerned, we notice that its improvement in hurricane intensity forecasts becomes less with the increase of the forecast time (Fig. 2). The improvement of hurricane CSLP and MSW at 24h forecast is much more remarkable than that at 48h and 72h forecasts. In the track forecasts, however, experiment GB has the most remarkable improvement at 72h forecast over the experiment CT. The model and initial fields have a process of adapting each other in initial stage of integration, which results in smallest improvement from the BDA scheme in the earlier time of hurricane track forecast.

Further analyzing the forecasts of every case reveals a more sound assessment of the BDA scheme on hurricane forecasts (Table 2). Among the 21 cases at 24 h forecast, 12 cases have a reduction in track error, and 9 cases produce an increased track error. At 48 h forecast, 14 cases have a reduction in track error, and 7 cases produce an increased track error. At 72 h forecast, 12 cases have a reduction in track error, and 9 cases produce an increased track error. In general, assimilation of hurricane bogus data reduces the mean track error at all forecast times, with the largest reduction occurring at 48 h. However, the tracks in BDA experiment (GB) are not always better than control (CT). In some cases BDA produces larger track error than that of CT experiment. The errors of hurricane central SLP and maximum surface wind (MSW) have the same characteristics. At 24 h forecast, only one case produces an increased intensity error, but the number increases to six at 48 h forecast and eight at 72h forecast. With the model forecast time increasing, more BDA cases have increased intensity error compared to CT, but the forecast skill is improved in general.

Statistically, it is found that there is no obvious relationship of the forecast improvement by BDA between hurricane track and intensity. Hurricane track is most influenced by its environment, but intensity is mainly impacted by its internal, dynamical and thermo-dynamical structures. The degrees of BDA reflecting in hurricane vortex and in large-scale circulations are the keys to balance the track and intensity improvement, but it is difficult to tell in our scheme. Perhaps the track improvement is mainly attributed to the GTS assimilation.

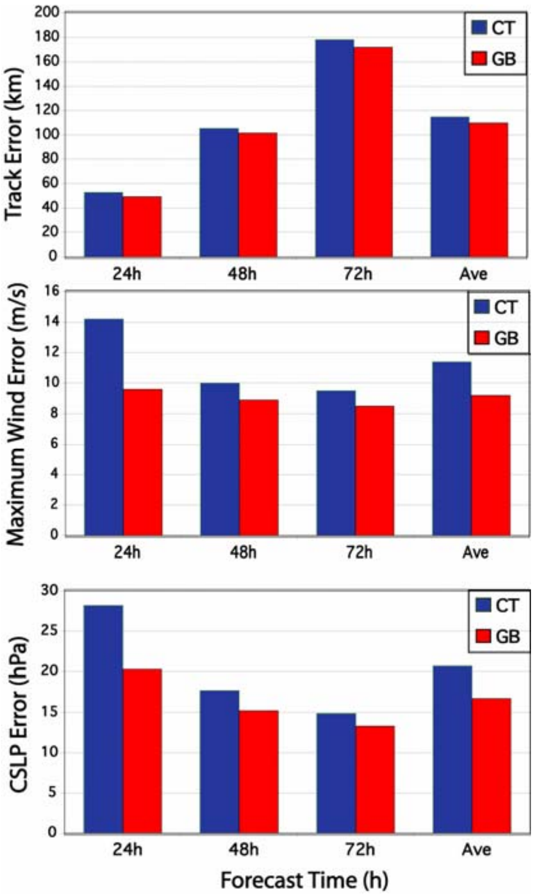

Figure 2: The absolute errors of the hurricane track (top), maximum surface wind (MSW, middle) and central sea-level pressure (CSLP, bottom) for the forecasts from statistics of 21 cases listed in Table 1. The light and dark bars are the statistical results for control experiment (CT) and BDA experiment (GB), respectively. The errors of 24, 48 and 72 hrs forecasts, and their average are shown.

Table 2: Numbers of cases with decreased (dcsd) or increased (icsd) errors at 24, 48 and 72 hr forecasts for the hurricane track and intensity (central sea-level pressure and maximum surface wind) in the 21 BDA experiments compared with control experiments

	24h		48h		72h	
	dcsd	icsd	dcsd	icsd	dcsd	icsd
Track(km)	12	9	14	7	12	9
CSLP(hPa)	20	1	14	7	13	8
MSW(m/s)	20	1	15	6	13	8

5. Summary and Conclusions

One of the most challenging problems for the hurricane forecaster and researcher is defining the structure of the hurricane and its adjacent synoptic features with insufficient observations over the ocean. In this study, a bogussing algorithm using WRF 3DVAR system was tested by assimilating the hurricane bogus observations in the 3DVAR analysis. 21 cases from 7 hurricanes in 2004 and 2005 seasons were used to verify the BDA in WRF 3DVAR for forecasts of the hurricanes. WRF ARW forecasts using the 3DVAR analysis show an improved forecast skill in hurricane track and intensity. The major results of this study are summarized as follows:

- Using the WRF 3DVAR system, we assimilate the hurricane bogus SLP and wind profiles data. It is indicated that the BDA scheme in WRF 3DVAR is very efficient in recovering the initial structure of hurricanes. It works properly in the numerical experiments.
- The dynamical and statistical balance embedded in the 3DVAR system is used as a constraint to generate the hurricane structures while the bogus SLP and wind profiles are assimilated. The hurricane analysis is thus more balanced with the model than that from just interpolation with WPS.
- Numerical experiments indicate that assimilation of the hurricane bogus data obtains improved track and intensity forecasts. With BDA, the largest improvement is in the forecast of center SLP. The improvement in hurricane maximum surface wind is also significant. The track has the smallest improvement among the three verification parameters.
- The improvement in hurricane intensity forecasts becomes less with the increase of the forecast time. The improvement of hurricane CSLP and MSW at 24h forecast is much more remarkable than that at 48h and 72h forecasts. In the track forecasts, however, BDA results in the most remarkable improvement at 72h forecast.

Although initial results from WRF 3DVAR bogus data assimilation are promising, we found that not all cases can be improved with BDA. The bogus data contain errors and it is difficult to determine the magnitude of the errors for different stages of hurricane development. As more and more real data from satellite and radar are made available, it is prudent to invest more in satellite data assimilation and radar data assimilation for hurricane initialization. These are the work we are currently conducting, and the results will be reported in the future.

***Acknowledgment**:*

The authors acknowledge the support of NOAA 05111076 grant for this research.

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