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A Relocation-based Initialization Scheme to Improve Track-forecasting of Tropical Cyclones

GAO Feng*[1,2], Peter P. CHILDS[3], Xiang-Yu HUANG[2], Neil A. JACOBS[3], and Jinzhong MIN[1,4]

[1]*Nanjing University of Information Science & Technology, Nanjing* 210044
[2]*National Center for Atmospheric Research, Boulder, Colorado, USA* 80307
[3]*Panasonic Avionics Corporation Morrisville, North Carolina, USA*
[4]*Key Laboratory of Meteorological Disaster of the Ministry of Education, Nanjing* 210044

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ABSTRACT

A relocation procedure to initialize tropical cyclones was developed to improve the representation of the initial conditions and the track forecast for Panasonic Weather Solutions Tropical Operational Forecasts. This scheme separates the vortex perturbation and environment field from the first guess, then relocates the initial vortex perturbations to the observed position by merging them with the environment field.

The relationships of wind vector components with stream function and velocity potential are used for separating the vortex disturbance from first guess. For the separation of scalars, a low-pass Barnes filter is employed. The irregular-shaped relocation area corresponding to the specific initial conditions is determined by mapping the edge of the vortex radius in 36 directions.Then, the non-vortex perturbations in the relocation area are removed by a two-pass Barnes filter to retain the vortex perturbations, while the variable fields outside the perimeter of the modified vortex are kept identical to the original first guess.

The potential impacts of this scheme on track forecasts were examined for three hurricane cases in the 2011–12 hurricane season. The experimental results demonstrate that the initialization scheme is able to effectively separate the vortex field from the environment field and maintain a relatively balanced and accurate relocated first guess. As the initial track error is reduced, the following track forecasts are considerably improved. The 72-h average track forecast error was reduced by 32.6% for the cold-start cases, and by 38.4% when using the full-cycling data assimilation because of the accumulated improvements from the initialization scheme.

Key words: tropical cyclone, vortex relocation, data assimilation, Barnes filtering

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1. Introduction

Numerical weather prediction (NWP) of tropical cyclones (TCs) often relies on a short-term forecast of less than 6 h as a first guess of the background field, which typically originates from either a high-resolution limited-area model or a lower resolution global model. In both situations, the ability of the first guess to accurately resolve the center of the storm is limited by either forecast error or too few grid points to properly resolve the vortex structure, especially within weak circulations (Kurihara et al., 1993, 1995; Rappaport et al., 2009). As a result of erratic movement during the initial stages of prediction, the skill of the subsequent track forecasts is significantly degraded.

Some past studies have done a good job at addressing initialization schemes to improve the representation of the vortex, mainly through the use of nonconventional observations and "bogus" techniques. Zhu et al. (2002) and Weng et al. (2007) reported improved representation of temperature, humidity and wind fields around the vortex core by verifying the potential impacts of microwave observations. Whereas, since the impact is a function of flow-dependent observation information from the definite satellite track and time (Pan et al., 2011), radiance observations alone are unable to revise the track forecast at the assimilation and analysis time. As a further practical technique, some studies have focused on the initialization of the vortex by generating bogus observations that meet the TC empirical structure. To construct this classic TC structure, there are two conventional methods that are typically employed. The first directly introduces the new vortex (e.g., Kurihara et al., 1990; Lord, 1991; Low-Nam and Davis, 2001); while the second, called the Bogus Data Assimilation (BDA) method, utilizes a variational framework (Xiao et al.,

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* Corresponding Author: Feng GAO
E-mail: fgao@ucar.edu

2000; Pu and Braun, 2001; Zhang et al., 2003).

In the Low-Nam method (Low-Nam and Davis, 2001), the splitting process of the initial vortex meets the dynamic and thermodynamics balance relationship. Since only the bogus axis-symmetry structure of the wind, mass and humidity fields are presented, this scheme is largely used for testing, and rarely for real-time operational forecasts. Kurihara et al. (1990) and Lord (1991) specified a bogus vortex including both axisymmetric and asymmetric components. A critical issue in such an approach is the continuity of the vortex with the properties of the prediction model (Mathur, 1991). Xiao et al. (2000), Pu and Braun (2001) and Zhang et al. (2003) addressed this issue by using 3D/4D variational assimilation methods to insert bogus sea-level pressure and wind data, derived from empirical functions, into the first guess. One of the advantages in this minimization procedure is that the synthetic vortex structure is introduced gradually into the initial conditions, which objectively satisfies the dynamic and physical constraints for the model atmosphere. However, a limitation is that the bogus data are generated by empirical functions. These could be limited in their scope of suitability across types and stages of TC systems and the surrounding circulation structure—considering that the changeable asymmetric radius of maximum wind (RMW) in reality is a sensitive parameter (Xiao et al., 2000).

Although the position of the TC center is not typically recognized by Global Forecast System (GFS) analysis, and the intensity quite often becomes weaker because of the inability to resolve subgrid-scale convection with parameterized physics, the model can still capture the general flow around the TC in the first-guess field. Using these considerations, a practical method was developed by Kurihara et al. (1993), at the Geophysical Fluid Dynamics Laboratory (GFDL), to reconstruct the initial vortex. In their study, the initial vortex in the GFS analysis was filtered out to derive the asymmetric wind components. The axisymmetric vortex came from the time integration of the axisymmetric hurricane prediction model, where the variables meet the dynamic and thermal constraints dependent on the background during the spin-up phase. Then, the symmetric and asymmetric flows were implanted into the environment field at the observed position. This technique ensures a smooth transition between the environment and the structural consistency of the generated vortex. During the initial phase, the environment field does not always capture features related to TC growth and vortex intensity. Likewise, when the TC itself is weak, it can also lead to a less accurate prediction (Kurihara et al., 1995).

To overcome this limitation, Kurihara et al. (1995) further improved the scheme by revising the environment field to minimize the removal of important non-TC features near the storm region. This enabled the environment field to more accurately resolve irregular patterns that are inherent in developing TC storm structure, which substantially improved the ability to forecast the TC track. More recently, a similar vortex relocation technique, based on the Kurihara et al. (1995) vortex separation method, was developed and implemented in the National Centers for Environmental Prediction (NCEP) GFS (Liu et al., 2000). Instead of inserting a spun-up vortex, this relocation method fetched the model-predicted vortex and directly moved it to the observed position. This reduced the false spin-up problems typically caused by inconsistencies between the initial conditions and the model dynamics and physics.

This TC vortex relocation method was also implemented in the Weather Research and Forecasting model (WRF)-Advanced Research WRF (ARW) system at the Taiwan Central Weather Bureau (Hsiao et al., 2010), where the process to filter out the non-hurricane perturbations employed a two-pass Barnes filter. Results indicated that the variable transitioned smoothly at the vortex edges, and the track forecasts steadily improved during the operational implementation.

In summary, the vortex separation method in Kurihara et al. (1995) has played a crucial role in track forecasting, and many operational centers presently use variations of this scheme. In this paper, an updated TC relocation scheme is introduced to improve the representation of the initial conditions and TC forecast accuracy for Panasonic Weather Solutions Tropical Operational Forecasts. The relocation scheme is based on a combination of the Kurihara et al. (1995) and Low-Nam and Davis (2001) separation methods, the Liu et al. (2000) method for extracting the vortex structure from the first guess, and the non-vortex perturbation filtering method of Hsiao et al. (2010). The revised details are presented in this paper. In addition, the GFDL conditions have been revised to adapt the scheme to cases surrounded by topography.

The remainder of the paper is arranged as follows. In section 2, the implementation of the initialization methodology is presented in detail. Section 3 sets out the experimental configuration, and then the experimental results, including information on the process of relocation and track forecast statistics, are presented in section 4. Finally, conclusions and plans for future work are discussed in section 5.

2. Vortex initialization

The vortex initialization process can briefly be summarized by the following steps:

(1) Split a first guess into a basic field and a disturbance field that includes vortex circulation related to TC structure and non-vortex circulation consisting of noise at various wavelengths. The sum of the basic field and non-vortex circulation is called the “environmental field”.

(2) Filter out the vortex circulation within the irregular-shaped area corresponding to the specific environment by mapping the radius of the vortex edges in 36 directions.

(3) Generate the environment field.

(4) Relocate the vortex to the observed location, and merge it with the environment field.

2.1. *Splitting of the disturbance field*

According to the vortex separation method of Kurihara et al. (1995), a variable V can be split into the basic field ($V_{\rm b}$) and the disturbance field ($V_{\rm d}$):

$$V = V_{\rm b} + V_{\rm d}\ . \tag{1}$$

The disturbance consists of the vortex circulation V_{tc} and the non-vortex circulation $V_{\mathrm{non\text{-}tc}}$, which mainly consists of noise with various wavelengths:

$$V_{\mathrm{d}} = V_{\mathrm{tc}} + V_{\mathrm{non\text{-}tc}}\ . \tag{2}$$

Thus, the environment field V_{e} is expressed as

$$V_{\mathrm{e}} = V - V_{\mathrm{tc}} = V_{\mathrm{b}} + V_{\mathrm{non\text{-}tc}}\ . \tag{3}$$

In this study, the Low-Nam method (Low-Nam and Davis, 2001) is used to split the disturbance field of wind vector components. Considering the relationship between wind vector components and the stream function, the equations are given as

$$\nabla^2 \psi = \zeta\ , \tag{4}$$

$$v_\psi = \hat{k} \times \nabla_\psi\ , \tag{5}$$

wherek $\hat{k}$ is base vector, ψ is the stream function, ζ is relative vorticity, and v_ψ is the non-divergent wind.

The computation of the divergent wind is similar to Eqs. (4) and (5):

$$\nabla^2 \chi = \delta\ , \tag{6}$$

$$v_\chi = \nabla_\chi\ , \tag{7}$$

where χ is the velocity potential, δ is the divergence, and v_χ is the divergent wind. As shown above, the disturbance fields (V_{d}) of vector components are obtained from Eqs. (4)–(7).

In the calculation of non-vortex perturbations $(V_{\mathrm{non\text{-}tc}})$, two-pass Barnes filtering is employed, while scalar filtering uses a Barnes low-pass filter (Barnes, 1994), as the first estimate for Eq. (8). The first estimate of the two-pass Barnes filter is expressed as

$$F_{i,j}^{(1)} = \frac{\sum_{n=1}^{N} w_n F_{i_n,j_n}}{\sum_{n=1}^{N} w_n}\ , \tag{8}$$

where F_{i_n,j_n} is the variable field filtered, $F_{i,j}^{(1)}$ is the first estimate field, and N is the number of grid points calculated. The weighting function, w_n, is

$$w_n = e^{-\frac{r_n^2}{R^2}}\ , \tag{9}$$

where r is the distance between the calculated and estimated grid point, and the constant R is chosen to fit a particular application of the scheme. In the second estimate, the final grid point values are given by Eq. (10), and the updated weighting function is expressed in Eq. (11):

$$F_{i,j}^{(2)} = F_{i,j}^{(1)} + \frac{\sum_{n=1}^{N} w'_n D_{i_n,j_n}}{\sum_{n=1}^{N} w'_n}\ , \tag{10}$$

$$w'_n = e^{-\frac{r_n^2}{0.3R^2}}\ , \tag{11}$$

where $D_{i_n,j_n} = F_{i_n,j_n} - F_{i_n,j_n}^{(1)}$ is the difference between the variable field and the first estimate.

The disturbance fields for scalars are obtained by subtracting the first estimate from the first guess. The coefficient R is defined as 1000. In the process of dealing with the non-vortex perturbations, R is defined as 300.

2.2. *Determination of the vortex perturbation*

The isolation of the vortex perturbation V_{tc} from the disturbance field V_{d} is accomplished by mapping the radial edge of the vortex perturbation. Kurihara et al. (1995) give an empirical condition to determine the vortex edge radius in GFDL, which is based on the assumption that the disturbance wind is strong in the region of the storm.

Generally, one or more indices, such as maximum vorticity, minimum radial wind magnitude, geopotential height at 850 hPa, 700 hPa, or sea-level pressure, are typically used to ascertain the TC center position and track (Liu et al., 2000; Low-Nam and Davis, 2001; Hsiao et al., 2010). Although the weighted center is sufficient for relocation, it is not necessary to be the point of minimum radial wind magnitude when considering the different phase positions of TC structure in the vertical profile. This can result in an inaccurate calculation of the maximum wind radius and vortex perturbation edges, especially for the weaker TC systems.

In this study, for the process of defining vortex edges, the 850-hPa minimum radial wind magnitude is considered the center for outward calculations of the radius of maximum radial wind magnitude. Furthermore, the tracker application[a] developed by the Development Testbed Center (DTC) in the Hurricane Weather Research and Forecasting (HWRF) model is used to obtain the hurricane center by weighting certain indices—in the first guess for the computation of relocation distance and in the forecasts for track computation.

Considering the impacts of terrain and a weak TC system, a revised condition is used in this study. The revised GFDL condition is that of radial wind magnitude V_{edge} and its gradient as follows:

$$V_{\mathrm{edge}} < 5.0\ \mathrm{m\ s^{-1}}\ , \tag{12}$$

$$-\partial V_{\mathrm{edge}}/\partial r < 4 \times 10^{-6}\ \mathrm{s^{-1}}\ . \tag{13}$$

At 850 hPa, the condition is checked outward from the radius of maximum wind magnitude along 36 directions (one point per 10°) at an incremental resolution of 15 km. On the third occasion this condition is met, or $V_{\mathrm{edge}} < 3\ \mathrm{m\ s^{-1}}$, the radius is assumed to contain the major portion of the vortex circulation, and the relocation area is then defined by the edges. It is worth noting that Eq. (12) is a reasonable but not optimal criterion for all terrain cases, which should be based on long-term statistical results.

2.3. *Relocation of the vortex circulation*

After defining the relocation area, the vortex perturbation V_{tc}, including the u and v components, temperature, specific humidity, and sea-level pressure, is separated by removing

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[a] http://www.dtcenter.org/HurrWRF/users/docs/users_guide/HWRF_UG_v3.4a.pdf

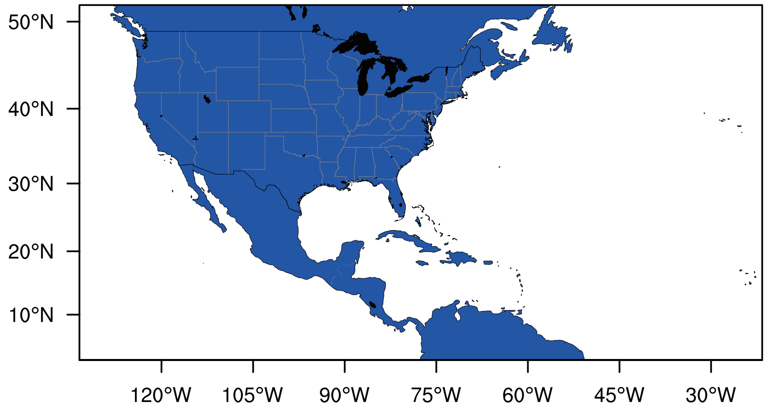

Fig. 1. The operational forecast domain used for the experiments.

Table 1. Initialization time, intensities (minimum central sea level pressure, CSLP) and the relocation distances of the three cases, which developed and landed around the continental US in the 2011–12 hurricane season. The initialization time is the start of the forecast from the analysis, which is the output from the data assimilation process after relocating. For the Isaac case, the real-time runs employed the full-cycle implementation. The relocation distances are according to the sequence of cycle times.

Case name	Initialization date	Min_CSLP (hPa)	Type category	First guess generation	Relo distance (km)
IRENE	1200 UTC 25 Aug. 2011	942	Hurricane	cold-start	33.5
RINA	0000 UTC 25 Oct. 2011	966	Hurricane	cold-start	30.0
ISAAC	0000 UTC 27 Aug. 2012	968	Hurricane	full-cycle	0, 54, 15, 21.2, 30

the non-vortex perturbation $V_{\text{non-tc}}$ according to Eqs. (8)–(11), and relocated to the observed position by merging V_{tc} with the environment field V_{e}. In order to maintain balance within the model variables, the new potential temperature, specific humidity, and surface pressure are used to recalculate geopotential height and dry air mass, which follows the methodology in Skamarock et al. (2008) and Hsiao et al. (2010).

3. Experimental design

The assimilation and forecast experiments reported in this paper were run based on WRFDA (Huang et al., 2009; Wang and Huang, 2012; Barker et al., 2012) and the WRF model (Skamarock et al., 2008). A tropical operational forecast domain, which covered the continental United States (CONUS) and tropical Atlantic Ocean area (Fig. 1), was mapped on a 718 × 373 horizontal grid with 15-km spacing and 43 vertical levels and a model top at 50 hPa. We analyze three land-falling TCs from the 2011–12 hurricane season, which contain a variety of conditions inherent to typical forecasting skill. The initialization time, intensity (i.e., minimum central sea-level pressure, CSLP), and the relocation distances are presented for these cases in Table 1.

For the first two landing-hurricane cases, the cold-start scheme, which uses the 6-h forecast initialized from NCEP GFS global analysis as the first guess, was employed for avoiding the coarse resolution of the initial conditions. In these cases, which employed the conventional methodology (6-h cold-start but no relocation process), a poor track forecast was produced for Rina, and a slightly better forecast was produced for Irene. In the case of TC Isaac, a real-time full-cycle implementation in the operational configuration was run, where the first guess was obtained from the 6-h forecast of the previous analysis cycle. For comparison, the relocation experiment used an identical configuration as the conventional forecast, with the exception of the relocated vortex in the first guess.

The observations used for the 3D variational (3D-Var) data assimilation consisted of NCEP operational Global Telecommunication System (GTS) data (e.g., SYNOP, GEOAMV, RAOB etc.). The time window for the data assim-

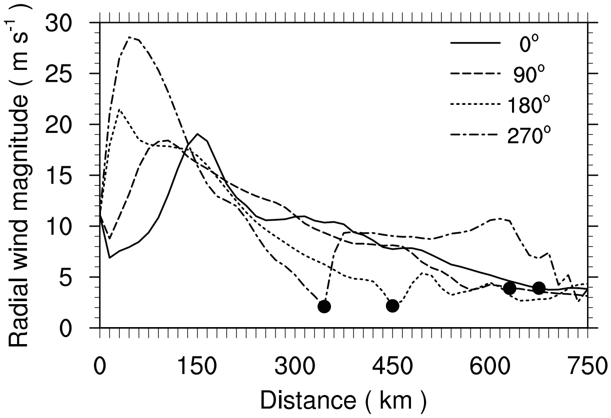

Fig. 2. The radial wind magnitude in four directions (0°, 90°, 180°, 270°), centered at the position of minimum wind magnitude (0 km) at 850 hPa, in the case of Rina at 0000 UTC 25 October 2011. The solid-circles are the edges of the relocation area in these directions.

ilation was 2 h on either side of the analysis time. Although the assimilation variables for the conventional wind observations are not directly observed variables (Gao et al., 2012; Huang et al., 2013), the corresponding observation errors are estimated in the default WRFDA table by long-term statistics (Kalnay et al., 1996). The NMC method (Parrish and Derber, 1992) was employed to generate the background error covariance by using past monthly statistics of differences between 24- and 12-h daily forecasts. The lateral boundary conditions for the model forecasts were provided by the NCEP GFS global forecasts. The Kain-Fritsch cumulus parameterization scheme was employed along with the Goddard cloud microphysics scheme, and the Yonsei University (YSU) planetary boundary layer parameterization scheme. Finally, it should be noted that an inherent requirement of the initialization scheme is that the grid spacing must be less than the relocation distance (i.e., subgrid-scale relocations are not resolvable).

4. Results

4.1. *Implementation of relocation*

For idealized conditions, the relocation scheme requires the relocation distance (i.e., 6-h track forecast error) to be large enough to necessitate relocation, while the background flow supports a steady track. Rina, which can be considered a typical major hurricane, formed in the western Caribbean and moved toward the Yucatan Peninsula on 24 October 2011. This was a difficult situation in terms of assimilation and relocation because of sparse observations and the surrounding topography. The first guess contained an inaccurate vortex position of approximately 30 km. In the initial step, the disturbance fields are filtered from the first guess according to Eq. (1) and Eqs. (4)–(7). Following this step, the radial wind magnitude is calculated in 36 directions to determine the edge of the vortex based on the criteria explained in section 2.2. The radial wind magnitude and vortex perturbation

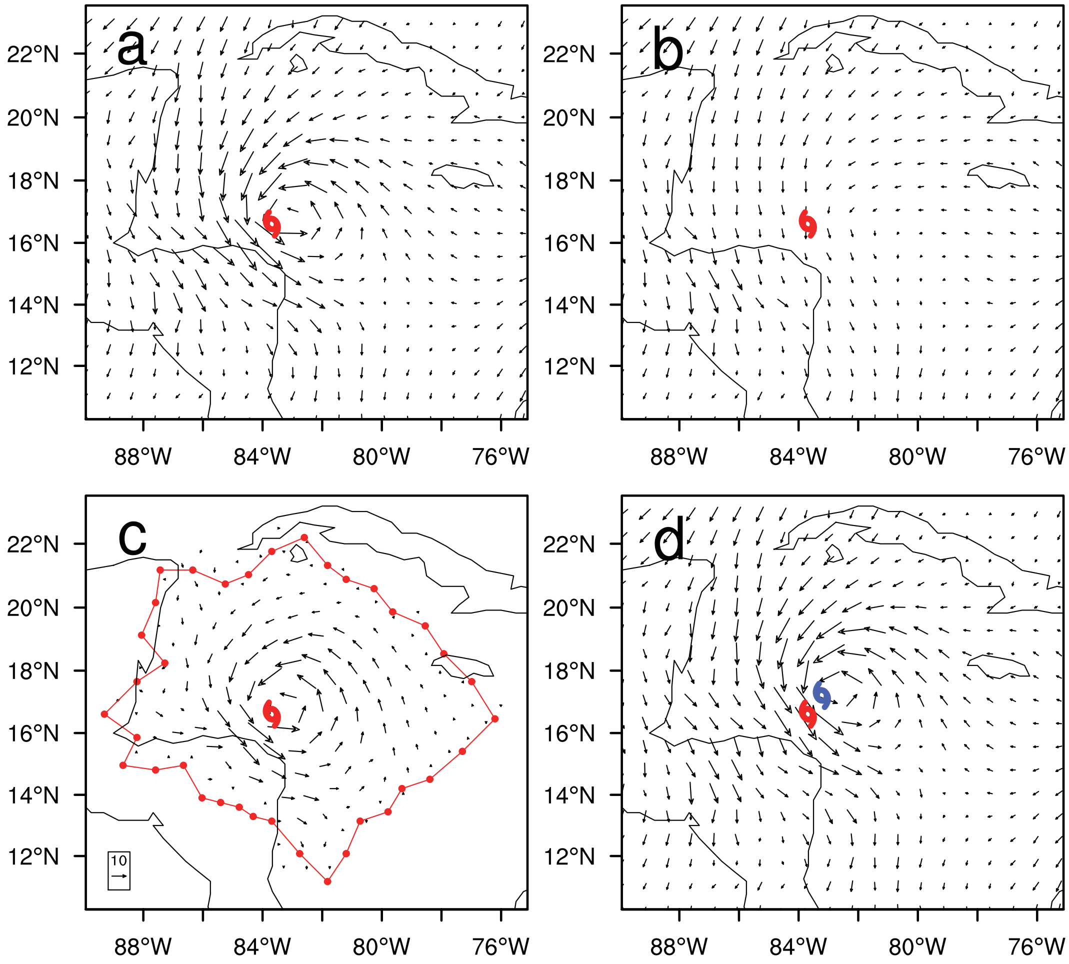

Fig. 3. The 850-hPa wind circulations of hurricane Rina at 0000 UTC 25 October 2011. The red TC marker is the initial track and the blue one in (d) is the relocated track, i.e., the observed TC center. The first guess (a) is split into the environment field (b) and the vortex perturbation field (c); (d) is the total wind field after relocation. Thus, (a) is the input to data assimilation for the conventional forecasts, and (d) is that for the relocation forecasts. The scale of wind vector arrows shown in (c) applies to all panels. The solid circles and lines in (c) are the edges of the vortex in the 36 directions, which surround the relocation area. Outside the red lines, the relocated first guess field is identical to the original first guess.

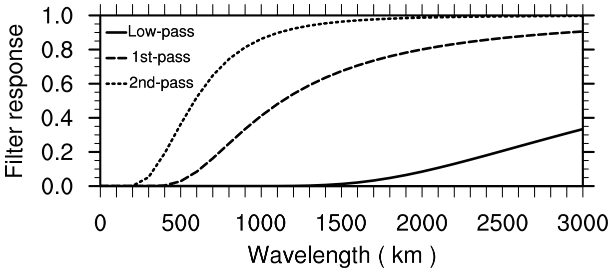

Fig. 4. The response function of low-, first- and second-pass Barnes filtering for separating the temperature, specific humidity and surface pressure disturbance and vortex fields from the first guess.

edges from four of these 36 directions (i.e., 0, 90°, 180° and 270°) are shown in Fig. 2.

At most operational centers (Liu et al., 2000; Hsiao et al., 2010), this case would be rejected for relocation because of the close proximity of the terrain, where the isolated vortex structure could miss key vortex perturbation components due to the friction force interaction. The influence of the terrain on the wind circulation and vortex intensity is evident in the 180° and 270° transects, where the edges are more than 200 km closer to the vortex center when compared to the other directions of 0 and 90° (Fig. 2). To mitigate this situation, the revised GFDL criteria were applied to reduce the risk of missing the vortex perturbation. The following experimental

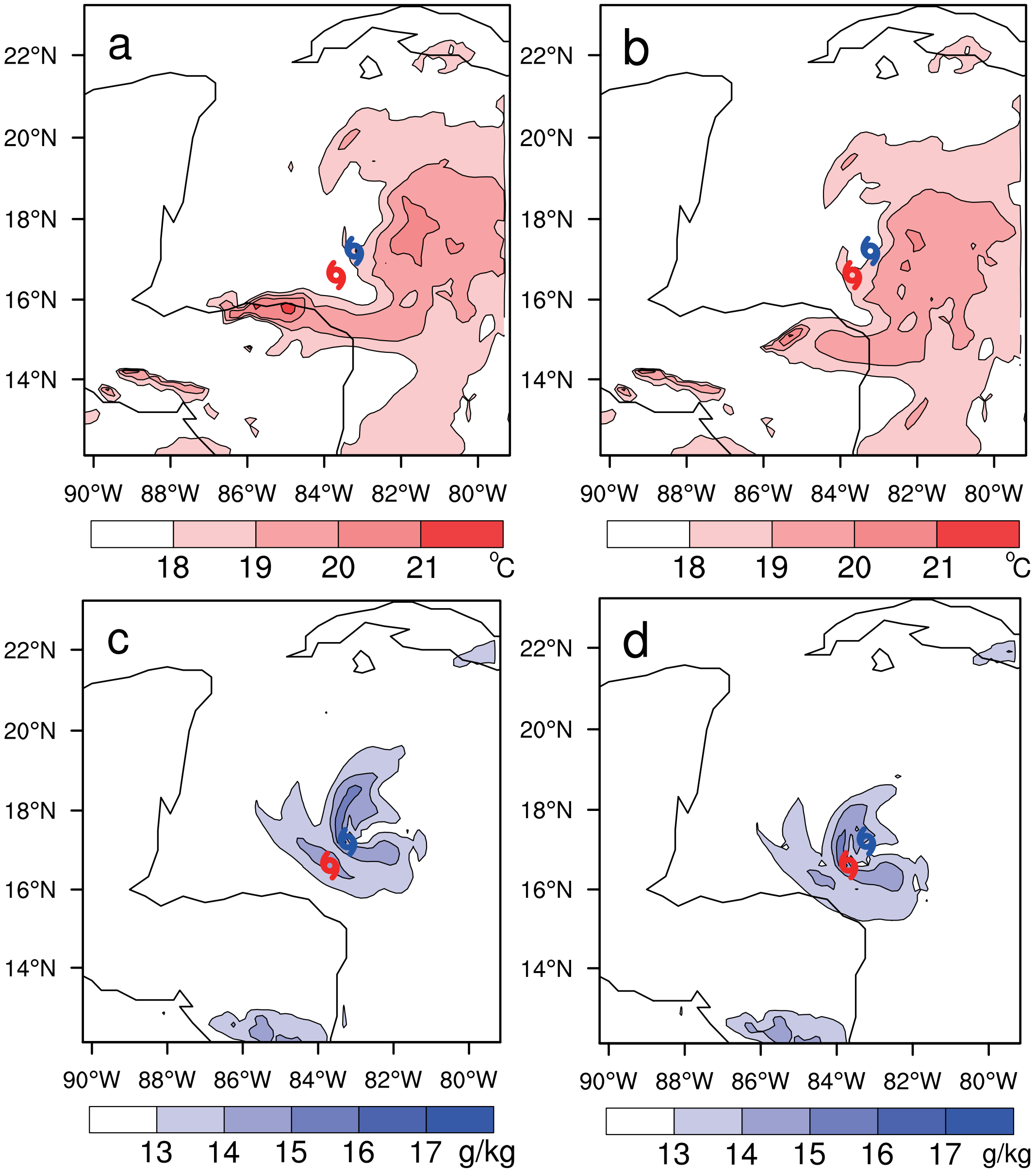

Fig. 5. The 850-hPa temperature (upper) and relative humidity (bottom) field of hurricane Rina at 0000 UTC 25 October 2011. The left column is the relocated first guess, used as the input to data assimilation for the relocation forecasts; the right column is the original first guess. The blue TC marker is the relocated track, i.e., the observed TC center, and the red one is the initial track in the first guess.

results support the hypothesis that the relocation scheme remains effective in its ability to improve the track forecast for these cases.

The 850-hPa vortex circulation of hurricane Rina, valid at 0000 UTC 25 October 2011, is shown in Fig. 3. The first guess (Fig. 3a) is separated into the environment field (Fig. 3b) and vortex perturbation field (Fig. 3c). The solid circles and lines in Fig. 3c are the edges of the vortex along 36 directions, which defines the relocation area. With the exception of the vortex region, the relocated first guess field is identical to the original first guess. The two-pass Barnes filtering produces a smooth transition and diffuse gradient around the edges in the new first guess. Figure 3d contains the first guess with the relocated vortex, which is used in the data assimilation. It is also apparent that, in this initialization scheme, the storm intensity has no visible changes.

For the scalar variables (i.e., temperature, humidity and surface pressure), low-pass Barnes filtering was employed for separating the disturbance field from the first guess, and then the non-vortex perturbations over the vortex circulation domain, as a part of environment field, were filtered out from the disturbance field by two-pass Barnes filtering. The responses of the Barnes filtering of 850-hPa temperature and relative humidity in hurricane Rina are shown in Fig. 4. In order to limit the noise from non-vortex-relative perturbations while still retaining all perturbations relative to the vortex, wavelengths smaller than 1200 km were first removed through the low-pass filtering process. The disturbance field, which includes the vortex perturbation, was the only difference between the first guess and the filtered (basic) field. Whereas, for filtering out the non-vortex perturbations along the edges of the vortex in 36 directions, a two-pass filtering was used by decreasing the coefficient R in Eq. (10), which was able to calculate the localized (by the second-pass filter, which recovers some perturbations with the shorter wavelengths) but relatively smooth (by the first-pass filter) non-vortex perturbations. After this process of removing the non-vortex perturbations is complete, the vortex is relocated to the best track position.

The original and relocated first guess fields of 850-hPa temperature and relative humidity for hurricane Rina, valid at 0000 UTC 25 October 2011, are shown in Fig. 5. The major parts related to the vortex in the first guess were successfully relocated to the observed TC location, especially for specific humidity with a smooth gradient distributed around the topography. Whereas for temperature (Fig. 5a), an extreme heat along the topography was created from the corresponding position in the original first guess. Actually, it is not necessary for the heat center in the original first guess, which could have been influenced by local factors, to be related to the vortex, and therefore should not be relocated. However, further studies are needed to address this kind of problem.

4.2. *Track forecasts*

The conventional 6-h track forecast error from the GFS analysis for Rina, as shown in Table 1, is 30 km. As stated above, the relocation distance is required to be greater than the grid spacing. The background flow supports a parallel motion to the best track (Fig. 6), which suggests that the prediction model could produce a better track forecast if it is provided with an accurate initial location.

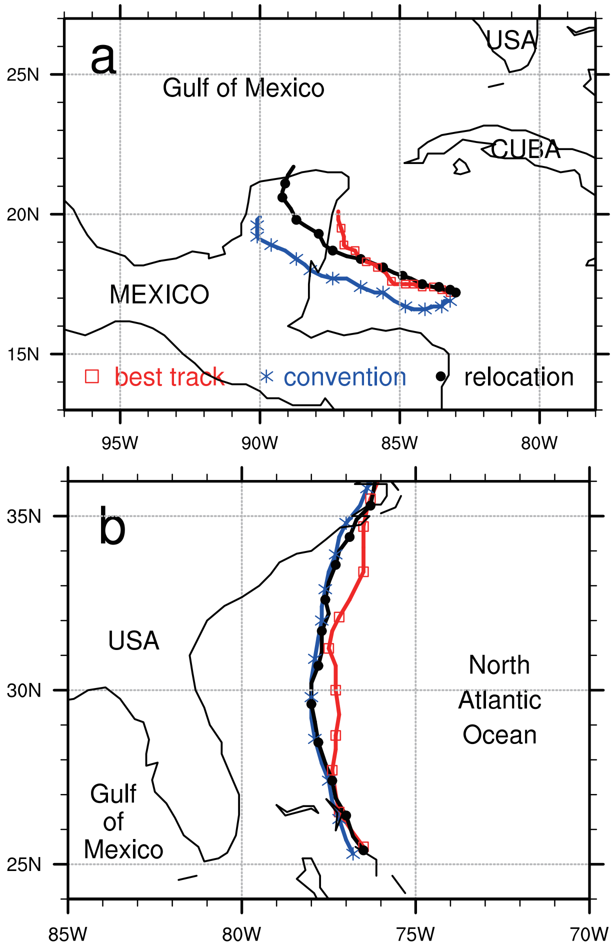

Fig. 6. The 72-h track forecasts from the conventional prediction (blue line, crosses) and the relocation scheme (black line, circles), as well as the best track (red line, squares). The upper panel (a) is initialized at 0000 UTC 25 October 2011 for Rina, where the skill of conventional forecasts is lacking. The bottom one (b) is initialized at 1200 UTC 25 August 2011 for Irene, where conventional forecasts do sufficiently well in terms of the landing position and track.

The 72-h track forecast from the conventional prediction and the relocation scheme, as well as the observed track (i.e., best track) for Rina and Irene are shown in Fig. 6. For Rina, the relocation forecast uses the best track in the first guess, which also provides an accurate location estimate for the following cycle in the operational implementation. This produces an average improvement in track forecast of 58 km (39.46%) over 72 h. The new scheme also improves the track forecast by 25.78% for Irene, which was fairly well forecasted by the conventional method, despite the boundary conditions and background flow causing the tracks to converge in the longer-range forecast.

Although the same dataset and methodology were used, the first guess relocation is closer to the true state of atmosphere, so the defined observation errors will better represent the real errors in the area of observation influence. In this sense, a more accurate relocation has a positive effect on the general data assimilation process. For Rina, the landfall position error was also likely a function of the very sparse observations over this region of Mexico. The forward speed and under-forecasted intensity may have also influenced the track slightly. It is expected that nonconventional data would mitigate this issue (Zhu et al., 2002; Weng et al., 2007), but this is beyond the scope of the present paper.

The track forecasts for Issac, which use the full-cycling operational configuration, are shown in Fig. 7. The first cycle is initialized at 0000 UTC 27 August 2012. The first guess for the first cycle, initialized at 1800 UTC 26 August, has the same vortex center grid point as the best track (Table 1; 0 km relocation distance), so that the initialization scheme will not run. This means that, for the second cycle, the relocation distance is the 12-h forecast track error from the 1800 UTC 26 August cycle. For this reason, the relocation distance of 54 km is much larger than those at any other cycle times (Table 1).

Although the relocation distance is large, the forecast from the new scheme appears to follow the conventional scheme (Fig. 7a). Forecasts pointing to the best track at the initial stage are responsible for this. Furthermore, it is also likely that the relocation scheme does not alter the upstream steering flow. However, the 6-h track forecast error at every cycle step is accumulated for the next cycle (Figs. 7b–d). Despite continuing to compound each cycle through data assimilation, the conventional forecasts are not able to revise the analysis track to the best track by the impacts of observations only.

The improvement in the track forecast corresponding to Fig. 7 are shown in Fig. 8, where the forecast errors from the

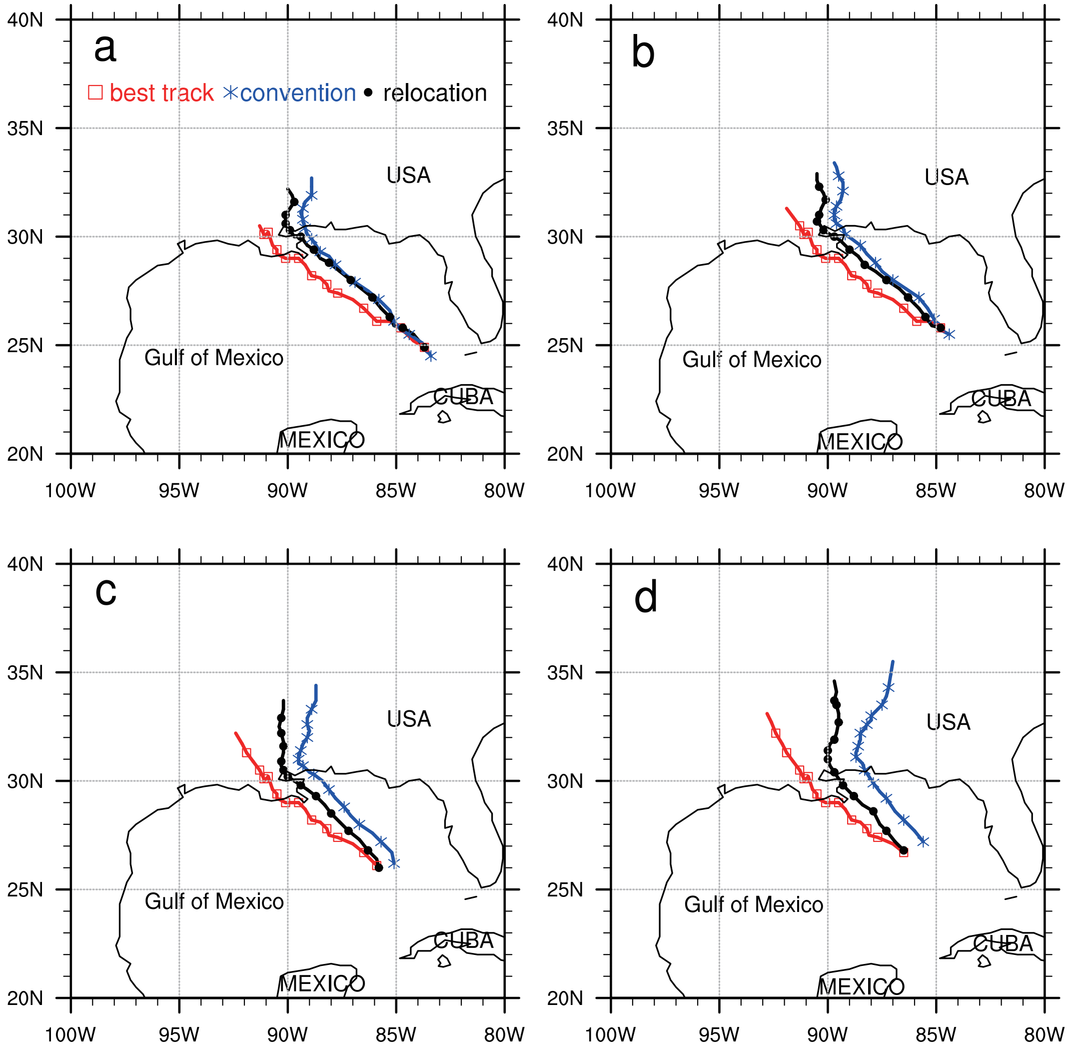

Fig. 7. The real-time full-cycle 72-h track forecast from the conventional prediction (blue line, crosses) and the relocation scheme (black line, circles), as well as the best track (red line, squares) for Isaac. The panel (a) is initialized at 0600 UTC 27 August 2012 as the second cycle. Panels (b)–(d) represent the other three cycles with 6-h intervals until 0000 UTC 28 August 2012.

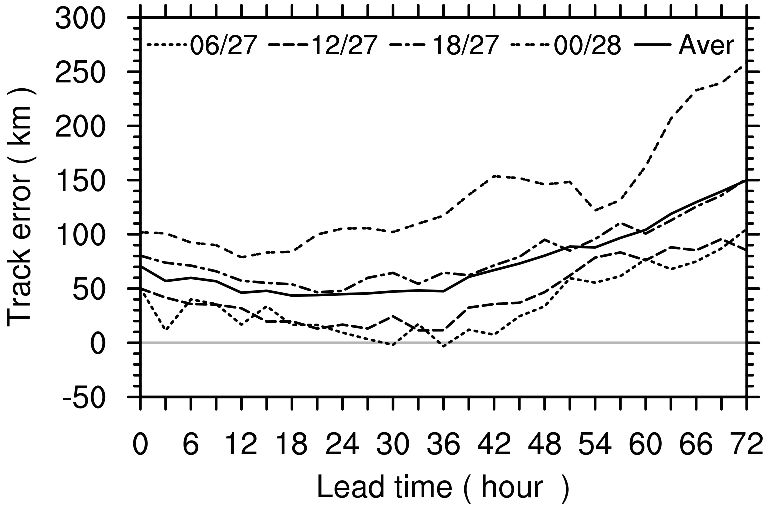

Fig. 8. The improvement of 72-h track forecast errors for Isaac corresponding to Fig. 7, calculated by subtracting the track error in the new scheme from that in the conventional forecast. The initialization times in the format (UTC HH/DD) are indicated. The solid line (Aver) is the average improvement from the four cycles.

relocation scheme for hurricane Isaac are subtracted from the conventional forecast errors. Since the error is not fully compounded with each cycle, as stated above for the conventional method, the improvements by relocation increase with each cycle step from 28.23% to 49.08%. The average improvement before 36 h is around 50 km, after which the improvement increases significantly. However, given the study only used operational Global Telecommunication System (GTS) data for assimilation, caution is warranted when extrapolating these significant improvements to real operational applications where some types of nonconventional observations are generally employed.

5. Conclusions and outlook

Accurate track forecasting of TCs is one of the most important aspects of providing early warning for this type of public disaster. It is crucial for TC prediction to precisely represent the initial conditions, including location, because large track forecast sensitivities exist around the vortex center (Wang et al., 2011). Despite the initial inaccuracy of the TC center, the first guess models the real-time circulation surrounding the vortex, which plays an important role in the development and motion of the system. For this reason, an initialization scheme by vortex relocation was developed.

We tested three typical TC cases in the 2011–12 hurricane season to assess the scheme within the WRF and WRFDA. The initialization scheme considers any stage of the TC. The calculated vortex perturbation area is irregular in a specific pattern depending on the real-time wind circulation, which enables the ability to filter out an accurate vortex relative to the real-time developing TC system. In order to deal with the boundary transition of the vortex, the filter function is used along the edge computation, while the field outside the main vortex is left unaltered. This action allows for better stability in the new first guess because it produces a smooth gradient at the edges.

The vortex in the first guess being relocated to the observed position can also provide a more accurate first guess (6-h forecast) for the following cycle. This has the added benefit of enabling better data assimilation of observations in the vicinity of the storm, but unrelated to the observed vortex position. The information accumulated over each cycle helps the new scheme improve track forecasts significantly. However, the track forecast is still subject to the limitations of the background flow and boundary conditions. As demonstrated in the full-cycle runs for Isaac, the relocation distance increases with the number of cycles, and the landing positions are similar, which, in this case, suggested that the upstream steering current became a dominate factor later in the forecast period. The assimilation of additional observations, especially nonconventional observation types with better representativeness, should improve the environmental flow and the core intensity. This initialization scheme focuses on refining the position accuracy of the vortex center and the stability of the variable fields. Subsequent work will look at merging the relocation scheme with an intensity-fitting scheme, and will be tested in the operational configuration.

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