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Performance of the experimental HWRF in the 2008 Hurricane Season

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Abstract In response to the needs of improving hurricane forecasts, we have built an experimental version of the operational Hurricane Weather Research and Forecasting Model (HWRF), which is based on the Weather Research and Forecasting Nonhydrostatic Mesoscale Model of the National Oceanic and Atmospheric Administration (NOAA). The experimental HWRF (HWRFx) is adopted to study the intensity change problem at the highest possible resolutions with the existing computing facility, using moving nests to focus the model resolution in the vicinity of the storms. Although this is at an early stage of development, results from real-time experiments in the 2008 hurricane season show that the HWRFx is generally comparable to the NOAA operational models, in terms of the accuracy of both track and intensity forecasts. The HWRFx, however, has a negative bias in the intensity forecasts as opposed to the positive biases of the NOAA operational models. We present in this article a brief description of the HWRFx and its performance during the 2008 hurricane season in comparison with the NOAA operational models.

Keywords Hurricane modeling · Tropical cyclone · 2008 Hurricane Season · HWRF · HWRFx · WRF · NMM · NOAA · EMC · AOML · ESRL · HFIP · GFS · GFDL · Vortex initialization

1 Introduction

Atlantic hurricanes typically originate from the eastern tropical Atlantic Ocean, intensify as they propagate westward over warm sea surfaces, and dissipate as they make landfall. They are difficult to predict because of their complicated and dramatically evolving nature

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associated with the interaction of their fine-scale structure and the large-scale environment, among many other factors.

In response to the needs of improving hurricane forecasts and warnings, the National Oceanic and Atmospheric Administration (NOAA) has initiated the Hurricane Forecast Improvement Project (HFIP) with the goal to reduce both track and intensity errors by 50% in 10 years. The NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) has been actively participating in the HFIP by conducting field experiments with aircraft and by building an experimental version of the Hurricane Weather Research and Forecasting Model (HWRF, Bernardet 2010) for hurricane modeling and data assimilation, in collaboration with the NOAA Earth System Research Laboratory (ESRL) and the NOAA Environmental Modeling Center (EMC).

We present in this article a brief description of the experimental HWRF (HWRFx) and its performance during the 2008 hurricane season. The HWRFx is compared to the NOAA operational models, including the HWRF modeling system and the Global Forecast System (GFS, http://www.emc.ncep.noaa.gov/gmb/moorthi/gam.html) developed at NOAA EMC, and the hurricane model originally developed by Kurihara et al. (1998) at the NOAA Geophysical Fluid Dynamics Laboratory (GFDL) and recently upgraded by Bender et al. (2007). Although this is at an early stage of development, it is encouraging that the performance of the HWRFx is comparable to those of the operational models in terms of the accuracy of both track and intensity forecasts. In particular, we illustrate the characteristics of the HWRFx with its forecasts for Ike and Gustav—the two strongest Atlantic hurricanes in 2008, which also struck the United States and caused severe damage. These evaluations provide guidance for the future development of the HWRFx.

2 The experimental HWRF (HWRFx)

Both the HWRF and the HWRFx are regional modeling systems based on the Weather Research and Forecasting (WRF) Nonhydrostatic Mesoscale Model (NMM) with the same model dynamics for frictionless and adiabatic motion (Janjic et al. 2001). We develop and test new techniques with the HWRFx and evaluate their potential to improve hurricane forecasts, before they are formally adopted for operation with the HWRF. Figure 1 shows the modeling framework of the HWRFx, where vortex initialization, data assimilation, and the ocean model are important for hurricane forecasts, but not yet functioning in this early stage of development. Products from other sources are used in place of the missing components for numerical experiments in the 2008 hurricane season. The results presented in this article are thus preliminary and serve as a baseline for further improvement.

As track forecasts are largely determined by the large-scale environment flows provided by the global models that drive the regional models, the development of the HWRFx is focused on improving intensity forecasts with the highest possible model resolutions, under the circumstances that track forecasts be also consistently improved with increasing resolutions. Our strategy is to effectively use available computing power with moving nests that enhance the model resolution in the vicinity of the storms. Figure 2 shows an example of the HWRFx domain configuration used in the 2008 hurricane season, where the outer domain is about $60° \times 60°$ at 27-km resolution, and the inner domain is about $9° \times 9°$ at 9-km resolution. The outer domain is fixed during each forecast, but the inner domain moves with the storm, and is embedded in the outer domain with two-way interaction (Gopalakrishnan 2006).

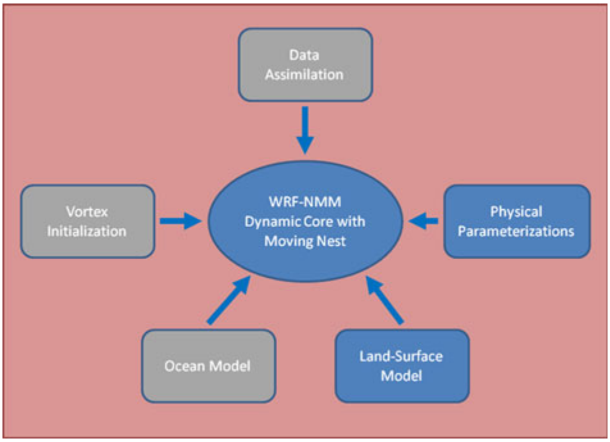


Fig. 1 HWRFx modeling framework. The components in gray are under development but not yet functioning for the results presented in this article

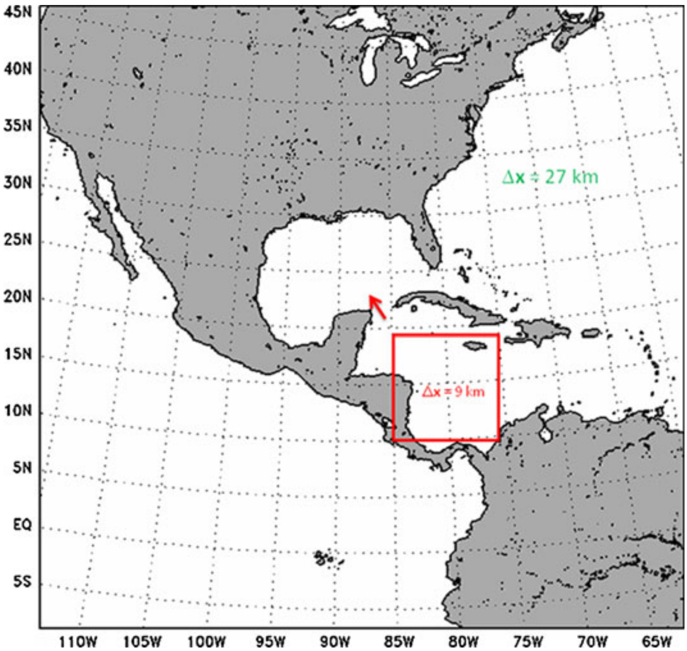


Fig. 2 An example of the HWRFx domain configuration for the 2008 hurricane season. The outer domain is about 60° × 60° at 27-km resolution, and the moving inner domain (red box) is about 9° × 9° at 9-km resolution

Table 1 summarizes the domain configurations of the hurricane models to be compared with. Note that both the HWRFx and the HWRF use rotated latitude-longitude (lat-lon) grids that have the grid points aligned with the rotated spherical coordinates but not with the Earth coordinates, as illustrated in Fig. 2. The GFDL model has three domains with the

Table 1 Domain configurations for the 2008 hurricane season

Domain configuration	HWRFx	HWRF	GFDL
Outer domain dimension	$60° \times 60°$	$75° \times 75°$	$75° \times 75°$
Outer domain resolution	27 km	27 km	55 km
Intermediate domain dimension	(N/A)	(N/A)	$11° \times 11°$
Intermediate domain resolution	(N/A)	(N/A)	18 km
Inner domain dimension	$9° \times 9°$	$6° \times 6°$	$5° \times 5°$
Inner domain resolution	9 km	9 km	9 km

The dimensions refer to the rotated lat-lon grids used in HWRFx and HWRF, but the regular lat-lon grid for the GFDL model. The resolutions are approximated in km for convenience

grid points aligned with the Earth coordinates, and the smaller domains are moving within the next larger domains. The domain dimensions shown in Table 1 refer to the types of grid used in the corresponding models, and the resolutions are described in units of km approximately. The GFS has a global domain with approximately 35-km resolution in the forecast region (until the recent 2010 upgrade).

As the HWRF vortex initialization (Liu 2006) was still under development in 2008, we have adopted GFDL initial conditions (Kurihara et al. 1993, 1995) for HWRFx forecasts during the 2008 hurricane season. The GFDL initial conditions are constructed with an axisymmetric version of the GFDL hurricane model to emphasize the dynamical consistency, so as to avoid the false spinup problem that often leads to deficiency in intensity forecast and sometimes significant error in track forecast (Kurihara et al. 1993). Our experiments in 2008 are, however, intended for testing the impact of GFDL initial conditions on dynamical consistency without reproducing them, while investigating the possibility of obtaining reasonably accurate forecasts with various types of physical forcing.

Based on the WRF-NMM dynamic core and the GFDL initial conditions, we have adopted the scheme proposed by Ferrier et al. (2002) to provide the latent heating due to the resolvable-scale microphysical processes in the atmosphere and the Arakawa and Schubert scheme (1974) simplified by Hong and Pan (1998) to parameterize subgrid cumulus-cloud activity. The effect of solar radiation on the atmosphere is approximated with the Dudhia scheme (1989), and the radiative transfer within the atmosphere is emulated with the method of Mlawer et al. (1997). The forcing at the lower boundary of the atmosphere over land surfaces is provided with the "Noah" land-surface model (Ek et al. 2003), and the forcing over sea surfaces is provided with the sea-surface temperatures (SSTs) of the GFS analysis at 1° resolution, which are prescribed at the beginning of each forecast and are kept constant throughout the forecast. In addition, we enhance the forcing at the lower boundary of the atmosphere with the surface scheme of Moon et al. (2007) and parameterize the mixing in the planetary boundary layer with the scheme of Hong and Pan (1996). Table 2 summarizes the physical parameterizations used in the models being compared. Unlike the HWRFx, the HWRF and GFDL models employ the short-wave radiation of Lacis and Hansen (1974) and the long-wave-radiation of Schwarzkopf and Fels (1991), and they are coupled to the land-surface model of Tuleya (1994) and the ocean model of Bender (2000). On the other hand, the GFS employs the short-wave radiation of Hou (2002), the long-wave-radiation of Zhao and Carr (1997), and the surface-layer parameterization of Sirutis and Miyakoda (1990) with the modification of Zeng et al. (1998).

Table 2 Physical parameterizations of the models used in the 2008 hurricane season

Physics	HWRFx	HWRF/GFDL	GFS
SW radiation	Dudhia (1989)	Lacis and Hansen (1974)	Hou (2002)
LW radiation	Mlawer et al. (1997)	Schwarzkopf and Fels (1991)	Mlawer et al. (1997)
Microphysics	Ferrier et al. (2002)	Ferrier et al. (2002)	Zhao and Carr (1997)
Convection	Hong and Pan (1998)	Hong and Pan (1998)	Hong and Pan (1998)
Boundary layer	Hong and Pan (1996)	Hong and Pan (1996)	Hong and Pan (1996)
Surface layer	Moon et al. (2007)	Moon et al. (2007)	Sirutis and Miyakoda (1990), Zeng et al. (1998)
Land surface	Ek et al. (2003)	Tuleya (1994)	Ek et al. (2003)
Ocean surface	GFS SST analysis	Bender (2000)	GFS SST analysis

SW short-wave, *LW* long-wave

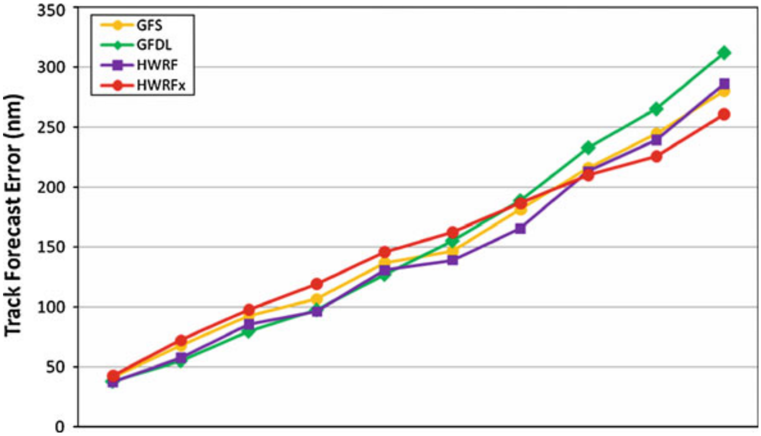
3 Model Performance in the 2008 Hurricane Season

The 2008 hurricane season was very active with 16 named storms (sustained wind ≥35 kt), including five major hurricanes of Category 3 or higher (sustained wind ≥96 kt), according to the best-track information provided by the National Hurricane Center (NHC). Due to limited resources, we only forecasted about 20% of the operational cases, with priority for storms that had the potential to make landfall in the United States. Each forecast was initiated with the operational GFDL initial condition at 1/6° resolution and was run for a 5-day period, during which the lateral boundary condition of the outer domain was updated with the operational GFDL forecast data at 1/6° resolution every 6 h, and the boundary of the inner domain was provided by the outer domain. We evaluate the track and intensity forecast errors against the NHC best tracks.

Figure 3 shows the average track forecast errors of the HWRFx (red), the HWRF (purple), the GFDL (green), and the GFS (yellow) models. We see that the HWRFx track forecasts are generally comparable to those of the operational models. It should be noted that these track errors are evaluated with very limited numbers of cases that may lead to certain degree of bias due to sampling issues. A more general report on the performance of the operational models for the 2008 Atlantic tropical cyclones (Tuleya 2008) reveals that both the HWRF and the GFDL models perform substantially better than for the selected cases shown in Fig. 3. For example, the HWRF has an average 120-h track error of only 250 nm for the first ten 2008 Atlantic tropical cyclones (130 cases), as opposed to 286 nm for the 20 cases shown here.

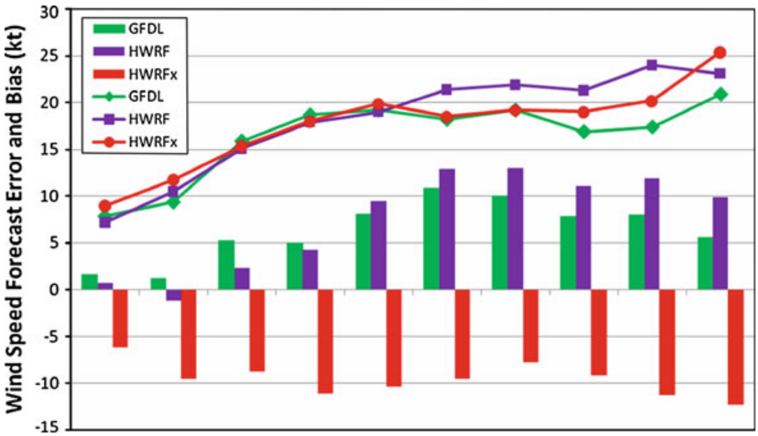
From Fig. 3, we also note that the enhanced resolution of the regional models does not lead to very much improvement on the track forecasts over the GFS model, which has a relatively low resolution. This is probably due to the common low-resolution large-scale environment flows shared by these models, as hurricane tracks are largely determined by the large-scale environment flows that drive the movement of hurricane vortices. Both the GFDL and HWRF initial conditions are based on the GFS analysis except with different types of vortex construction, and both the GFDL and HWRF forecasts are driven by the GFS lateral boundary conditions, while the HWRFx has used the same GFDL initial conditions and has been driven by the GFDL lateral boundary conditions.

Figure 4 summarizes the intensity forecasts of the HWRFx (red), the HWRF (purple), and the GFDL (green) models, all from the inner domain at 9-km resolution—the GFS is



Time	12 h	24 h	36 h	48 h	60 h	72 h	84 h	96 h	108 h	120 h
GFS	41.6	68.4	93.2	107.1	137.3	147.1	181.3	216.2	244.9	280.4
GFDL	38.1	55.3	80.0	97.9	127.5	155.6	188.6	232.9	265.3	312.3
HWRF	37.5	57.8	85.8	96.6	131.0	139.3	165.5	213.0	239.1	286.2
HWRFx	42.6	72.4	98.2	119.6	146.3	162.6	186.3	210.0	225.5	260.9
Cases	57	51	46	40	38	32	29	25	21	20

Fig. 3 2008 hurricane track forecast errors (nm) of GFS, GFDL, HWRF, and HWRFx, which are averages of the numbers of cases shown in the last row



Time	12 h	24 h	36 h	48 h	60 h	72 h	84 h	96 h	108 h	120 h
GFDL	7.9/1.6	9.4/1.2	15.9/5.2	18.7/5.0	19.2/8.1	18.2/10.9	19.2/10.0	16.9/7.8	17.4/8.0	20.9/5.6
HWRF	7.2/0.7	10.5/-1.2	15.1/2.3	17.9/4.3	19.0/9.5	21.4/12.9	21.9/13.0	21.3/11.1	24.0/11.9	23.1/9.9
HWRFx	9.0/-6.2	11.8/-9.5	15.4/-8.8	18.0/-11.1	19.9/-10.4	18.5/-9.5	19.2/-7.8	19.0/-9.2	20.2/-11.3	25.4/-12.3
Cases	62	57	52	46	43	37	33	30	27	24

Fig. 4 2008 hurricane 10-m wind speed forecast errors (*curves*) and biases (*bars*) of GFDL, HWRF, and HWRFx, which are averages of the numbers of cases in the last row. The error values are also shown in the table with the first number in each box of rows 2–4 referring to the absolute error (kt) and the second referring to the bias (kt)

not compared here, as wind speed forecasts are sensitive to the model resolution. We see that the absolute errors of the HWRFx forecasts for the wind speed at 10-m height are of the same order of magnitude as those of the GFDL and HWRF forecasts, but the HWRFx has an average negative bias as opposed to the positive biases of the operational models. Unlike the operational models, the HWRFx bias is prominent from the beginning of the forecast and remains in the same order of magnitude throughout the entire forecast period. Further experiments with the HWRF initial conditions (to be shown in a subsequent paper) indicate that the negative bias of the HWRFx using GFDL initial conditions is due to the inconsistency between the two model's dynamics.

To be more specific about the HWRFx performance, we examine its forecasts for Gustav and Ike—the two strongest hurricanes (Category 4) that made the landfall in the US in 2008. Figure 5 shows the HWRFx forecasts for Hurricane Gustav initiated at 00Z August 27–30. The 8/27 (Fig. 5a) and 8/28 (Fig. 5b) cases appear to be relatively more difficult for the HWRFx in track prediction, compared to the 8/29 (Fig. 5c) and 8/30

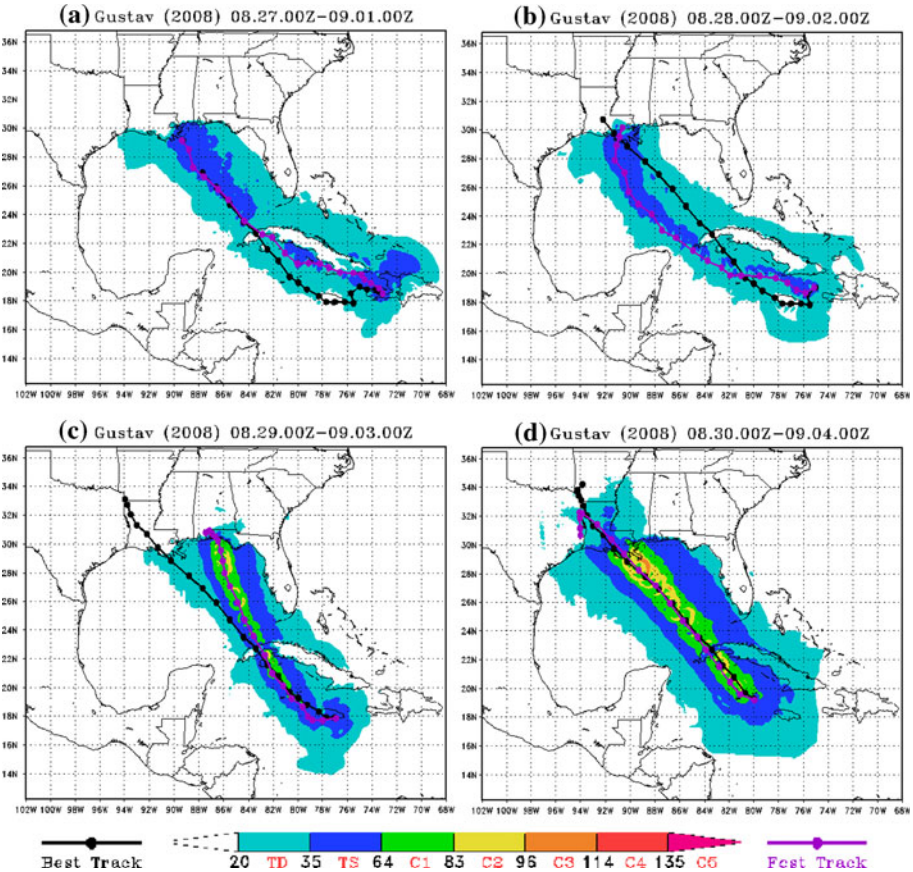


Fig. 5 HWRFx forecasts for Hurricane Gustav initiated at 00Z August 27–30, 2008. The observed best tracks (*black circles*) and the model-forecasted tracks (*purple circles*) are depicted every 6 h. *Color shades* illustrate intensity forecasts with 10-m wind swaths in terms of Tropical Depression (TD), Tropical Storm (TS), and Hurricane Category 1–5 (C1–C5) as defined by the wind speed (kt) shown on the color bar in the Saffir-Simpson scale

(Fig. 5d) cases, for short-range forecast periods. This may be associated with the fact that the storm was relatively disorganized on August 27–28, and it was in close proximity to the steep terrain in the Hispaniola, southeastern Cuba, and Jamaica. After the storm makes landfall, the model tracks seem to struggle with terrain interaction (Fig. 5c, d), revealing possible deficiency in the model's storm tracker or in the application of the land-surface model in the continental US. Figure 5 also illustrates the intensity forecasts with 10-m wind swaths (maximum local winds), which are generally underestimated for this case (not shown), consistent with what is shown for all cases in Fig. 4.

Figure 6 shows the HWRFx forecasts for Hurricane Ike initiated at 00Z September 8–11. The HWRFx predicted the tracks quite well for the 9/08 (Fig. 6a) and 9/11 (Fig. 6d) cases, but not for the 9/09 (Fig. 6b) and 9/10 (Fig. 6c) cases, which are two extreme cases where the HWRFx shows significant track errors. Although the dynamical inconsistency due to the initial conditions can sometimes lead to significant track errors (Kurihara et al. 1993), it does not seem so for the 9/09 and 9/10 cases, as the HWRFx tracks have matched the best tracks quite well in the first 48 h of forecast. A more likely cause of the significant track errors is perhaps the misrepresentation of the large-scale environment when the storm was in central Gulf of Mexico. Figure 7 shows the GFS analysis and the HWRFx forecast

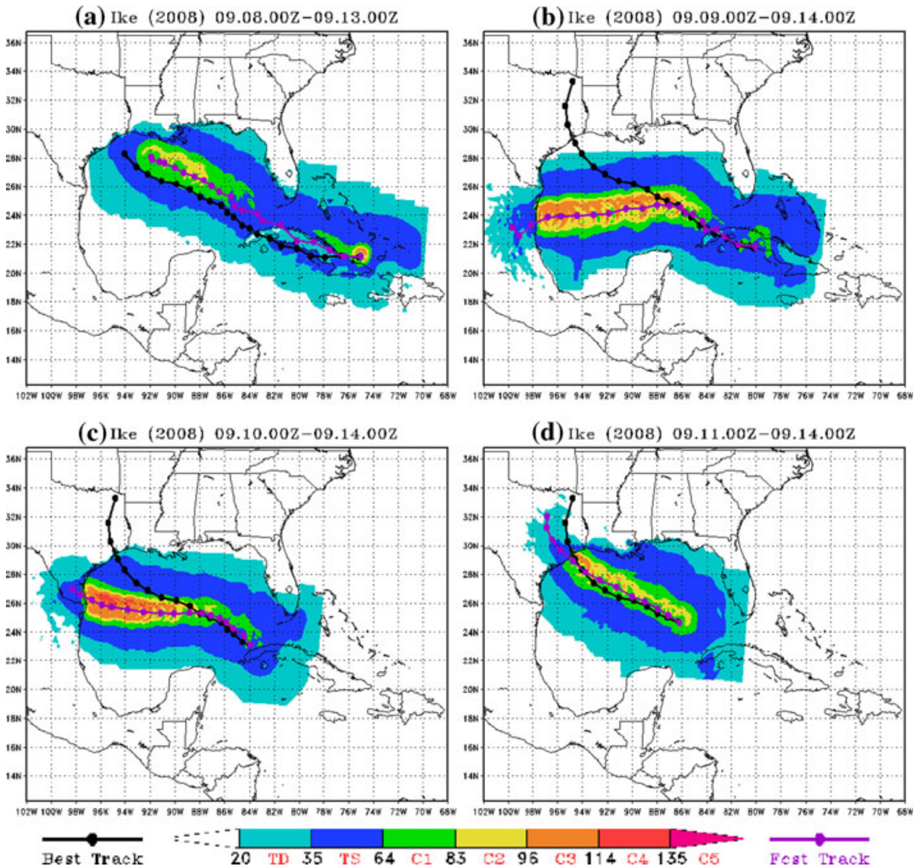


Fig. 6 As in Fig. 5 but for Hurricane Ike initiated at 00Z September 8–11, 2008

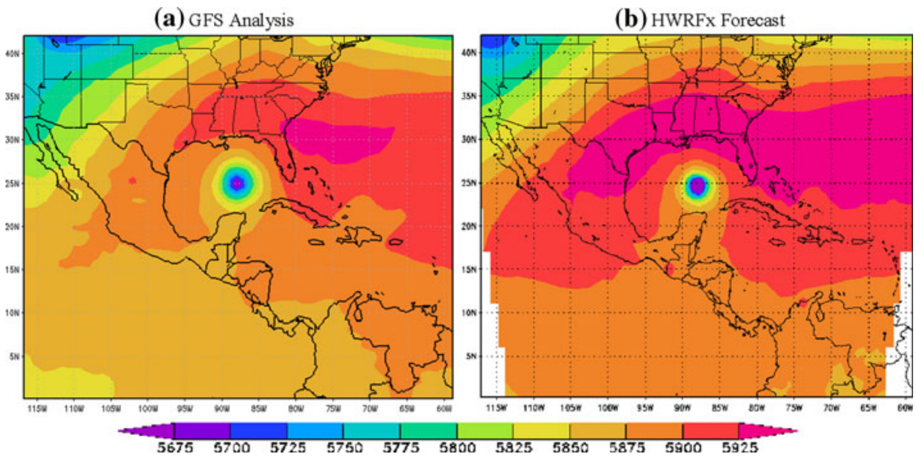


Fig. 7 500-mb height (m) of Hurricane Ike valid at 12Z September 11, 2008, when the HWRFx model track started to diverge from the best track in the 9/09 case (Fig. 6b). Both the GFS analysis (**a**) and the HWRFx 60-h forecast within the outer domain (**b**) are shown at 1° resolution

for the 500-mb height of Hurricane Ike valid at 12Z September 11, when the model track started to diverge from the best track in the 9/09 case (Fig. 6b). Compared to the GFS analysis (Fig. 7a), the ridge over the U.S. Great Plains is too strong and too far to the west in the HWRFx forecast (Fig. 7b), leading to a southward deflection of the model track to the left of the best track (Fig. 6b). The HWRFx model ridge continues to grow in the next 12 h (not shown) and remains strong and too far west throughout the rest of the forecast period, amplifying the westward track bias for the remainder of the forecast. We have also observed a similar situation for the 9/10 case, but not for the 9/08 and 9/11 cases.

Standard track and intensity forecast verifications are often considered separately, such a practice can be very misleading sometimes. Taking the 9/09 case (Fig. 6b) for example, the HWRFx has a very good intensity forecast verification, but a very bad track forecast. According to the model scenario, the HWRFx predicted the landfall of a Category-3 hurricane in northeastern Mexico although the landfall actually occurred in Galveston, Texas, at 06Z September 13. This shows that a good intensity forecast at a wrong location contributes negatively to the forecast skill, and the track-intensity correlation is an important factor for hurricane model evaluation.

4 Summary and future development

During the transition of NOAA's operation for hurricane forecasting from the GFDL model to the HWRF in 2008, we have tested the impact of GFDL initial conditions on the HWRFx, which is an experimental version of the HWRF with the same model dynamics but somewhat different model physics. Results from real-time experiments show that the HWRFx is generally comparable to both GFDL and HWRF in terms of the accuracy in both track and intensity forecasts, but the HWRFx has a negative bias as opposed to the positive biases of GFDL and HWRF, due to the inconsistency between the GFDL initial conditions and HWRFx model dynamics.

We have found that the enhanced resolution of the regional models does not result in very much improvement on the track forecasts over the GFS, perhaps due to the common low-resolution environment flows from the GFS. It is desirable to test whether the use of the HWRF initial conditions would improve the HWRFx track forecast in the early stage, and how the HWRF initial conditions would impact the intensity forecast together with ocean model coupling. We have also found it necessary to extend the scope of hurricane model evaluation with more metrics, such as the track–intensity correlation.

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