SUPPLEMENT

PREDICTING HURRICANE INTENSITY AND ASSOCIATED HAZARDS

A Five-Year Real-Time Forecast Experiment with Assimilation of Airborne Doppler-Radar Observations

BY FUQING ZHANG AND YONGHUI WENG

This document is a supplement to "Predicting Hurricane Intensity and Associated Hazards: A Five-Year Real-Time Forecast Experiment with Assimilation of Airborne Doppler-Radar Observations," by Fuqing Zhang and Yonghui Weng (*Bull. Amer. Meteor. Soc.*, **96,** 25–33) • ©2015 American Meteorological Society • *Corresponding author:* Fuqing Zhang, Department of Meteorology, Pennsylvania State University, University Park, PA 16801 • E-mail: fzhang@psu.edu • DOI: 10.1175/BAMS-D-13-00231.2

CONFIGURATIONS OF THE WRF-ENKF HURRICANE ANALYSIS AND FORECAST SYSTEM. The prototype ensemble analysis and prediction WRF-EnKF system developed for this study follows closely that of Zhang et al. (2011), but with an increase in model spatial resolution (the grid spacing of the innermost domain is decreased from 4.5 km to 3 km, and the vertical levels are increased from 35 to 44), an update of the WRF model to the newest 3.4.1 version, and an improved model physics for air–sea flux parameterizations (from using the default Option 0 to an empirical configuration that blends Options 0 and 2). As an example, the initial domain configuration for the first P3 mission into Hurricane Sandy (around 0000 UTC 26 October 2012) is shown in Fig. ES1.

More details on the model physics schemes used: The Grell-Devenyi cumulus parameterization scheme is used in D1 only, while all three domains use the WSM 6-class graupel microphysics scheme. The YSU planetary boundary layer (PBL) scheme with Monin-Obukov surface layer scheme is used. The Rapid Radiative Transfer Model (RRTM) scheme is used for short-wave radiations, while the Duhdia scheme is used for long-wave radiations.

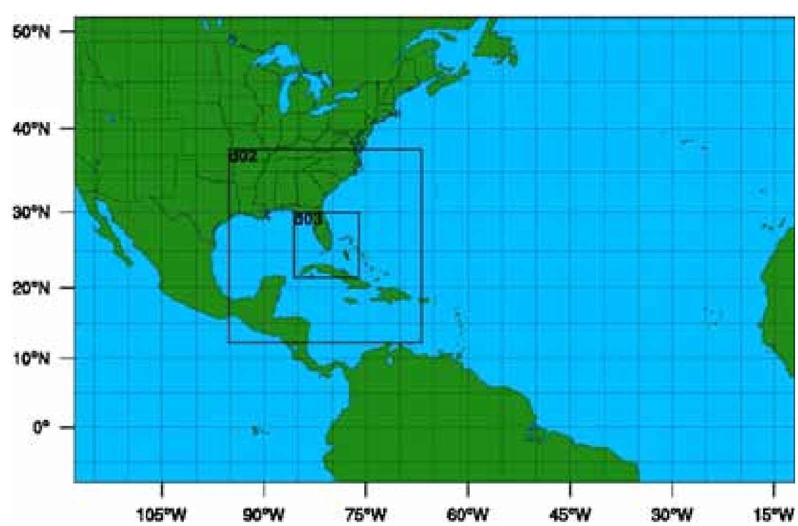

FIG. ES1. A sample model domain configuration that was used for Hurricane Sandy (2012), initialized at 1200 UTC 25 Oct 2012. D1 is fixed for all storms while D2 and D3 are vortex-following domains that move with the storm center of the case in study or forecast.

Table ES1. List of the names of all storms along with the number of applicable airborne P3 Doppler mission cases for each storm for each year.

Year	Cases	Storm (cases)
2008	35	Dolly (6), Fay (6), Gustav (6), Ike (6), Kyle (8), Paloma(3)
2009	10	Ana (1), Claudette (4), Danny (5)
2010	25	Alex (1), Two (3), Earl (11), Karl (4), Gaston (1), Tomas (5)
2011	13	Irene (7), Lee (1), Ophelia (1), Rina (4)
2012	19	Isaac (9), Leslie (3), Sandy (7)
Total	102	22 storms

Except for using an increased ensemble size (from 30 to 60 members), the EnKF configuration for the current study is the same as that used in Zhang et al. (2011). Most notably, the covariance relaxation method of Zhang et al. (2004) is used for preventing filter divergence with a relaxation coefficient of 0.6 while the successive covariance localization (SCL) with successive radius of influence of 1215, 405, and 135 km are used for different batches of super-observations (SOs).

Our five-year experimental study focuses exclusively on the added value of assimilating airborne Doppler observations, while ongoing research further explores the impacts of ingesting other in situ or remotely sensed inner-core data from reconnaissance aircraft and/or satellites. The ensemble is initialized by the NOAA Global Forecast System (GFS) operational analysis 6–12 h before a scheduled airborne Doppler mission, and uses the corresponding GFS operational forecast for its boundary conditions. Generation of the initial and boundary perturbations for the ensemble are the same as in Weng and Zhang (2012). For example, if the airborne observations are to be taken between 2130 and 2330 UTC, the WRF ensemble will be initialized at 1200 UTC based on the 1200 UTC GFS analysis, and the cycled EnKF assimilation will be performed at 2200 and 2300 UTC, respectively. The EnKF analysis at 2300 UTC will then be integrated to 0000 UTC of the next day, and GFS forecasts at this time will be used to update the boundary conditions. Then the subsequent 126-h single deterministic WRF forecast will be performed using the next-day 0000 UTC GFS forecasts as the boundary conditions.

The GFS operational analysis and forecasts are freely available and archived at NOAA: http://rda.ucar.edu/datasets/ds335.0/.

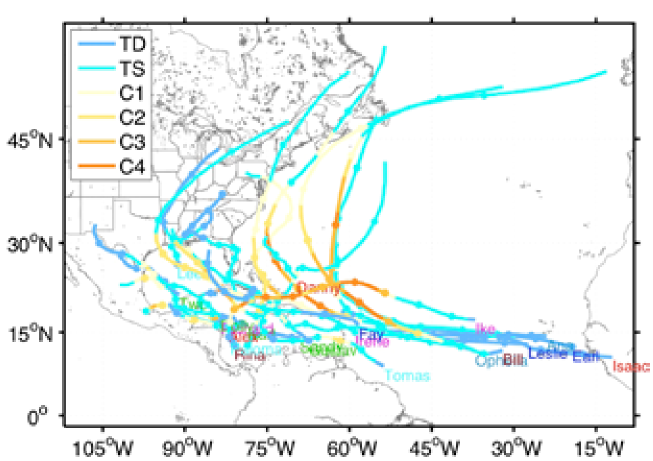

Fig. ES2. Intensity-coded tracks of all Atlantic tropical cyclones that had applicable airborne Doppler missions during 2008–12. TD stands for tropical depression, TS for tropical storm, and C1-C4 for Category 1 to Category 4 hurricanes (no Category 5 hurricane during 2008–12). The dot indicates the 0000 UTC position.

DOPPLER OBSERVATIONS, DATA THINNING AND QUALITY CONTROL. Our experimental forecasts span a total of 102 applicable airborne Doppler missions with the NOAA P3 reconnaissance planes for 22 storms from 2008 through 2012, which include the PSU experimental real-time prediction for 2012 as part of the HFIP demonstration projects and the retrospective runs by the same system for 2008–11. Figure ES2 shows the intensity-coded tracks of all storms examined in this study. The list of all storms along with the number of applicable airborne P3 Doppler missions for each storm is given in Table ES1.

The SOs are created using the procedure of Weng and Zhang (2012) and are now implemented operationally in all P3 reconnaissance missions that are archived and freely available at NOAA: ftp://ftp.aoml.noaa.gov/pub/hrd/gamache/FuqingSO.

The SO procedure provides quality control and thins the voluminous P3 airborne Doppler velocity observations to a spatial resolution comparable to that of the assimilation and forecasting system; the significantly thinned data can then be transmitted in real time from the aircraft to the Hurricane Research Division of NOAA (contact: John Gamache) to allow for timely assimilation into the forecast model.

VERIFICATION ON THE FIVE-YEAR PERFORMANCE OF THE WRF-ENKF HURRICANE PREDICTION. *Verification against Best Tracks.* The position and intensity of tropical cy-

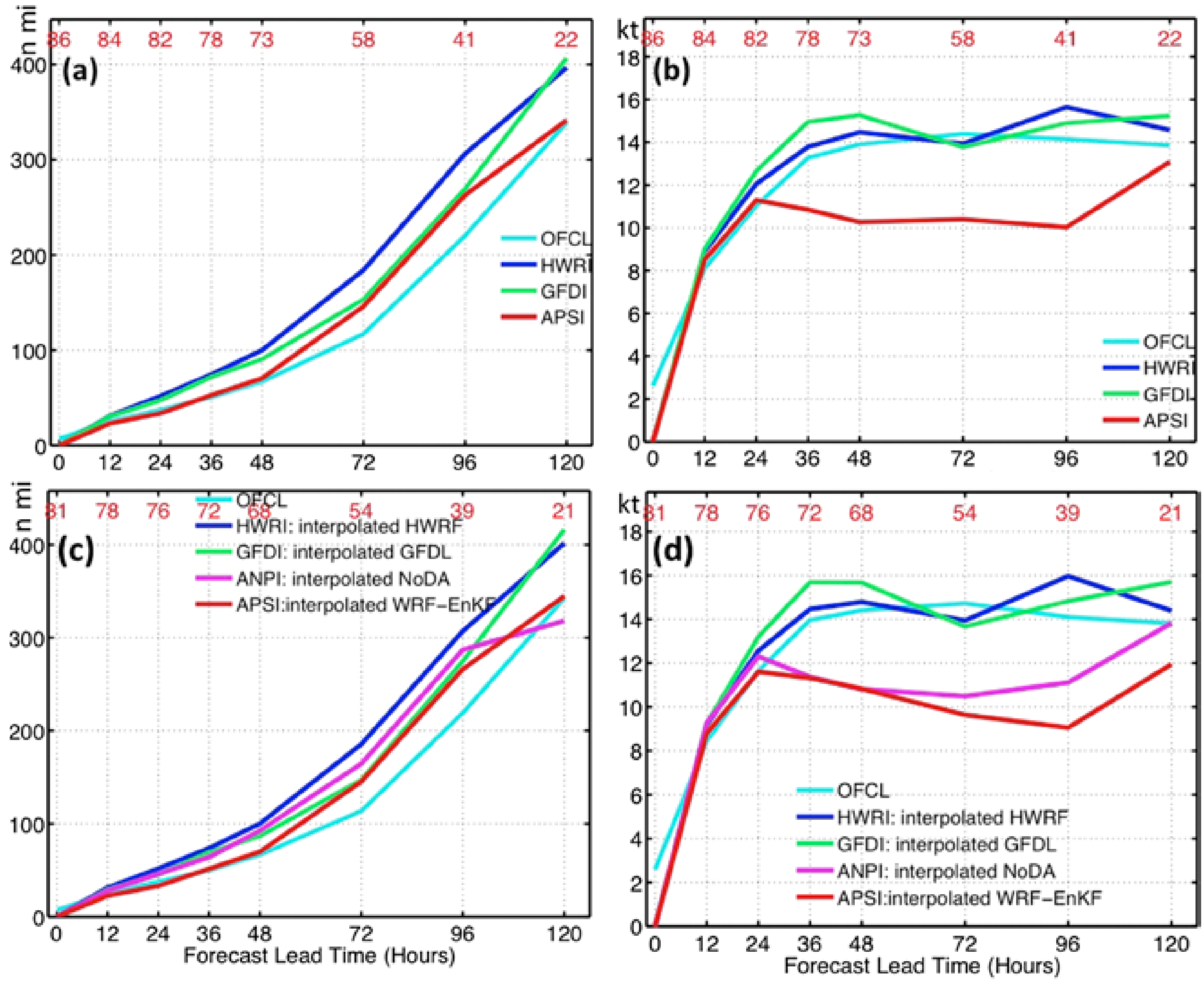

Fig. ES3. Absolute track (left column, unit: n mi) and intensity (right column, unit: knot) forecast errors. All dynamic models are treated as "later model" and interpolated to 6 h later. The track forecasts are directly shifted to the 6-h time-lagged forecasts, while the intensity forecasts use a 30-h interpolation method, which is used for later model in NHC. The interpolator process first applies a 1–2-1 smoother to an individual intensity forecast and then applies 30-h interpolation with 6-h time lag to the forecast based on when the model guidance is available. The interpolator applies the full adjustment to the time-lagged forecast out to 18 h, applies a linearly decreasing adjustment from 18 to 30 h, and then no adjustment for the remainder of the forecast. The numbers listed on the top of each panel are the sample size of the homogenized verification. The top row is the homogeneous comparison between the NHC official (OFCL, cyan), the current NHC regional dynamical models HWRF (HWRI, blue) and GFDL (GFDI, green), and the PSU WRF-EnKF deterministic forecast (APSI, red); the bottom row is the homogeneous comparison among the APSI, OFCI, HWRI, GFDI, and WRF deterministic forecast initialized with operational GFS analysis (ANPI, pink).

clones are not observed directly; they are analyzed by NHC based on all conventional observations, satellite detection, and reconnaissance data, and referred to as "best track" and used as observations. The best-track dataset contains the six-hourly representative estimates of the cyclone's center location and maximum sustained wind as well as other parameters of all known tropical cyclones across the North Atlantic basin, including the Gulf of Mexico and Caribbean Sea. The dataset is called HURDAT. The NHC best-track observations for all storms that are used for verification were downloaded from the NOAA website: ftp://ftp.nhc.noaa.gov/atcf/archive/.

The NHC Official forecast (OFCL) and other model forecasts are collected by NHC in the Automated Tropical Cyclone Forecast (ATCF) "a-deck" file format (see www.nrlmry.navy.mil/atcf_web/docs/database/new/abrdeck.html). The NHC operational forecasts of all storms, including the official forecasts used in this study, can be downloaded from the

TABLE ES2. List of the details on the number and timing of the SOs and the PSU WRF-EnKF assimilation and forecasts for all applicable P3 Doppler missions during 2008–12.

TC ID	TC Name	P3 Doppler Mission ID	Radar sampling time (UTC)	SO Number	Init Time (t=-12 h) (DDHH) (UTC)	Init storm position (lat, lon) (degrees)	EnKF Start Time (hours after init time)	EnKF End Time	Forecast Start Time (t = 0 h) (DDHH) (UTC)
AL042008	Hurricane Dolly	080720H1	1200–1510	16903	2000	17.8, −83.6	12	15	2012
200807		080720I1	2130–2730	17518	2012	19.8, −85.8	10	12	2100
2012–2700		080721H1	1053–1330	9437	2100	21.8, −88.8	11	13	2112
		080721I1	2228–2622	17803	2112	23.0, −92.0	11	12	2200
		080722H1	1105–1415	16686	2200	23.7, −94.1	12	14	2212
		080722H2	2310–2615	16397	2212	24.9, −95.7	12	14	2300
AL062008	Tropical Storm Fay	080814I1	0420–0900	53813	1318	18.0, −61.0	11	14	1406
200808		080814H1	1615–1942	24831	1406	18.0, −63.0	11	13	1418
1512–2806		080815I1	0419–0730	37035	1418	18.0, −65.0	11	13	1506
		080815H1	1810–1950	11141	1512	18.5, −68.5	7	8	1600
		080818H1	1603–1815,	10541	1806	24.0, −81.5	10	12	1818
		080819I1	0340–0750	6577	1818	25.5, −81.8	10	13	1906
AL072008	Hurricane Gustav	080829H1	2200–2608	9053	2912	19.2, −80.0	11	12	3000
200808		080830I1	0923–1255	26155	3000	20.7, −81.6	10	12	3012
2500–0512		080830H1	2118–2500	12365	3012	22.7, −83.5	10	12	3100
		080831I1	0926–1415	33733	3100	24.8, −85.5	10	14	3112
		080831H1	2032–2632	15234	3112	26.9, −87.7	9	12	0100
		080901I1	0900–1410	65939	0100	28.8, −90.3	9	12	0112
AL092008	Hurricane Ike	080909H1	2116–2341	9766	0912	23.1, −84.0	10	11	1000
09/01–09/15		080910I1	0920–1424	34418	1000	23.8, −85.2	10	14	1012
		080910H1	2110–2650	30920	1012	24.7, −86.4	10	14	1100
		080911I1	0956–1450	31122	1100	25.5, −88.0	10	12	1112
		080911H1	2128–2345	17848	1112	26.1, −900	10	11	1200
		080912I1	1235–1715	52388	1206	26.9, −92.2	7	11	1218
AL112008	Hurricane Kyle	080923H1	2213–2525	4130	2312	20.0, −70.0	11	12	2400
200808		080924I1	1128–1340	6360	2400	20.5, −70.5	13	13	2412
09/25–09/30		080924H1	2232–2554	26945	2412	20.9, −70.3	11	12	2500
		080925I1	1041–1153	5012	2500	22.4, −68.7	11	12	2512
		080925H1	2252–2447	13158	2512	24.0, −68.0	11	12	2600
		080926I1	1545–1729	13096	2606	26.9, −68.6	10	11	2618
		080926H1	2333–2638	27220	2612	28.7, −68.6	12	14	2700
		080927I1	1413–1700	11167	2706	33.3, −69.7	10	11	2718

AL172008 11/05–11/14	Hurricane Paloma	081107I1	0538–0853	8573	0618	17.4, −81.7	12	14	0706
		081107I2	1645–2039	31425	0706	18.0, −81.6	11	12	0718
		081108I1	1551–1945	28272	0806	19.8, −76.9	10	12	0818
AL022009 200908 1006–1612	Tropical Storm Ana	090816I1	2057–2312	5256	1612	15.5, −60.0	9	11	1700
AL032009 200908 1506–2600	Hurricane Bill	090818I1	2126–2629	25567	1812	17.0, −53.0	10	12	1900
		090819I1	0852–1325	12554	1900	18.5, −56.1	9	12	1912
		090819I1	2137–2624	26941	1912	20.5, −58.7	10	12	2000
AL052009 200908 2609–2900	Tropical Storm Danny	090820I1	0906–1126	4920	2000	22.2, −61.2	10	11	2012
		090826I1	1053–1256	5599	2600	24.5, −69.5	11	13	2612
		090826I1	2214–2620	4648	2612	26.0, −70.5	11	14	2700
		090827I1	1005–1314	7188	2700	27.5, −72.5	11	13	2712
		090827I1	2142–2530	19408	2712	27.5, −73.5	10	13	2800
		090828I1	1010–1031	1234	2800	27.5, −73.5	10	10	2812
AL012010 0625–0702	Hurricane Alex	100628H1	2300–2420	10050	2812	20.7, −91.7	11	12	2900
AL022010 0708–0708	Tropical Depression Two	100706H1	2153–2600	25275	0612	21.2, −90.8	10	12	0700
		100707H1	0958–1352	46421	0700	22.0, −92.0	10	12	0712
		100707H2	2201–2517	28445	0712	23.6, −93.6	10	12	0800
AL072010 0825–0905	Hurricane Earl	100828I1	2101–2456	33680	2812	16.5, −54.6	9	12	2900
		100829H1	0900–1350	47692	2900	17.1, −57.7	11	13	2912
		100829I1	2032–2517	41087	2912	17.7, −60.4	9	12	3000
		100830H1	1040–1312	28059	3000	18.5, −63.0	11	13	3012
		100830I1	2049–2403	27945	3012	19.6, −65.2	9	12	3100
		100901H1	1030–1247	19559	0100	24.5, −71.6	11	12	0112
		100901I1	2324–2547	19749	0112	28.0, −73.0	12	13	0200
		100902H1	0914–1234	30026	0200	30.1, −74.8	10	12	0212
		100902I1	2136–2613	32069	0212	33.0, −74.7	10	12	0300
		100903H1	1244–1603	20877	0306	37.6, −72.2	7	10	0318
		100903I1	2113–2524	24300	0312	39.0, −70.8	10	12	0400
AL132010 0914–0918	Hurricane Karl	100912I1	2309–2623	17887	1212	15.8, −73.8	12	14	1300
		100913H1	1245–1455	29811	1306	16.3, −78.5	7	9	1318
		100913I1	2452–2642	2618	1318	17.0, −81.1	7	8	1406
		100916H1	1817–2110	27507	1606	19.6, −93.3	12	14	1618
AL192010 1021–1025	Hurricane Richard	101023I1	0513–0753	38844	2218	15.8, −82.1	12	14	2300

AL212010 10/29–11/07	Hurricane Tomas	101103H1	2356–2630	3055	0312	15.2, −75.0	12	14	0400
		101104I1	1125–1413	25781	0400	16.0, −76.0	12	14	0412
		101104H1	2204–2436	21753	0412	17.0, −75.8	10	12	0500
		101106I1	0925–1331	38152	0600	22.6, −70.9	10	12	0612
		101106H1	2121–2454	30510	0612	24.9, −69.7	10	12	0700
AL092011 8/20–8/29	Hurricane Irene	110823H1	2338–2529	19091	2312	21.3, −72.3	12	13	2400
		110824H1	1024–1406	38458	2400	22.0, −73.5	11	14	2412
		110825I1	0929–1357	36954	2500	24.8, −76.2	10	13	2512
		110825H1	2048–2627	49614	2512	26.5, −77.5	9	12	2600
		110826I1	0907–1335	37748	2600	30.0, −77.8	10	11	2612
		110826H1	2105–2514	37961	2612	32.2, −77.1	10	13	2700
		110827I1	0937–1105	14941	2700	34.2, −76.4	10	11	2712
AL132011 9/2–9/5	Tropical Storm Lee	110901H1	1924–2215	9177	0112	26.6, −91.4	8	10	0200
AL162011 9/21–10/03	Hurricane Ophelia	110924I1	1707–2030	20397	2406	17.7, −57.0	11	14	2418
AL182011 10/23–10/28	Hurricane Rina	111025H1	2341–2540	18899	2512	17.8, −84.8	12	13	2600
		111026H1	1421–1642	26384	2606	17.9, −85.5	9	11	2618
		111026H2	2320–2341	2662	2612	18.0, −85.6	12	12	2700
		111027H1	1258–1540	30158	2706	19.2, −86.8	7	10	2718
AL092012 8/21–8/30	Hurricane Isaac	120822H1	2059–2710	54917	2212	16.1, −61.2	10	12	2300
		120823H1	0854–1414	70361	2300	16.8, −64.8	9	12	2312
		120823H2	2210–2620	29906	2312	17.6, −70.5	10	12	2400
		120824H1	0946–1144	19871	2400	15.9, −70.4	10	12	2412
		120826H1	2148–2532	40606	2612	25.0, −82.7	10	12	2700
		120827H1	0847–1443	76014	2700	26.2, −84.8	9	12	2712
		120827H2	2100–2638	66570	2712	27.4, −86.4	9	12	2800
		120828H1	0907–1502	75376	2800	28.5, −87.6	10	12	2812
		120828H2	2325–2520	27826	2812	29.2, −89.2	12	13	2900
AL122012 8/30–9/11	Hurricane Leslie	120907H1	1126–1338	12730	0700	26.8, −62.5	12	13	0712
		120907N1	2343–2545	8330	0712	27.3, −62.8	12	13	0800
		120908H1	1105–1309	10975	0800	28.0, −62.5	12	13	0812
AL182012 10/22–10/30	Hurricane Sandy	121025H1	2147–2704	65339	2512	24.2, −76.2	10	12	2600
		121026H1	0858–1356	31933	2600	26.3, −76.5	9	12	2612
		121026H2	2056–2650	24795	2612	27.9, −77.7	9	12	2700
		121027H1	0851–1438	50888	2700	29.1, −76.3	9	12	2712
		121027H2	2124–2555	43485	2712	30.7, −75.0	10	12	2800
		121028H1	0946–1313	36494	2800	32.2, −73.7	10	12	2812
		121028H2	2149–2515	37922	2812	34.2, −71.7	10	12	2900

NOAA website: ftp://ftp.nhc.noaa.gov/atcf/archive/.

The postprocessing program to derive the tropical cyclone position and intensity from the WRF output is the GFDL tracker, which was mainly developed by NCEP and calculates the hurricane center by averaging positions analyzed by the parameters of MSLP, vorticity at 10 m, 700 hPa, and 850 hPa, and geopotential heights of 700 hPa and 850 hPa. We applied WRF Postprocessor (WPP, see www.dtcenter.org/wrf-nmm/users/OnLineTutorial/NMM/WPP/) software to convert the original NetCDF format WRF files to Grib1 format files, and then used the GFDL Tracker to calculate the tropical cyclone tracks every 6 h. The PSU WRF-EnKF forecasts for these cases in ATCF a-deck format can be downloaded from the PSU website: http://hfip.psu.edu/Wengyonghui/Paper/BAMS2014/APSU_d2012_adecks.zip.

Track forecast error is defined as the great-circle distance between a cyclone's forecast position and the best-track position at the forecast verification time. Forecast intensity error is defined as the absolute value of the difference between the forecast and best-track intensity at the forecast verifying time. The Mean Absolute Error (MAE) verification is widely used for tropical cyclone prediction verification (for detail, please see www.nhc.noaa.gov/verification/verify2.shtml), and is used for verification in Fig. 2. Each OFCL forecast contains projections valid 12, 24, 36, 48, 72, 96, and 120 h after the forecast's nominal initial time (0000, 0600, 1200, and 1800 UTC, respectively), so the valid lead times with the homogenous verification in Fig. 2 are 12, 24, 36, 48, 72, 96, and 120 h, respectively.

Supplementary to the intensity forecast comparison presented in Fig. 2b of the main document, Table ES3 lists the total homogenized number of cases for verifications and comparison between NHC official forecasts and the PSU WRF-EnKF forecast mean absolute intensity error in terms of 10-m maximum surface wind, as well as the percentage of mean error reduction by the PSU WRF-EnKF forecast for each of the lead forecast times. Although there are a total of 102 applicable Doppler missions, the total number of homogenized cases in the verifications at 12-h forecast lead time is only 87. That number dropped to only 25 at the 120-h forecast lead time because 1) a few of the cases sampled have never been classified as a named tropical storm, 2) some of the storms dissipated soon after the P3 missions or before the 5-day lead time, and 3) either the NHC or the WRF-EnKF did not provide a valid tropical cyclone forecast at this lead time due to homogenized comparison. The same is also true at other forecast lead times.

Similar to Figs. 2a,b, Fig. ES3 compares the track and intensity forecast errors of the PSU WRF-EnKF with the operational NHC regional dynamic models HWRF and GFDL, as well as with the WRF control runs without TDR radar data assimilation. The control runs are directly initialized with the operational GFS analysis, which inserts a bogus vortex with the hurricane relocation technique and assimilates all conventional observations and satellite radiance data with GSI. For all comparisons in Fig. ES3, all dynamical model forecasts are treated as NHC "late model runs" that are interpolated to be the 6 h later. The homogeneous verification among the PSU WRF-EnKF deterministic forecasts, OFCL, HWRF, and GFDL shows that the PSU forecast has smaller track and intensity forecast errors than both operational intensity forecast models (HWRF and GFDL), especially for intensity. Compared to the control runs (the bottom row in Fig. ES3), both the PSU WRF runs have smaller intensity errors than OFCL, HWRF, and GFDL. The improvements of the PSU WRF-EnKF against the control runs without TDR are also evident, but to a considerably lesser degree than in comparison with the operational dynamical models. This suggests that the assimilation of TDR observations does have positive impacts on both the track and intensity forecasts, though the model resolution and physics used may also contribute considerably to the success of the PSU WRF-EnKF runs. Note also that, strictly speaking, these GSI-initiated WRF simulations are not the real control runs. The PSU WRF-EnKF runs are initialized with the 12-h early GFS analysis and assimilate TDR during −5–+2h, while these runs

TABLE ES3. List of total number of cases, mean absolute intensity forecast error for both NHC official and PSU WRF-EnKF forecasts in each of the forecast lead times, along with the percentage of mean error reduction by the PSU WRF-EnKF forecasts.

Lead forecast time (hours)	12	24	36	48	72	96	120
Homogenized number of cases	87	84	82	72	58	38	25
NHC official forecast mean error (knots)	7.8	11.7	13.5	14.1	16.0	15.3	14.4
WRF-EnKF mean forecast error (knots)	6.1	10.0	10.6	11.2	10.0	8.7	10.8
Average improvement	22%	15%	21%	21%	38%	43%	25%

ingest all other observations except TDR around 0 h.

Independent Verification. Over the total of 102 cases during 2008–12, the cases during 2008–11 are retrospective runs with the PSU 2012 Demo system for HFIP, while the cases in 2012 are conducted in real time. The forecast files of the retrospective run are sent to TCMT for verification before the 2012 Atlantic hurricane season as one of the HFIP stream 1.5 model candidates. The evaluation by TCMT is available online at www.ral.ucar.edu/projects/hfip/includes/h2012/2012-Stream15-PSU.pdf. The real-time runs in 2012 are sent to TCMT in real time. The TCMT verification for 2012 real-time performance can be found at www.ral.ucar.edu/projects/hfip/d2012/verify/ by selecting "PSU" model and "APSI" configuration.

Uncertainty. The larger uncertainties are shown in Fig. 3 for Hurricane Ike and Sandy track forecasts, while smaller track forecast uncertainty is shown for Hurricane Irene, which was also reflected in the other dynamic models issued by NHC with the ATCF system (Fig. ES4).

Maximum Wind Swatch against Surface Observation. HRD Hurricane Wind analysis (HWind) is an operational objective method analysis product for hurricane surface winds operated by HRD. The inputs for Hwind include all available surface weather observations (e.g., ships, buoys, coastal platforms, surface aviation reports, reconnaissance aircraft data adjusted to the surface), and remotely sensed winds from the polar-orbiting SSM/I and ERS, the QuikScat platform and TRMM microwave imager satellites, and GOES cloud drift winds derived from tracking low-level near-infrared cloud imagery from these geostationary satellites. These data are composited relative to the storm over a 4–6 h period. Fig. ES5 provides a reference for Fig. 4 to verify the surface wind intensity and distribution.

FOR FURTHER READING

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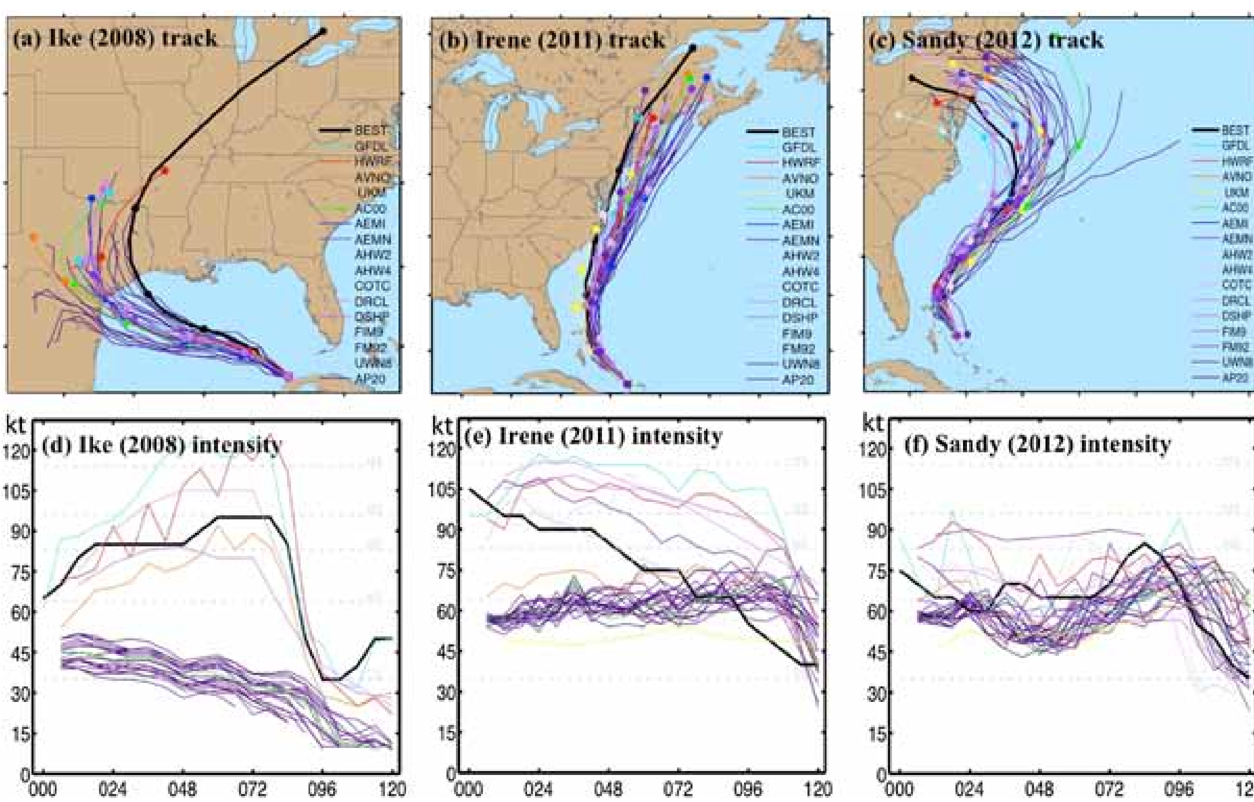

Fig. ES4. Hurricanes Ike (left column), Irene (middle column), Sandy (right column) track (top row) and intensity (bottom row) forecasts of operational dynamic models collected by ATCF.

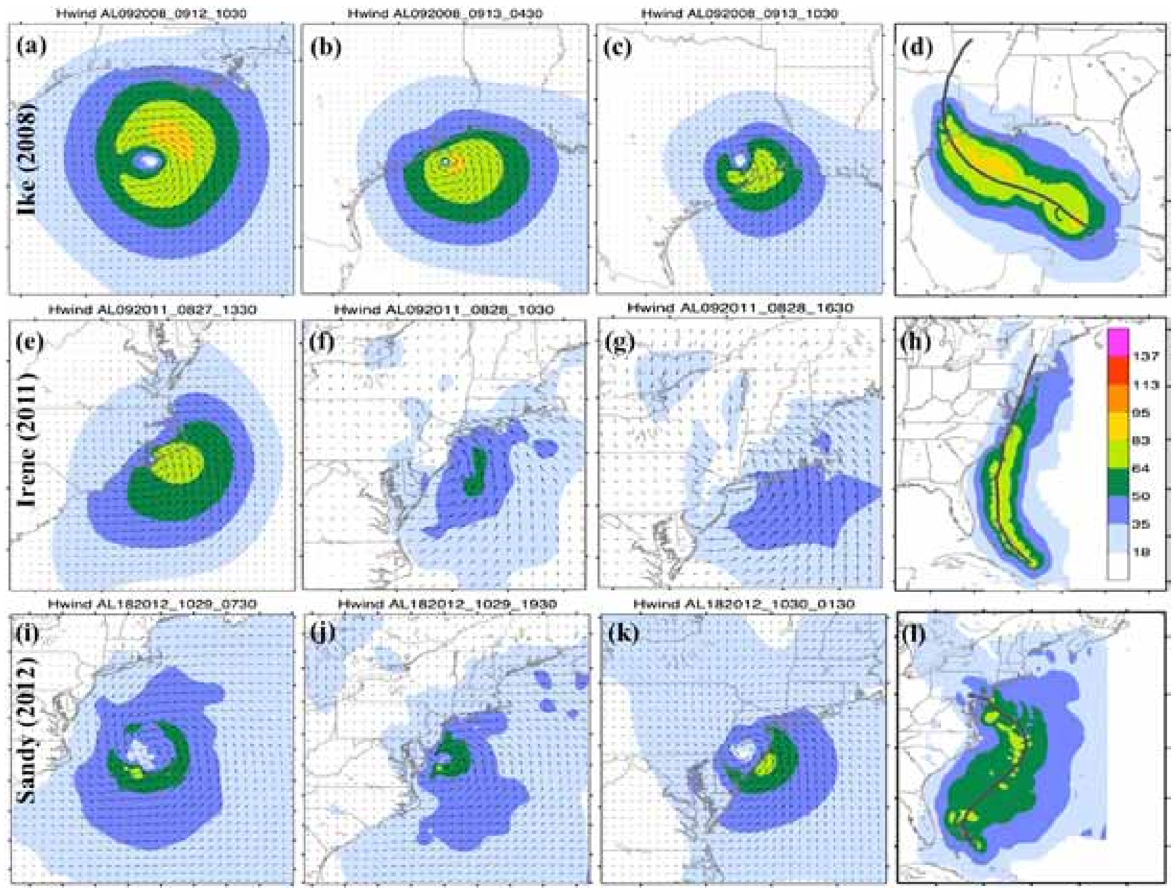

Fig. ES5. HWind for Hurricanes Ike (top row), Irene (middle row), and Sandy (bottom row) when the storms were over the ocean (first column), before landing (second column), after landing (third column), and the composite (fourth column).

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