Performance of convection-permitting hurricane initialization and prediction during 2008–2010 with ensemble data assimilation of inner-core airborne Doppler radar observations

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[1] This study examines a hurricane prediction system that uses an ensemble Kalman filter (EnKF) to assimilate high-resolution airborne radar observations for convection-permitting hurricane initialization and forecasting. This system demonstrated very promising performance, especially on hurricane intensity forecasts, through experiments over all 61 applicable NOAA P-3 airborne Doppler missions during the 2008–2010 Atlantic hurricane seasons. The mean absolute intensity forecast errors initialized with the EnKF-analysis of the airborne Doppler observations at the 24- to 120-h lead forecast times were 20–40% lower than the National Hurricane Center's official forecasts issued at similar times. This prototype system was first implemented in real-time for Hurricane Ike (2008). It represents the first time that airborne Doppler radar observations were successfully assimilated in real-time into a hurricane prediction model. It also represents the first time that the convection-permitting ensemble analyses and forecasts for hurricanes were performed in real-time. Also unprecedented was the on-demand usage of more than 23,000 computer cluster processors simultaneously in real-time. **Citation:** Zhang, F., Y. Weng, J. F. Gamache, and F. D. Marks (2011), Performance of convection-permitting hurricane initialization and prediction during 2008–2010 with ensemble data assimilation of inner-core airborne Doppler radar observations, *Geophys. Res. Lett.*, *38*, L15810, doi:10.1029/2011GL048469.

1. Introduction

[2] Over the last few decades, significant progress has been made in the short-range predictions of tropical cyclones, most notably in the track forecast. The current-day average 72-h forecast position is as accurate as a 36-h track forecast 15 years ago [*Franklin*, 2009]. However, there is virtually no improvement in our ability to predict hurricane intensity in terms of maximum surface wind speed, and we have very limited skill in predicting tropical cyclone formation or rapid intensity changes [*Elsberry et al.*, 2007]. Part of the difficulties in the lack of improvement in hurricane intensity forecasts originates from the deficiencies in the current generation of the operational forecast models that the forecasters use to provide forecast guidance. For example, the highest-resolution National Oceanic and Atmospheric Administration (NOAA) operational forecast models [both the Hurricane Weather Research and Forecast (HWRF) and Geophysical Fluid Dynamical Laboratory Hurricane Forecast (GFDL) models] have a horizontal grid-size of 6–9 km, which is insufficient to resolve moist convection and eyewall dynamics, both of which are key to hurricane intensity change [*Houze et al.*, 2007]. Moreover, both of these operational regional-scale intensity guidance models rely heavily on initializing the storms through some forms of vortex initialization devoid of inner core observations beyond the central pressure, while neither of these two operational models currently assimilates high-resolution hurricane inner-core observations such as those from ground-based or airborne Doppler radars, which can be key to intensity prediction [e.g., *Zhang et al.*, 2009; *Pu et al.*, 2009]. By far the best operational intensity forecast models (DSHP and LGEM) are statistical in nature; in other words, the dynamical models have thus far not attained the skill levels of the simpler statistical models [*Franklin*, 2009].

[3] Given the destructive potential of hurricanes to human lives and property, there are ever increasing demands for more accurate guidance with longer lead times to provide more precise and advanced warnings. This study examines the performance of a prototype regional-scale convection-permitting hurricane prediction system that assimilates high-resolution inner-core airborne Doppler radar observations. This prototype system is based on the Weather Research and Forecast (WRF) model, which is applicable to convective, mesoscale and regional scale weather predictions [*Skamarock et al.*, 2005], and an ensemble Kalman filter (EnKF) which uses ensemble forecasts to estimate flow-dependent background error covariance or other probabilistic aspects of the background forecast [*Evensen*, 1994]. The feasibility and performance of the EnKF from convective to regional scales have been demonstrated in numerous studies using both simulated and real-data observations since *Snyder and Zhang* [2003] and *Dowell et al.* [2004]; please refer to *Meng and Zhang* [2011] for a most up-to-date exclusive review. Notably, a recent study on a month-long warm-season data assimilation experiment (June 2003) over the continental United States demonstrated that a WRF-based EnKF consistently outperforms both a three-dimensional and a four-dimensional variational (3DVar/4DVar) data assimilation system also based on the same model at the regional scales [*Zhang et al.*, 2011]. This same WRF-based regional-scale EnKF system was also recently adapted for initializing convection-permitting tropical cyclone prediction capable of assimilating in-situ and remote observations, including high-resolution ground-based and airborne Doppler radar

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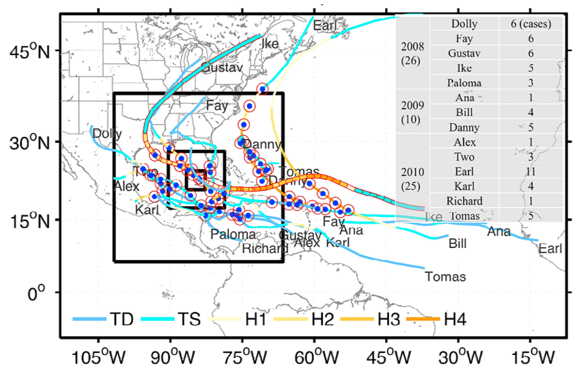

Figure 1. WRF-ARW model domain configuration and TC tracks with NOAA airborne Doppler radar mission. The domain configuration is a sample for hurricane Ike (2008) initialized at 1200 UTC 9 September 2008, the outer domain is fixed for all cases, while the 3 inner domains are centered at the storm's center at the initial time and movable following model vortex center during the forecast. 14 storm tracks are colorized lines with storm intensity. 61 missions of NOAA airborne Doppler radar observation are marked with blue dots circled with red. All the storms and case numbers are listed on the right top.

observations [*Zhang et al.*, 2009; *Weng et al.*, 2011; *Weng and Zhang*, 2011].

[4] The current study presents the summary performance of the hurricane forecasts initialized with this WRF-EnKF system using inner-core airborne Doppler radar observations for all 61 applicable cases over the 2008–2010 Atlantic hurricane seasons (list of the cases shown in Figure 1). Also highlighted is the first real-time test of this prototype system during Hurricane Ike (2008). It represents the first time that airborne Doppler radar observations are assimilated into hurricane prediction models in real-time with an EnKF, and that the convection-permitting ensemble analyses and forecasts for hurricanes are performed in real-time.

2. Methodology and Experimental Design

[5] The current study uses the same WRF-based ensemble analysis and prediction system as in work by *Zhang et al.* [2009] and *Weng and Zhang* [2011] capable of assimilating hurricane inner-core observations using EnKF. The WRF model has four two-way-nested domains "D1 to D4" with horizontal grid spacing of 40.5, 13.5, 4.5 and 1.5 km, covering a total area of 10206 km × 6561 km, 3402 km × 3402 km, 1134 km × 1134 km, and 378 km × 378 km, respectively (Figure 1). D1 covers a fix area as shown in Figure 1 while D2-D4 are centered on the initial storm location and these latter domains are movable following the center of the tropical cyclones.

[6] The current study focuses exclusively on the added values of assimilating airborne Doppler observations from the NOAA P-3 aircrafts [*Gamache et al.*, 1995; *Marks*, 2003]. There were 30 ensemble members used in the real-time WRF-EnKF system (as is the case of Hurricane Ike of 2008 highlighted in section 3) while the hindcast EnKF analyses and forecasts for all the 61 cases during 2008–2010 used 60 members (as in section 4). The ensemble is initialized with perturbations derived from the WRF variational background error covariance [*Barker et al.*, 2004] based on the NOAA Global Forecast System (GFS) operational analysis at 9–12 h prior to the assimilation of the first available or expected airborne Doppler observations, while the updated GFS operational forecast closest to the airborne radar observation time is used for boundary conditions for the subsequent 126-h forecasts. Model physics and generation of the initial and boundary perturbations for the ensemble are the same as in the work of *Weng and Zhang* [2011]. For example, if the airborne observations are to be taken between 2130 – 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 time-shifted and regarded as initial condition of 0000 UTC of the next day for the subsequent 126-h single deterministic WRF forecast, which uses the next-day 0000-UTC GFS run as the boundary conditions.

[7] The raw airborne Doppler velocity observations first pass through a rigorous data thinning and quality control procedure (Joint Hurricane Testbed final report 2005, available at http://www.nhc.noaa.gov/jht/2003-2005reports/DOPLRgamache_JHTfinalreport.pdf) that was developed and implemented on the aircraft radar computer workstation [*Griffin et al.*, 1992]. Since the airborne radar observations are not used routinely in any current NOAA operational models in real-time, and since the volume of radar data is too big to be transferred from the reconnaissance aircraft to the ground in a timely manner, we developed a data thinning and additional quality control procedure implemented on the aircraft computers to allow us to summarize the massive amount of airborne Doppler radar observations into a few thousand 'super-observations' (SOs) per leg (straight flight path through the storm center) that can be transferred to the ground computers in real-time. The detailed procedure to generate SOs for the airborne Doppler observations can be found in work by *Weng and Zhang* [2011], which is similar to that developed for the ground-based Doppler radars in work by *Zhang et al.* [2009].

3. First Real-Time Experiment for Hurricane Ike 2008

[8] With the same WRF and EnKF configurations as in the work of *Weng and Zhang* [2011] for Hurricane Katrina (2005), we conducted high-resolution ensemble analysis and forecast experiments for three storms (Tropical Storm Fay, Hurricanes Gustav and Ike) in real-time during the 2008 Atlantic hurricane season. The last, but also the first complete end-to-end testing of the real-time convection-permitting ensemble analysis and forecasting was conducted for Hurricane Ike, one of the most costly storms on record. The EnKF data assimilation was performed for two consecutive P-3 missions, one with 2 flight legs between 2125–2341 UTC 9 September and the other with 2 flight legs between 2121–2349 UTC 10 September 2008. Figures 2a and 2b show the final EnKF analysis of wind speed and temperature at the flight level versus in-situ aircraft measurements (not assimilated) for the first mission, and shows reasonably agreement between analysis and independent observations.

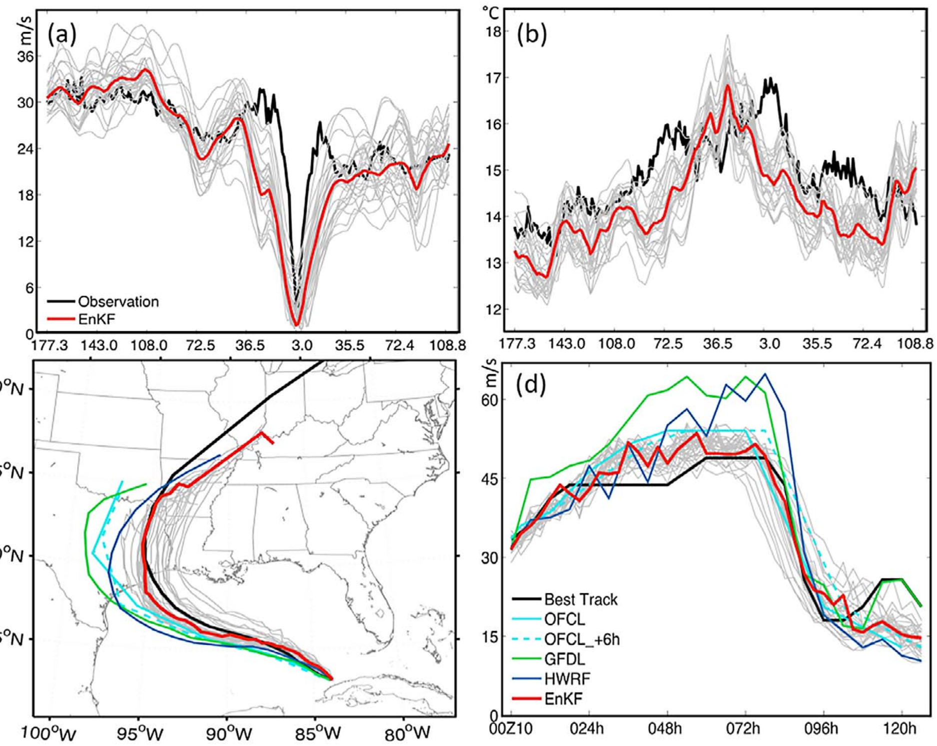

Figure 2. Comparison of the final EnKF analysis (red) and its perturbations (gray) of (a) wind speed and (b) temperature against independent aircraft flight-level in-situ observations during the 2nd flight leg ending at 2341 UTC 9 September 2008 (black). The x-axis denotes the horizontal distance (km) of the measurement away from the Best-Track center position. (c) Track and (d) intensity forecasts of Hurricane Ike with the EnKF assimilation of airborne Doppler velocity (red) and by each member of the ensemble forecast initialized with EnKF perturbations (gray). Also plotted are the official forecast (OFCL) issued by NHC (solid cyan), 6-h later OFCL forecast (dash cyan), the NOAA operational forecasts by the GFDL hurricane model (green), the operational HWRF forecast (blue), and the NHC best-track observational analysis (black). All forecasts are initialized at 0000 UTC 10 September.

[9] A total of 62 convection-permitting 126-h WRF forecasts (31 4.5-km and 31 1.5-km control and ensemble runs; each member running on 384 computer processors) started at 0000 UTC 10 September 2008 was performed simultaneously on 23,808 processors in real-time for Hurricane Ike. Control and ensemble forecasts were initialized with the EnKF analysis and perturbations from D3 on a fourth nest domain with horizontal resolution of 1.5-km (D4) which give similar performance to the 4.5-km forecasts and thus not displayed.

[10] With coordinated efforts between scientists aboard the aircraft and on the ground, along with the availability of superior computing and support staff at the Texas Advanced Computing Center (TACC), the 126-h 4.5-km control (initialized from the EnKF analysis) and ensemble forecasts (initialized from EnKF perturbations) became available about 3.5 h after the last airborne observation was taken while the 1.5-km 126-h control and ensemble forecasts became available within 8 hours. These real-time experiments represented the first time that airborne Doppler radar observations were assimilated into any hurricane prediction model in real-time, and the first time that the convection-permitting ensemble analyses and forecasts were produced for hurricanes in real-time. Figures 2c and 2d show the performance of the 4.5-km deterministic and 30-member ensemble forecasts initialized with EnKF assimilation of the airborne Doppler observations, verified against the NHC best-track analysis, and compared to the HWRF and GFDL operational forecasts. The WRF-EnKF deterministic forecast from the mean analysis produced a track very close to the observed track of Ike, and it was dramatically better than both operational regional-scale forecast models (GFDL and HWRF), and the NHC official track forecast. The 0000-UTC WRF-EnKF forecast also outperformed the 0600-UTC NHC forecast also shown in Figure 2 since in operational practice the 0000 UTC WRF-EnKF forecast may not be available to the forecasters for initializing the 0000-UTC NHC official forecast.

[11] The EnKF also produced a tight ensemble spread in the track forecast suggesting the uncertainties in the WRF deterministic track forecast of Ike from this EnKF analysis may be low if the ensemble is assumed to be unbiased. Correspondingly, the ensemble intensity forecast for Ike is also very close to observed, also with a relatively narrow spread indicating low forecast uncertainty. This real-time WRF forecast initialized with the EnKF assimilation of airborne Doppler data at 0000 UTC 10 September was made available approximately 3.5 days prior to landfall of Ike. Although not showing, the 1.5-km real-time deterministic and ensemble forecasts initialized with the same 4.5-km EnKF analysis and perturbations performed similarly to the 4.5-km runs in this case.

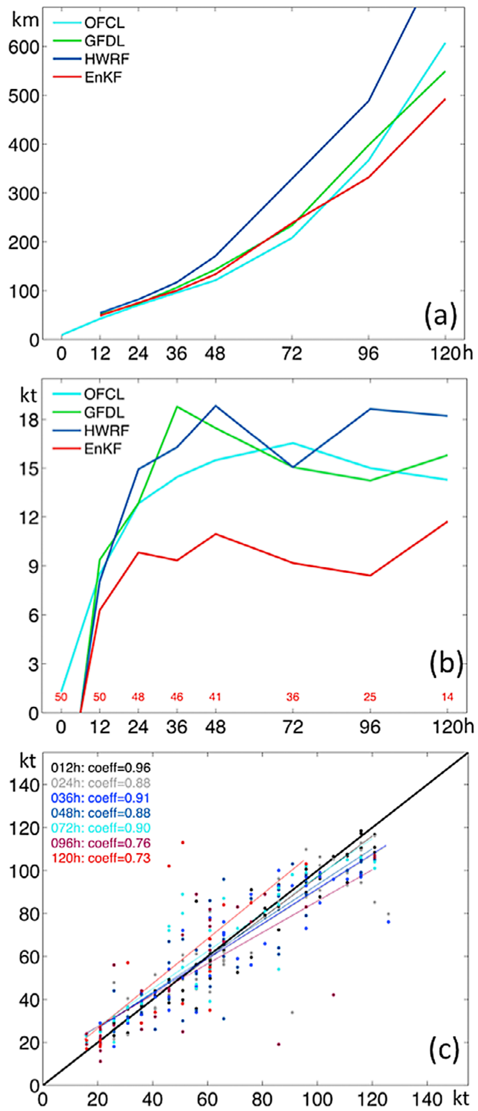

Figure 3. Mean absolute forecast error averaged over 50 samples homogenized by all 61 airborne Doppler missions during 2008–2010 for the NHC official forecast ('OFCL', solid cyan line), the 6-h later official forecast ('OFCL_+6h, dashed solid line), the GFDL hurricane model ('GFDL', green line), HWRF ('HWRF', dark blue line), and the WRF deterministic forecast in 4.5-km resolution initialized with EnKF analysis ('EnKF', red line) after making the samples homogeneous for all 5 forecasts for (a) the track position error (km) and (b) the 10-m maximum wind speed error (knots) with simple bias correction for all forecasts except for OFCL. (c) Scatters of NHC Best-track (Y-axis) and forecasts (X-axis) Vmax (knots) at 12, 24, 36, 48, 72, 96, 120 h lead-time for the WRF deterministic forecast in 4.5-km resolution initialized with the EnKF analysis.

4. Performance Over 61 Airborne Doppler Missions During 2008–2010

[12] As shown in Figure 1, there are a total of 61 applicable NOAA P-3 airborne Doppler radar missions that sampled a total of 14 tropical cyclones over the Atlantic basin that include 26 missions in 2008 for 5 storms (Hurricanes Dolly, Gustav, Ike, Paloma and Tropical Storm Fay), 10 missions in 2009 for 3 storms (Tropical Storms Ana and Danny, and Hurricane Bill) and 25 missions in 2010 for 6 storms (Hurricanes Alex, Earl, Karl, Richard, Tomas and Tropical Depression Two). These are primarily storms that posed a potential threat to the US.

[13] Using the same WRF and EnKF configurations in the real-time system demonstrated for Hurricane Ike (2008) except for doubling the ensemble size to 60 members, we performed the 4.5-km WRF-EnKF analysis for each of these 61 applicable airborne Doppler missions during the 2008–2010 Atlantic hurricane seasons. The deterministic forecast in each case is integrated for 126 h initialized with the EnKF analysis (time-shifted to the closest 0000, 0600, 1200 or 1800 UTC) that assimilates the airborne Doppler radar observations in D1-D3 (sample model domain configurations are given in Figure 1). Figures 3a and 3b show the overall performance of the WRF-EnKF system in terms of mean absolute forecast errors of track and maximum 10-m wind speed (verified against NHC best track estimates) with the two operational regional-scale dynamic models (HWRF and GFDL) as well as the NHC official forecasts issued at similar times (as well as at 6 h after). The homogeneous comparison was applied which means that these errors are averages over the same number of forecasts for each model or guidance at each forecast time. Following a similar procedure termed as "variable interpolator" for the "late models" used operationally at NHC (available at http://www.nhc.noaa.gov/modelsummary.shtml), a simple case-dependent bias correction is used in producing Figure 3b that modifies the maximum wind speed analysis and forecasts at 6-30 h lead times from 0 h by subtracting the difference between each model forecast and the NHC best track estimate from the intensity forecast scaled linearly as (36-t)/30, where t is the forecast lead time from 6 to 120 h. Likely due to the use of a coarser GFS analysis at approximately 9 to 12 h to initialize the initial ensemble for each case before assimilating the first airborne Doppler data, the intensity of the WRF forecasts initialized with the EnKF analysis have a low bias for the first 30 h (thus benefit from the bias correction).

[14] The WRF forecasts initialized with the EnKF assimilating high-resolution airborne Doppler radar observations substantially outperform both operational forecast models (HWRF and GFDL) as well as the NHC official intensity forecast at nearly all forecast lead times (Figure 3b), despite producing comparable or slightly smaller track forecast errors (Figure 3a). With the simple bias correction, the WRF-EnKF produced 20–40% smaller intensity forecast errors than the NHC official forecast issued at the similar times for lead times from 24–120 h. Moreover, the correlations of the EnKF-initialized intensity forecasts with the NHC best-track estimates are high at all forecast lead times (Figure 3c). Although not shown, we also performed the 1.5-km deterministic forecasts for all cases initialized from the 4.5-km EnKF analysis; the averaged performance of the 1.5-km WRF forecasts is comparable to the 4.5-km forecasts for both track and intensity. In the meantime, the WRF forecast initialized directly from the GFS analysis with the same model configuration but without the EnKF assimilation of airborne observations also outperformed considerably the operational models of GFDL and HWRF for this same set of cases, though the forecast with the EnKF assimilation of the

inner-core observations was still more skillful than without (with 10–20% smaller intensity forecast up to 72h, not shown).

[15] While it is beyond the scope of this study to pinpoint the exact reasons why the WRF intensity forecasts initialized with the EnKF analysis outperformed the operational regional-scale hurricane models of GFDL and HWRF, it is encouraging that our prototype hurricane system with increased model resolution and advanced data assimilation system assimilating high-resolution inner-core observations from airborne Doppler radar gives the potential to provide significantly improves numerical guidance on hurricane intensity in the future. However, we acknowledge that the number of cases being examines is still relatively small and thus more tests are needed. In this regard, we have very recently completed the EnKF assimilation of airborne Doppler observations from all 51 NOAA P3 missions during the 2004–2005 Atlantic Hurricanes seasons. Our preliminary analysis indicates that, though to a lesser degree, the advantage of our prototype hurricane analysis over existing operational products in terms of intensity remains substantial after averaged over these 5 years of more than 100 total cases. We also acknowledge that the computational demand of the high-resolution ensemble analysis and forecasts with the EnKF may be too high for operational implementation at present. To relieve this computational constraint, we also have encouraging preliminary results from using a pseudo ensemble derived from a standing hurricane vortex library (without the need of running a full convection- permitting ensemble in real time). Findings from these ongoing research projects will be reported elsewhere when thorough analyses have been completed.

5. Concluding Remarks

[16] In summary, this study examines a WRF-based prototype future hurricane prediction system that uses an EnKF to assimilate high-resolution airborne radar observations for convection-permitting hurricane initialization and forecasting. The prototype system was first successfully implemented in real-time to ingest and assimilate Doppler radar observations from NOAA P-3 aircraft for the high-impact landfalling event of Hurricane Ike (2008). This study represents the first time that airborne Doppler radar observations were assimilated in real-time into hurricane prediction models. It also represents the first time that the convection-permitting ensemble analyses and forecasts for hurricanes were performed in real-time. Also unprecedented was the coordination, parallelization, and on-demand usage of more than 23,000 cluster processors simultaneously in real-time at a high-performance computer cluster.

[17] Moreover, while more systematic experiments of the prototype system with many more cases are needed, the ensemble-based analysis and forecast system demonstrated very promising performance over the past three Atlantic hurricane seasons in terms of mean absolute intensity forecast errors averaged over all 61 NOAA P-3 airborne Doppler missions. The forecasts compared favorably against deterministic regional-scale operational forecast models initialized from corresponding three-dimensional variational analyses, as well as to the NHC official forecasts issued at similar times to the EnKF real-time forecasts. In addition, the ensemble system provides clear evidence of flow- or event-dependent uncertainty in hurricane analysis and prediction, which is still assumed to be the climatological average in the current operational practice. This study highlights the need for more in-depth investigations utilizing ensemble data assimilations techniques, Doppler observations, as well as convection-permitting ensemble analysis and forecasts for hurricane prediction. This study goes well beyond what NOAA could have accomplished with its current operational computing assets and provides a path to future development needed to demonstrate substantial improvement in future operational guidance.

[18] The current study provides insights and potential solutions for future hurricane prediction, especially the intensity forecast. The possible solutions are: (i) convection-permitting ensemble analysis and forecasting, (ii) enhanced surveillance (ground-based and airborne Doppler radars, rawinsondes and dropsondes, and satellite observations), and (iii) advanced computing capabilities and coordination [*Zhang*, 2011]. Other areas for future forecast improvement not discussed here, but that can also be important to include: (i) better models and dynamics including air-sea interaction, moist physics and turbulence [*Chen et al.*, 2007], (ii) on demand research and operational collaboration paradigm, (iii) education, risk management and mitigation; and (iv) limit of hurricane predictability.

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References

Barker, D. M., W. Huang, Y.-R. Guo, A. J. Bourgeois, and Q. N. Xiao (2004), A three-dimensional variational data assimilation system for MM5: Implementation and initial results, *Mon. Weather Rev.*, *132*, 897–914, doi:10.1175/1520-0493(2004)132<0897:ATVDAS>2.0.CO;2.

Chen, S. S., J. F. Price, W. Zhao, M. A. Donelan, and E. J. Walsh (2007), The CBLAST-Hurricane Program and the next-generation fully coupled atmosphere-wave-ocean models for hurricane research and prediction, *Bull. Am. Meteorol. Soc.*, *88*, 311–317, doi:10.1175/BAMS-88-3-311.

Dowell, D. C., F. Zhang, L. J. Wicker, C. Snyder, and N. A. Crook (2004), Wind and thermodynamic retrievals in the 17 May 1981 Arcadia, Oklahoma, supercell: Ensemble Kalman filter experiments, *Mon. Weather Rev.*, *132*, 1982–2005.

Elsberry, R. L., T. D. B. Lambert, and M. A. Boothe (2007), Accuracy of Atlantic and eastern North Pacific tropical cyclone intensity forecast guidance, *Weather Forecast.*, *22*, 747–762, doi:10.1175/WAF1015.1.

Evensen, G. (1994), Sequential data assimilation with a nonlinear quasi-geostrophic model using Monte Carlo methods to forecast error statistics, *J. Geophys. Res.*, *99*, 10,143–10,162, doi:10.1029/94JC00572.

Franklin, J. L. (2009), 2008 National Hurricane Center verification report, Trop. Predict. Cent., Natl. Hurricane Cent., Natl. Cent. for Environ. Predict., Natl. Weather Cent., NOAA, Miami, Fla. [Available at http://origin.www.nhc.noaa.gov/verification/pdfs/Verification_2008.pdf.]

Gamache, J. F., F. D. Marks, and F. Roux (1995), Comparison of three airborne Doppler sampling techniques with airborne in situ wind observations in Hurricane Gustav (1990), *J. Atmos. Oceanic Technol.*, *12*, 171–181, doi:10.1175/1520-0426(1995)012<0171:COTADS>2.0.CO;2.

Griffin, J. S., R. W. Burpee, F. D. Marks Jr., and J. L. Franklin (1992), Real-time airborne analysis of aircraft data supporting operational hurricane forecasting, *Weather Forecast.*, *7*, 480–490, doi:10.1175/1520-0434(1992)007<0480:RTAAOA>2.0.CO;2.

Houze, R. A., S. S. Chen, B. F. Smull, W.-C. Lee, and M. M. Bell (2007), Hurricane intensity and eyewall replacement, *Science*, *315*, 1235–1239, doi:10.1126/science.1135650.

Marks, F. D. (2003), State of the science: Radar view of tropical cyclones, *Meteorol. Monogr.*, *30*, 33–33, doi:10.1175/0065-9401(2003).

Meng, Z., and F. Zhang (2011), Limited area ensemble based data assimilation: A review, *Mon. Weather Rev.*, *139*, 2025–2045, doi:10.1175/2011MWR3418.1.

Pu, Z., X. Li, and E. J. Zipser (2009), Diagnosis of the initial and forecast errors in the numerical simulation of rapid intensification of Hurricane Emily, *Weather Forecast.*, *24*, 1236–1251, doi:10.1175/2009WAF2222195.1.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers (2005), A description of the advanced research WRF version 2, *Tech. Note NCAR/TN-468+STR*, Natl. Cent. for Atmos. Res., Boulder, Colo.

Snyder, C., and F. Zhang (2003), Tests of an ensemble Kalman filter for convective-scale data assimilation, *Mon. Weather Rev.*, *131*, 1663–1677, doi:10.1175//2555.1.

Weng, Y., and F. Zhang (2011), Assimilating airborne Doppler radar observations with an ensemble Kalman filter for cloud-resolving hurricane initialization and prediction: Katrina (2005), *Mon. Weather Rev.*, in press.

Weng, Y., M. Zhang, and F. Zhang (2011), Advanced data assimilation for cloud-resolving hurricane initialization and prediction, *Comput. Sci. Eng.*, *13*, 40–49.

Zhang, F. (2011), The future of hurricane prediction, *Comput. Sci. Eng.*, *13*, 9–12.

Zhang, F., Y. Weng, J. A. Sippel, Z. Meng, and C. H. Bishop (2009), Cloud-resolving hurricane initialization and prediction through assimilation of Doppler radar observations with an ensemble Kalman filter: Humberto (2007), *Mon. Weather Rev.*, *137*, 2105–2125, doi:10.1175/2009MWR2645.1.

Zhang, M., F. Zhang, X. Y. Huang, and X. Zhang (2011), Inter-comparison of an ensemble Kalman filter with three- and four-dimensional variational data assimilation methods in a limited-area model over the month of June 2003, *Mon. Weather Rev.*, doi:10.1175/2010MWR3610.1.

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