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Assimilation of coastal Doppler radar data with the ARPS 3DVAR and cloud analysis for the prediction of Hurricane Ike (2008)

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[1] The impact of radar data on the analysis and prediction of the structure, intensity, and track of landfalling Hurricane Ike (2008), at a cloud-resolving resolution, is examined. Radial velocity (Vr) and reflectivity (Z) data from coastal radars are assimilated over a 6-h period before Ike landfall, using the ARPS 3DVAR and cloud analysis package through 30-min assimilation cycles. Eighteen-hour predictions were made. All 4 experiments that assimilate radar data produce better structure, intensity and precipitation forecasts than that from operational GFS analysis. The improvement to the track forecast lasts for the entire 18 hours while that to intensity prediction lasts about 12 hours. The Vr data help improve the track forecast more while reflectivity data help improve intensity forecast most. Best results are obtained when both Z and Vr data are assimilated. **Citation:** Zhao, K., and M. Xue (2009), Assimilation of coastal Doppler radar data with the ARPS 3DVAR and cloud analysis for the prediction of Hurricane Ike (2008), *Geophys. Res. Lett.*, *36*, L12803, doi:10.1029/2009GL038658.

1. Introduction

[2] A landfalling hurricane or typhoon can cause billions of dollars of damage and loss of many lives. Accurate prediction of their track, intensity and structure is crucial for the protection of life and property. Over the past decades, significant progress has been made in the hurricane track forecasting, but intensity forecasting has improved very slowly [*Davis et al.*, 2008; *Houze et al.*, 2007]. One of the reasons is the lack of accurate initial conditions that capture the internal structures and precipitation systems in hurricanes [*Davis et al.*, 2008]. Doppler radar is the only observing platform that can observe the 3D structure and evolution of hurricanes with high temporal and spatial resolutions. A few recent studies have assimilated radar observations into hurricane/typhoon prediction models [*Xiao et al.*, 2007; *Zhao and Jin*, 2008]. While their results are encouraging, more research is needed since the assimilation of radar data is a challenging problem and its application to hurricane prediction is still at its infancy.

[3] To build up dynamically consistent hurricanes from radar observations, an assimilation method that takes advantage of the high temporal and spatial resolutions of the data is believed to be necessary. A procedure combining the 3DVAR and complex cloud analysis scheme within the ARPS system [*Xue et al.*, 2003] has proven to be very effective for initializing mid-latitude thunderstorms in a number of studies [e.g., *Hu et al.*, 2006] (hereinafter referred to as H06). The ARPS 3DVAR [*Gao et al.*, 2004] analyzes radar radial velocity (V_r) data directly while the cloud analysis procedure retrieves cloud and hydrometeor fields from reflectivity (Z) and other cloud observations and adjusts in-cloud moisture and temperature.

[4] This study explores for the first time the use of the ARPS 3DVAR and cloud analysis system to assimilate V_r and Z data for hurricane analysis and prediction. The case to be examined is Hurricane Ike (2008), the third most destructive hurricane to ever make landfall in the United States. Ike made landfall near Houston, Texas, at 0700 UTC 13 September, when its maximum wind speed was about $48\ \mathrm{m\ s^{-1}}$. After landfall, it quickly weakened to a tropical storm and then became extratropical when it intercepted with a cold front around 1200 UTC 14 September. When approaching the landfall, Ike, especially its inner core region, was within the range of coastal WSR-88D radars at Houston-Galveston (KHGX), Texas and Lake Charles (KLCH), Louisiana, which also provided some dual-Doppler coverage. These data are assimilated through 30-min intermittent cycles over a 6-hour period. The impact of the assimilation on the intensity, rainband structure, track and quantitative precipitation prediction of Ike is the focus of this study.

2. Method and Experimental Design

[5] The non-hydrostatic ARPS prediction model with full physics is used during the assimilation cycles and for the forecast. The physics options used include the Lin ice microphysics, Goddard long and shortwave radiation, a 2-layer soil model and the TKE-based subgrid-scale turbulence and PBL parameterization (see *Xue et al.* [2001] for details). A 803 × 803 × 53 grid at 4-km horizontal grid spacing is used. The domain depth is 25 km and the near-surface vertical grid spacing is about 50 m. The lateral boundary conditions (LBCs) are from 6-hourly NCEP GFS analyses combined with 3 h forecasts at 0.5° resolution. Full-resolution Level-II data from KHGX and KLCH radars are used. Quality control procedures within the 88d2arps program, including velocity dealiasing and ground clutter removal, were applied, and the data were further checked and edited manually using NCAR Solo software (R. Oye et al., Software for radar translation, visualization, editing, and interpolation, paper presented 27th Conference on Radar Meteorology, American Meteorological Society, Vail, Colorado, 1995).

[6] A baseline control forecast without radar assimilation (CNTL) starts from the 0600 UTC 13 September GFS analysis. In other experiments, radar data are assimilated

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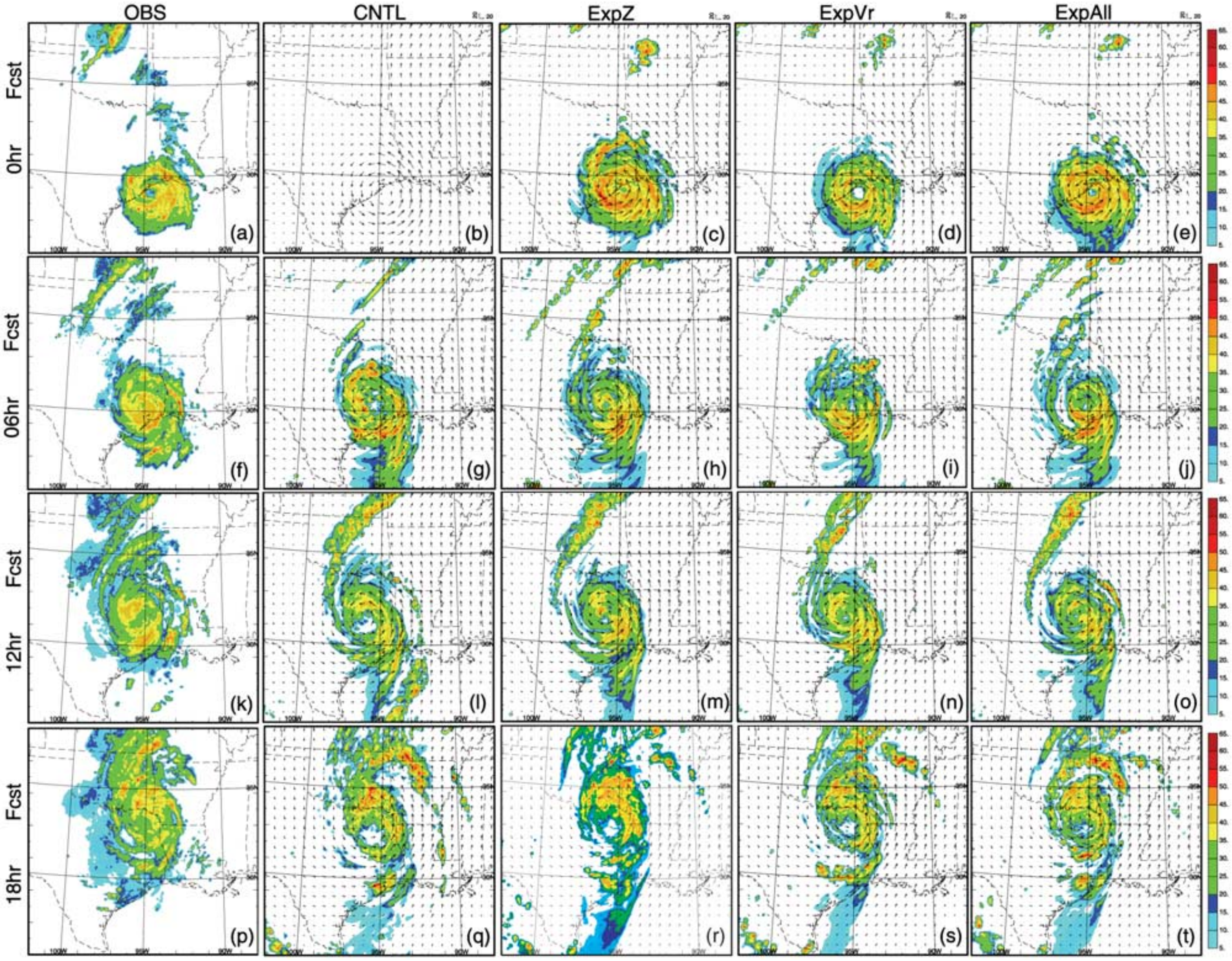

Figure 1. Composite reflectivity (color shaded) and wind vectors at 3 km height analyzed and predicted by experiments (b, g, l, and q) CNTL, (c, h, m, and r) ExpZ, (d, i, n, and s) ExpVr and (e, j, o, and t) ExpAll, as compared to (a, f, k, and p) observed composite reflectivity. The corresponding times are 0600 (initial time), 1200, 1800 UTC, September 13, and 0000 UTC September 14, 2008 (18 hour forecast time).

from 0000 to 0600 UTC every 30 minutes. Eighteen hour forecasts are then launched from 0600 UTC, covering the landfall and post-landfall periods of Ike. To study the impact of Z and V_r data individually and in combination, three assimilation experiments were performed: one with Z data only (ExpZ), one with V_r data only (ExpVr), and one with both Z and V_r data (ExpAll). Moreover, to evaluate the impact of adjusting in-cloud water vapor mixing ratio (q_v) in the cloud analysis, experiment ExpAllNQV is conducted, which is the same as ExpAll but without q_v adjustment. This experiment is motivated by a recent study (A. Schenkman et al., Storm-scale data assimilation for the analysis and prediction of a tornadic convective system: The impact of high-resolution X-band radar data, submitted to *Monthly Weather Review*, 2009) that found the moisture adjustment over-intensifies a continental mesoscale convective vortex.

3. Results of Experiments

3.1. Impact on the Analyzed and Predicted Structures of Ike

[7] We first examine the impact of radar data on the analyzed and predicted structures of Ike (2008). Figure 1 shows the analyzed and predicted radar composite (column maximum) reflectivity and 3-km height wind fields from CNTL, ExpZ, ExpVr and ExpAll, as compared to observed composite reflectivity (1^{st} column). A close examination of the final wind analyses shows a stronger and tighter circulation in the inner core region when radar data are assimilated (Figures 1c–1e versus Figure 1b). The GFS analysis used by CNTL contains no reflectivity. Among the other 3 experiments, ExpAll has a Z field (Figure 1e) that is closest to the observation (Figure 1a), while that of ExpZ is second. Both exhibit spiral rainband structures near the inner core region. In ExpVr, the assimilation cycles were also able to spin up the spiral band structures, which are however too weak.

[8] With improved initial conditions, the predictions of ExpZ, ExpVr and ExpAll are generally better than that of CNTL over the 18 h. At 6 h, the predicted vortex in CNTL (Figure 1g) is broader than in other cases, the Z field shows a "yin-yang" pattern with two rainbands located on the northwest and southeast side of the vortex center, respectively. There is also more precipitation extending further south over the ocean that was not observed. We note that CNTL

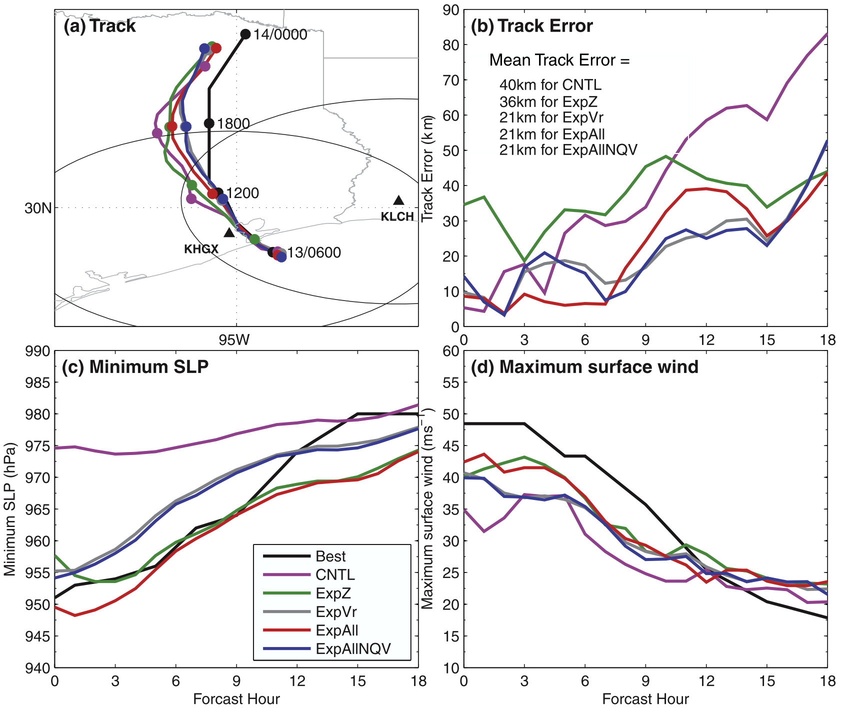

Figure 2. The predicted (a) tracks, (b) track errors, (c) minimum SLP, and (d) maximum surface wind speed, for Hurricane Ike (2008), from 0600 UTC 13 to 0000 UTC 14 September 14, 2008. The numbers in Figure 2b represent the mean track error over the 18 hour period. Large elliptic circles in Figure 2a are the 230-km range rings of KLCH and KHGX radars.

was able to quickly spin up rain bands within the first 1 to 2 hours of forecast (not shown). On the other hand, the 6-hour forecasts of ExpZ, ExpVr and ExpAll (Figures 1h–1j) all show tighter vortex circulations and more of spiral structures that match the observation better (Figure 1f). Among the three, ExpAll has the best organization of the spiral rainband pattern while that in ExpVr is least organized. In ExpVr, the precipitation in the northern half of the vortex is too weak.

[9] By 1200 UTC, the observed precipitation in Ike is completely over land and has developed more axis-asymmetric structure (Figure 1k). The main echo regions are now in the northwest and southeast quadrants, which are surrounded by much weaker outer rainbands, mostly on the north side. This general tendency is seen in all three forecasts with radar data (Figures 1m–1o), with that of ExpZ being the closest. CNTL experiment, however, exhibits more of a ‘double comma’ pattern, with two tails extending towards north then northeast, and to the south and south-southwest (Figure 1l). The inner core circulation is also broader as before, and there is a clear reflectivity hole at the center that is much more pronounced than in the observation (Figure 1k). All experiments predict a long tail of reflectivity extending to the north which is a result of the hurricane circulation interacting with a cold front.

[10] At 18 h (0000 UTC, September 14), the end of the forecasts, the precipitation pattern becomes even more axis-asymmetric (Figure 1p). The strongest precipitation is now found north of the vortex center, presumably due to the much stronger moisture transport from the Gulf on the east wide, and some interaction with the flow from the north. On the west side of the vortex, some of the air is now originated from the higher latitudes, behind the slow-moving cold front.

[11] This vortex eventually merged with the low pressure trough extending along a cold front (not shown). This general tendency is predicted well in all four experiments (Figures 1q–1t). By this time, based on the precipitation structure, it is no longer clear which forecast is better. The vortex center of CNTL is somewhat too far south, while that in the others are closer to the truth. The circulations in the forecasts with radar data do still appear tighter. The observed hurricane eye is filled with precipitation due to landfall, but all forecasts still exhibit a precipitation-free eye, suggesting over-prediction of intensity at this time. Overall, the assimilation of Vr and Z data improves the prediction of circulation and precipitation structures in the Ike in the 18 h examined, with the impact decreasing with forecast time. In general, the forecast assimilating both Vr and Z data is the best.

3.2. Impact on the Track and Intensity Prediction

[12] The predicted track of vortex center, maximum surface wind speed (MSW) and the associated minimum sea-level pressure (MSLP) from all experiments are plotted in Figure 2, together with the National Hurricane Center (NHC) best track data, for the 18-hour forecast period. Figure 2a shows the predicted and the best tracks, while Figure 2b shows the track errors at each forecast hour. Also included are the results of ExpAllNQV. In the first 3 h, all experiments have similarly low track errors of 5 to 15 km, except for ExpZ (Figure 2b). Apparently, without the help of Vr data, ExpZ with Z data only developed a significant

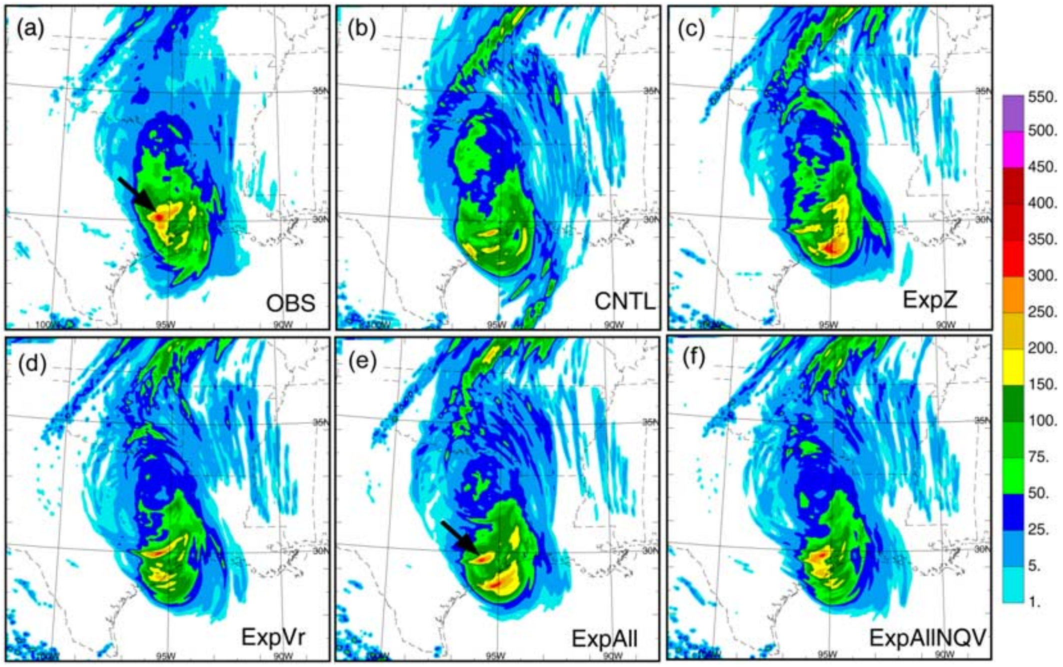

Figure 3. Eighteen-hour accumulated precipitation (mm) valid at 0000 UTC 14 Sep 2008 from (a) NCEP Stage IV precipitation analyses, and forecasts of (b) CNTL, (c) ExpZ, (d) ExpVr, (e) ExpAll and (f) ExpAllNQV.

position error of about 35 km at the end of the assimilation cycles so that the center is already at the coast (Figure 2a).

[13] In CNTL, the predicted hurricane took a west most track, resulting in largest track errors that exceed 80 km at the end of forecast, and a 18-hour mean track error of 40 km. ExpZ has the second largest mean error of 36 km. The mean track error of the other 3 experiments assimilating Vr or both Z and Vr data have the same mean track error of 21 km, although earlier on, ExpAllNQV has the smallest error while at the end the error of ExpAll is the smallest. The tracks of ExpVr and ExpAllNQV are very close, so are their MSLP and MSW (Figures 2c and 2d). This indicates that most of the effect of assimilating Z is lost when moisture field is not adjusted in the cloud analysis. In another experiment in which temperature instead of moisture adjustment is turned off, little change is found (not shown). This suggests that for tropical systems, moisture adjustment is more important than temperature adjustment, contrary to the case of continental deep convection reported by H06. This can be understood based on the fact that tropical systems usually have much smaller convective available potential energy (CAPE) so that the environment temperature profile is close to the moist adiabat of a lifted low-level air parcel. The temperature adjustment based on the moist-adiabat-method (K. Brewster, Recent advances in the diabatic initialization of a non-hydrostatic numerical model, paper presented at 21st Conference on Severe Local Storms, American Meteorological Society, San Antonio, Texas, 2002) therefore has a rather small effect. Another reason is that mid-latitude convection is mostly buoyancy-driven while convection in hurricanes is more dynamics-driven. The moisture is the primary fuel for hurricanes. These experiments show that the assimilation of Vr data has a bigger role in improving track forecasting in this case.

[14] As is apparent from Figures 2c and 2d, the hurricane in the GFS analysis is too weak. The MSLP at the initial time of CNTL is about 975 hPa versus the observed 951 hPa. The best track MSW is about 48 m s^{-1} while that in GFS analysis is 35 m s^{-1}. The analyzed intensity is increased in all cases that assimilate radar data, with that of ExpAll (MSLP = 950 hPa and MSW = 43 m s^{-1}) being closest to the truth. The analyzed MSLPs in ExpVr and ExpZ are 4 to 7 hPa higher than observed, but is still much better than in CNTL, which has an error of about 15 hPa.

[15] In the first hour of forecast, the MSLP of ExpAll decreases by about 3 hPa; it starts to increase and reaches the observed level by 5 h and remains close to the observed values until 9 h. From that time, the observed MSLP starts to rise more rapidly while the predicted MSLP continues to increase at a similar rate, indicating that the predicted Ike does not fill as fast as the observed one. Still, the overall agreement between the MSLP of ExpAll and the best track values is the best among all experiments. In comparison, CNTL significantly under-predicts the intensity in the first 12 hours of forecast.

[16] Among the other experiments, ExpZ is closest to ExpAll in terms of MSLP. It starts with a MSLP that is about 7 hPa higher, but its MSLP decreases quickly in the first 2 h, and becomes very close to ExpAll by 6 h. They maintain almost identical MSLPs afterwards. This suggests that the Z assimilation via cloud analysis does have a significant impact on the Ike prediction, and this is achieved mainly through the introduction of latent heat energy by adjusting q_v field, and through the improvement to cloud and hydrometeor fields.

[17] Similar to the track, the MSLP and MSW predictions in ExpVr and ExpAllNQV are almost identical, and they show weaker vortices and winds than observed until about 12 h. After that, the observed Ike is weaker. The fact that predicted Ike weakens slower after landfall is a subject for further investigation. It may be related to the surface flux and/or microphysics parameterizations. Running a nested

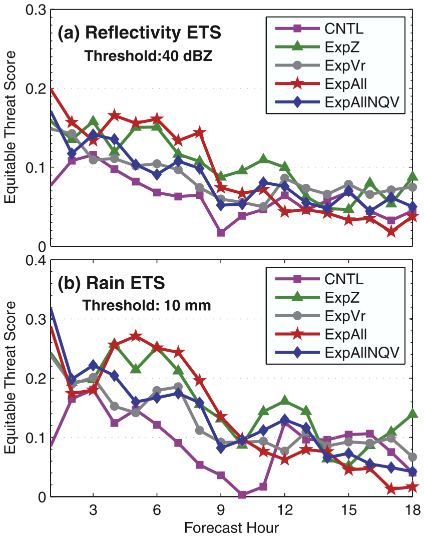

Figure 4. Equitable threat scores of (a) predicted composite reflectivity at 40-dBZ threshold, and (b) predicted hourly accumulated precipitation at the 10 mm h^{-1} threshold for experiments CNTL, ExpZ, ExpVr, ExpAll and ExpAllNQV.

1.33 km forecast did not change this trend noticeably so resolution does not appear to be the main issue.

3.3. Impact on Precipitation Forecast

[18] Inland flooding is the biggest hazard of landfalling hurricanes. Accurate precipitation forecast is therefore very important. Figure 3 compares the total accumulated precipitation during the 18-hour forecast from all 5 experiments with the corresponding NCEP 4-km-resolution Stage IV precipitation analysis (Y. Lin and K. E. Mitchell, The NCEP Stage II/IV hourly precipitation analyses: Development and applications, paper presented at 19th Conference on Hydrology, American Meteorological Society, San Diego, California, 2005). It is clear that CNTL (Figure 3b) distinctively underestimates the precipitation, especially the observed strong precipitation band and maximum center near 30 N, north of Houston (black arrow in Figure 3a). The prediction of this band is improved in all radar-assimilating experiments, especially in ExpAll (Figure 3e), even though the predicted band is somewhat south of the observed one. For lighter precipitation, the general pattern is similar to the observed in all experiments.

[19] Overly strong precipitation is found along the coast in ExpAll (Figure 3e) and ExpZ (Figure 3c) and we can infer that it is probably due to too much moisture "pumping" within the assimilation cycles. This is supported by the fact that no such over-prediction exists in ExpAllNQV; additional tuning to the cloud analysis procedure may improve the precipitation forecast.

[20] Finally, we present in Figure 4 the equitable threat scores (ETS) for the hourly accumulated precipitation for the 10 mm h^{-1} threshold, and for the instantaneous composite reflectivity at 40 dBZ threshold. The Stage IV precipitation analysis is again used here, together with composite Z fields constructed from level-II radar data. ETS here is used in a similar way as in H06 and calculated for the domain shown in Figure 1. In general, the two sets of ETSs tell a very similar story. Among all experiments, CNTL has the lowest scores until 12 h. In the first 10 h, ExpAll shows highest scores, while the scores of other experiments are in-between. These quantitative results are in agreement with our earlier subjective assessment (Figure 1). After 12-h forecast, the scores among the experiments become similar, indicating the loss of radar data impact after this time.

[21] It is noted that the scores of ExpAll decrease quickly in the first couple of hours then increase over the next few hours. This U shape of ETS curves is also observed by H06, and is suggested to be due to the imbalance among the analyzed variables and subsequent adjustments for the variables to better fit the model dynamics and physics. After the initial adjustment, the precipitation bands become better organized.

4. Summary

[22] We examined the impact of high-resolution radar data on the analysis and prediction of the structure, intensity and track of landfalling Hurricane Ike (2008), at a cloud-resolving resolution. The Z and V_r data from two coastal operational WSR-88D radars are assimilated over a 6-h period shortly before the center of Ike reaches the coast, using the ARPS 3DVAR and cloud analysis package through 30-min assimilation cycles. Eighteen-hour predictions using the ARPS model followed.

[23] Results show that all 4 experiments that assimilate radar data produce better structure and intensity forecasts than the forecast starting from operational GFS analysis. The improvement to the track forecast lasts for the entire 18 h while that to intensity prediction lasts about 12 h. The Vr data appear to help improve track forecast more while the Z data help improve intensity forecast most. The moisture adjustment within the cloud analysis is found to be most important for reflectivity assimilation. Overall, the analysis and forecast are the best when both Z and Vr data are assimilated, and the benefits of Z and Vr data appear to be complementary. These conclusions are further supported by quantitative precipitation verification scores. The assimilation procedure used is relatively inexpensive and can easily be run in real time.

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