Progress Report

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A Partnership to Develop, Conduct, and Evaluate Realtime Advanced Data Assimilation and High-Resolution Ensemble and Deterministic Forecasts for Convective-scale Hazardous Weather: Toward the Goals of a Weather-Ready Nation

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1. Project scientific objectives

The realtime data assimilation and forecasting performed under this NOAA CSTAR project, together with retrospective analyses using the real time data, aim to address the scientific issues including:

(1) The value and cost-benefit trade-offs of storm-scale versus coarser-resolution short-range ensembles and even-higher-resolution deterministic forecasts;

(2) The most suitable perturbation methods for storm-scale ensembles, among breeding, ETKF (ensemble Transform Kalman filter), EnKF, physics perturbations, stochastic physics, and multi-model ensemble;

(3) Proper handling and use of lateral and lower boundary perturbations;

(4) The value and impact of assimilating high-resolution data including those from WSR-88D radars;

(5) The value and impact of using more advanced EnKF data assimilation methods on short (0-12 hours) and intermediate range (12-60 hours) predictions;

(6) The predictability limits of existing convection within the current diurnal cycle, convection that develop under mesoscale forcing within the second and third day diurnal cycles, and convection whose evolution is affected by earlier convection;

(7) The performance and impact of more sophisticated double-moment microphysics schemes for severe weather and quantitative precipitation forecasting;

(8) The accuracy and impacts of planetary boundary layer (PBL) parameterization on the prediction of low-level storm environment and on the location and timing of convective initiation;

(9) The most useful ensemble forecast products for the storm scales;

(10) The most effective ensemble post-processing and calibration methods at the convective scale, and

(11) The impact of unique convective-scale forecast products on realtime forecasting and warning.

2. Overview of CAPS SSEF program in supporting HWT SFE

The Center for Analysis and Prediction of Storm (CAPS) produced multi-model multi-physics storm-scale ensemble forecasts (SSEF) at convection-allowing horizontal grid spacing of 3-4 km in realtime every year since 2007 from late April to early June to support the NOAA Hazardous Weather Testbed (HWT) Spring Forecasting Experiment (SFE), (Kong et al. 2010, 2012; Xue et al. 2010). The primary funding came from the NOAA CSTAR grant as well as other NOAA grants and grants from other federal agencies such as NSF and ONR. During current three-year reporting period from 2014 to 2016, CAPS further extended the forecast domain and lead time, implemented experimental EnKF data assimilation and ensemble forecast system, demonstrated 3D/4D visualization based on convection-allowing model (CAM) high frequency output, and in 2016 added a new operational model core NMMB and contributed and participated NOAA HMT FFaIR experiment (Kong et al. 2014, 2015, 2016). Table 1 outlines the SSEF highlights from 2014 to 2016 under current CSTAR grant. Figures 1 and 2 are SSEF domains used in 2014 season and in 2015-2016, respectively.

Table 1. CAPS SSEF highlights for the reporting period

	2014	2015	2016
member	24 (12)	20 (12)	24 (12)
Domain (grid)	CONUS (4 km)	CONUS (3 km)	CONUS (3 km)
Lead time	60 h	60 h	36-60 h
NWP model	ARW (v3.5.1) COAMPS	ARW (v3.6.1)	ARW (v3.7.1) NMMB
EnKF	EnKF full domain	EnKF full domain	GSI+EnKF full domain
3D visualization	yes	yes	yes

2.1 2014 CAPS SSEF overview for NOAA/HWT SEF2014

The CAPS 2014 spring forecast experiment started on 21 April 2013 and ended on 06 June, encompassing the HWT 2014 SPE that was officially between 05 May and 06 June. As in previous years, the forecasts were produced Monday through Friday, initialized at 0000 UTC (1900 CDT) of each day and made available in the early morning for evaluation at HWT. A 1200 UTC 8-member ensemble forecast was produced the same way but run on local computer system, the University of Oklahoma's Boomer system. The 00 UTC 4-km ensembles consist of 20 ARW and 4 COAMPS members for a total of 24 members. The 12 UTC ensembles are a subset of 00 UTC members. For the perturbed boundary members, 3-hourly forecasts from consistent NCEP SREF members are used to provide the lateral boundary conditions (Kong 2014).

In CAPS 2014 season, four ARW two-moment microphysics schemes (Thompson, Milbrandt-Yau, Morrison, and WDM6), as well as a newly developed P3 (Predicted Particle Properties) microphysics by Morrison and Milbrandt (Personal Communications) were used for SSEF ARW members. A modified Milbrandt-Yau scheme (MY2) addressing overly prediction of ice cloud anvil was also included. Model simulated radar reflectivity was computed within each individual microphysics algorithm. A modified YSU PBL scheme (YSU-T), made available by Greg Thompson (Personal Communications) to address the dry and warm bias issue in YSU, was also included.

Figure 1 shows the forecast domain for SFE 2014.

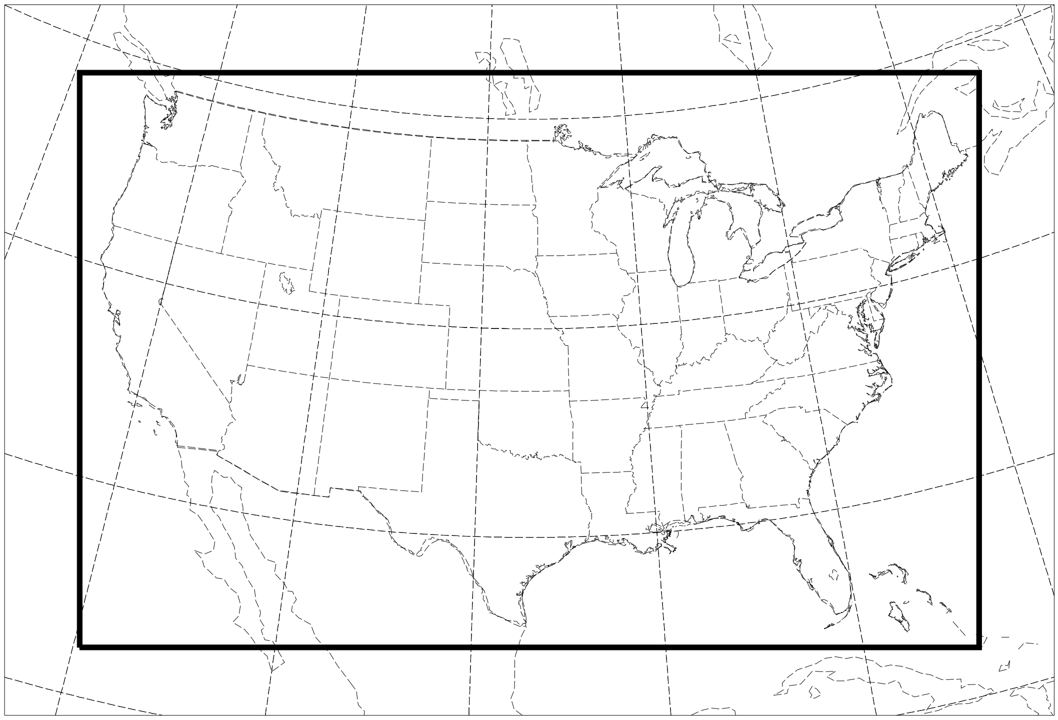

Figure 1. The CAPS Spring Forecast Experiment domain (thick inner box: 1200×768 horizontal grid points at 4 km) for the 2014 SSEF runs.

2.2 2015 CAPS SSEF overview for NOAA/HWT SEF2015

The CAPS 2015 Storm-Scale Ensemble Forecast started on 20 April through 5 June 2015, encompassing the NOAA HWT 2015 Spring Forecast Experiment that was officially between 4 May and 5 June. Different from past years, starting in 2015 the SSEF CONUS domain was changed from 4-km to 3-km horizontal grid spacing, resulting in 2.1 times more grid points and covering 18% more area than in the 2014 season (see Figure 2). The migration to a 3-km grid spacing makes CAPS SSEF more consistent with the operational HRRR setting. The regular 0000 UTC 3-km ensembles consist of 20 WRF-ARW members initialized with a onetime 3DVAR analysis, with the forecast lead time of 60 hours (Kong 2015). For the model microphysics, a second P3 (Predicted Particle Properties) microphysics scheme, a two-ice-category variant (Mrrison and Milbrandt, personal communications) was included to the MP family of other two-moment schemes available in ARW.

2.3 2016 CAPS SSEF overview for NOAA/HWT SEF2016

The CAPS 2016 Storm-Scale Ensemble Forecast ran two separate periods: One started on 18 April through 3 June 2016, encompassing the NOAA HWT 2016 Spring Forecasting Experiment that was officially between 2 May and 3 June; and the second period was from June 20 to July 22, with the July 4th week off, encompassing the NOAA HMT FFaIR Experiment (Kong 2016). Figure 2 shows the model domains (both ARW and NMMB) used in the 2016 season.

Operational NMMB model core was added in 2016 season, with 6 members. Only one NMMB member (nmmb_cn) had radar data analysis. Other five non-radar NMMB members had IC and LBC perturbations provided from SREF perturbed members. All NMMB members used a fixed set of physics configuration matching the NCEP operational high-res NMMB runs.

The CAPS non-cycled 3DVAR-based SSEF and the cycled GSI+EnKF based SSEF during NOAA/HWT SEF2016 also contribute into a larger Community Leveraged Unified Ensemble (CLUE) coordinated among various groups including NSSL, SPC, CAPS, NCAR, UND, EMC, GSD, and DTC, in an effort to provide guidance to the design of near-future operational SSEF systems (Clark et al. 2016).

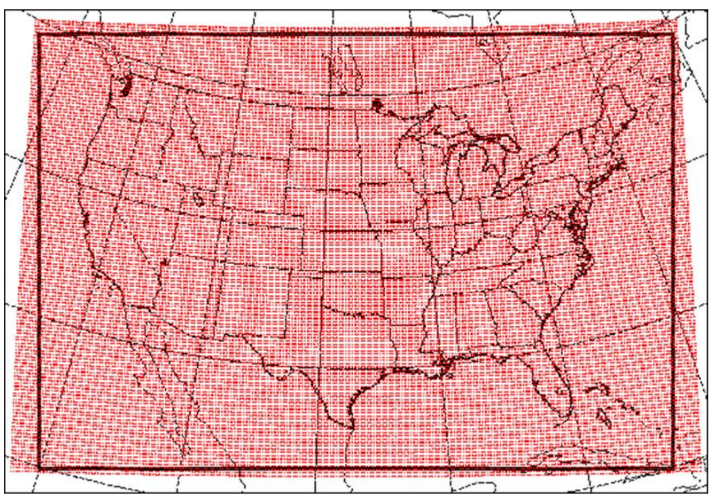

Figure 2. The 2015/2016 CAPS Spring Forecast Experiment domains, with ARW domain marked by thick lines (1680x1152 at 3 km) and the NMMB domain marked as red dots.

3. Experimental EnKF based SSEF

From 2014 to 2016 SFEs, CAPS implemented experimental EnKF based storm-scale ensemble forecast over CONUS domain and made comparisons with the 3DVAR based SSEF. CAPS EnKF package was used for its high efficiency in parallel processing large volume of Doppler radar data. In 2014, a 4-km ensemble of 24h forecasts, starting at 1800 UTC, with 40 WRF-ARW members was produced over the CONUS domain. This ensemble was configured with initial perturbations and mixed physics options to provide input for EnKF analysis. Each member used WSM6 microphysics with different parameter settings. All members also included random perturbations with recursive filtering of ~20 km horizontal correlations scales, with relatively small perturbations (0.5K for potential temperature and 5% for relative humidity). EnKF analysis (cycling), with radar data and other conventional data, was performed from 23 to 00 UTC every 15 min over the CONUS domain, using as background the 40-member ensemble. A 12- member ensemble forecast of 24h long followed using the 00 UTC EnKF analyses. In addition, two deterministic forecasts, one from the ensemble mean analysis and another from a 3DVAR analysis that was cycled from 23 UTC in every 15 min to 00 UTC started with the ensemble mean to allow direct comparison with EnKF mean forecast, were also produced (Figure 3).

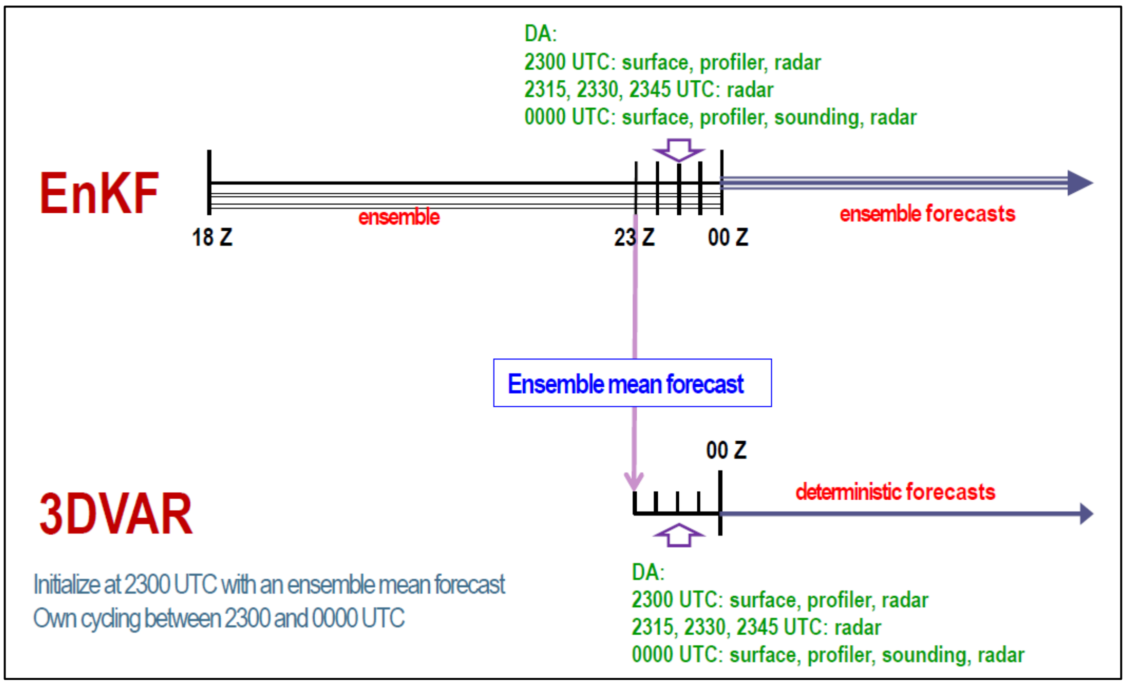

Figure 3. Flow diagram for the realtime EnKF and 3DVAR storm-scale forecasts. The EnKF DA are performed from 2300 UTC to 0000 UTC at 15 minute intervals. A 3DVAR DA is carried out on the ensemble mean forecast at 2300 UTC followed by its own DA cycles to facilitate direct comparison with the EnKF forecasts

In 2015 SFE, a same EnKF procedure as in 2014 (Figure 3) was employed, with exceptions in that the horizontal grid was changed to 3-km in consistent with the non-cycled 3DVAR SSEF setting; 60-h long forecasts were produced;; and additionally four deterministic forecasts, two (one with Thompson and another with WSM6 microphysics) from the ensemble mean analysis and another two (Thompson, WSM6) from 3DVAR cycling, were also produced, allowing further examination of model microphysics impact in these ensemble mean forecasts.

In 2016 SFE, different from the 2015 SFE for the experimental suite of SSEF, CAPS EnKF was combined with GSI EnKF in a 6-hour long cycling period (1800 – 0000 UTC) to add more observations to improve the ensemble initial conditions. First, a 40-member WRF-ARW ensemble was initiated at 1800 UTC over the same 3-km grid CONUS domain, using the 18Z NAM analysis with perturbations retrieved from SREF members. This ensemble was configured with initial perturbations and mixed physics options to provide input for EnKF analysis. Unlike in previous years, each member used Thompson microphysics (while in 2014 & 2015 seasons when WSM6 was used) with different parameter settings in graupel density. No radar data was analyzed for this set of runs until 2300 UTC. RAP/HRRR GSI data stream (except satellite data and Mesonet1 data) were assimilated hourly from 1900 to 0000 UTC using the GSI EnKF system. Radar reflectivity and radial velocity data were assimilated using CAPS EnKF system from 2300 to 0000 UTC every 15 min. A 12-member ensemble forecast of 60 h long followed using the 0000 UTC final GSI+EnKF analyses. Among them, nine were initiated using selected ensemble member analyses with mixed IC/LBC perturbations and physics options, and three were deterministic forecasts from the 0000 UTC ensemble mean analysis with three different microphysics schemes. Figure 4 is a workflow diagram showing the CAPS GSI+EnKF cycling process in 2016 SFE.

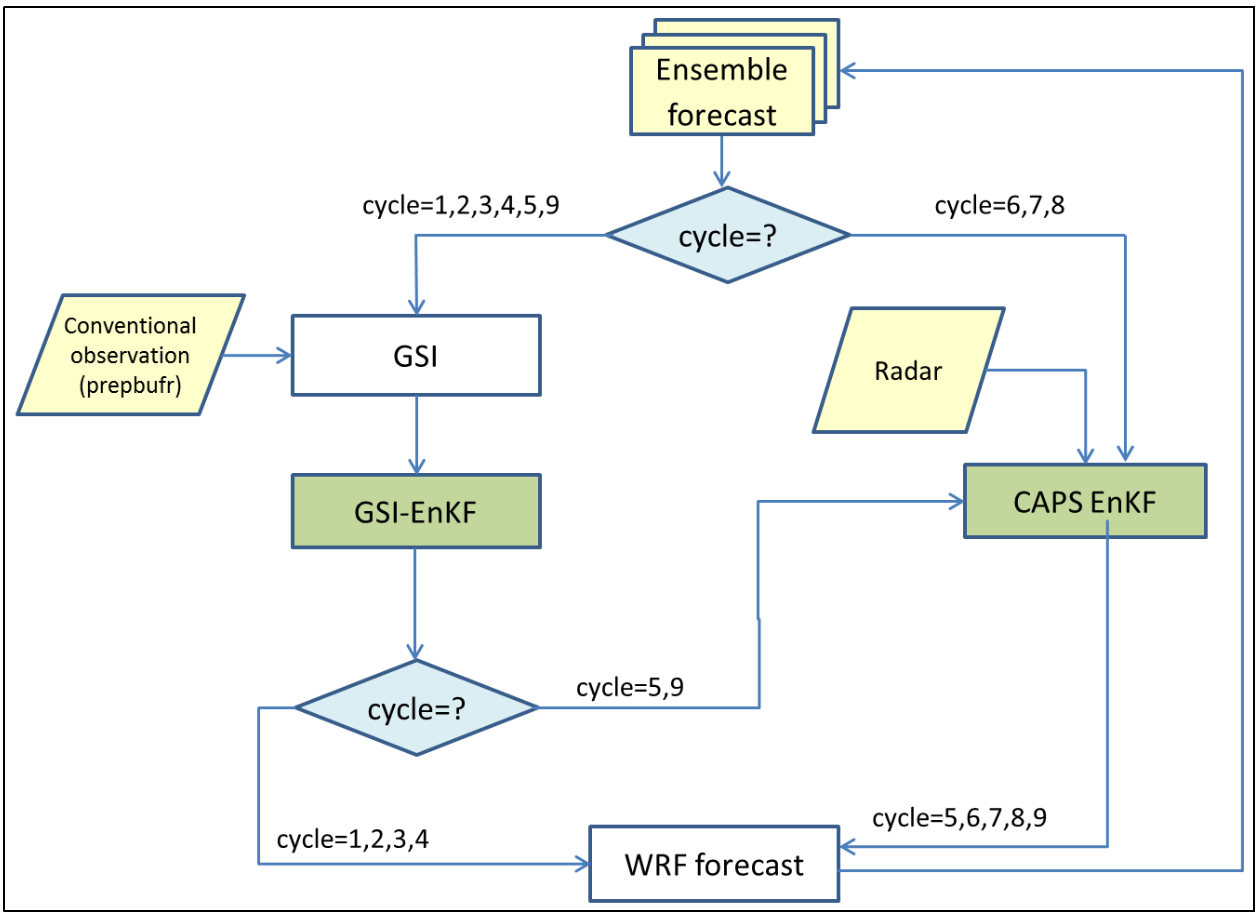

Figure 4. Diagram showing GSI+EnKF cycles in 2016 SFE.

4. CAPS participation to NOAA/HMT FFaIR-2016

4.1 CAPS HMT FFaIR Highlight

New in 2016, CAPS actively participated the NOAA Hydrometeorological Testbed (HMT) Flash Flood and Intensive Rainfall (FFaIR) Experiment by contributing a convection-allowing 3-km grid SSEF of 60 h long from June 20 through July 22 during the 4-week FFaIR experiment period (with the July 4-8 week off). The NOAA/HMT FFaIR2016 CAPS SSEF consist of 15 members of non-cycled 3DVAR-based ensemble configured with 13 ARW and 2 NMMB members (Tables 2 and 3). All model domains and data flow are the same as in the HWT component.

Table 2. ARW members for the NOAA/HMT FFaIR2016. NAMa and NAMf refer to 12 km NAM analysis and forecast, respectively. ARPSa refers to ARPS 3DVAR and cloud analysis

Member	IC	BC	Radar data	Microphy	LSM	PBL
arw_cn	00Z ARPSa	00Z NAMf	yes	Thompson	Noah	MYJ
arw_m2	arw_cn + arw-p1_pert	21Z SREF arw-p1	yes	Morrison	Noah	MYNN
arw_m3	arw_cn + arw-n1_pert	21Z SREF arw-n1	yes	MY	Noah	MYNN
arw_m4	arw_cn + arw-p2_pert	21Z SREF arw-p2	yes	Morrison	Noah	MYJ
arw_m5	arw_cn + arw-n2_pert	21Z SREF arw-n2	yes	Thompson	Noah	MYNN
arw_m6	arw_cn + nmmb-p1_pert	21Z SREF nmmb-p1	yes	MY	Noah	MYNN
arw_m7	arw_cn + nmmb-n1_pert	21Z SREF nmmb-n1	yes	Morrison	Noah	MYNN
arw_m8	arw_cn + nmmb-p2_pert	21Z SREF nmmb-p2	yes	Morrison	Noah	MYJ
arw_m9	arw_cn + nmmb-n2_pert	21Z SREF nmmb-n2	yes	Thompson	Noah	MYNN
arw_m10	00Z ARPSa	00Z NAMf	yes	P3	Noah	MYJ
arw_m11	00Z ARPSa	00Z NAMf	yes	Morrison	Noah	MYJ
arw_m12	00Z ARPSa	00Z NAMf	yes	MY	Noah	MYJ
arw_m13	arw_cn + arw-n2_pert	21Z SREF arw-n2	yes	Thompson	Noah	MYJ

Table 3. NMMB members for NOAA/HMT FFaIR2016

member	IC	BC	Radar data	mp_phy	lw_phy	sw-phy	sf_phy
nmmb_cn	00Z ARPSa	00Z NAMf	yes	Ferrier-Aligo	RRTMG	RRTMG	Noah
nmmb_m1	00Z NAMa+ arw-p3_pert	21Z SREF arw-p3	no	Ferrier-Aligo	RRTMG	RRTMG	Noah

Ensemble products were provided to the HMT in GEMPAK format. They include neighborhood probability of QPF exceedances of Flash Flood Guidance (FFG) and Recurrence Intervals (RI), as well as QPF probability matched means (PM) of various accumulation lengths (3-, 6-, 12-, and 24-h). In order to save disk space, the HMT GEMPAK data were trimmed off 100 grid points in west and south edges, 50 grid points in east edge, and 80 grid points in north edge (see Figure 5). This reduces the GEMPAK file sizes by 23%.

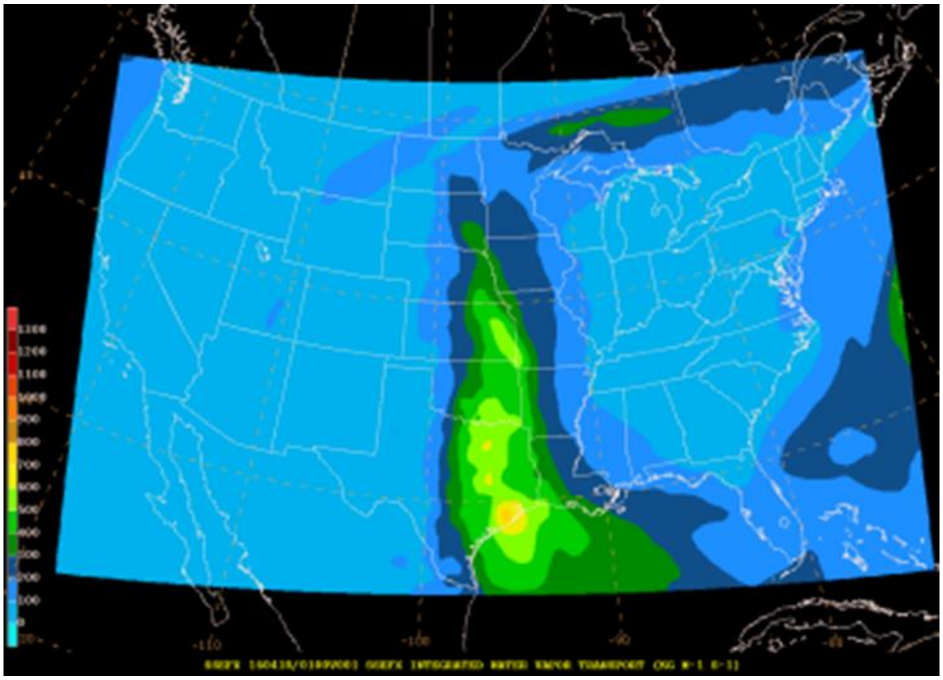

Figure 5. Sub-domain for the GEMPAK data for HMT FFaIR

The 2016 FFaIR Report ranked CAPS SSEF on the top with respect to Day 1 Subjective QPF scores and a close second to the NAMRR for the Day 2 QPF scores.

4.2 CAPS HMT SSEF Product Example: West Virginia Flash Flood Case

The West Virginia Flash Flood occurred during 23-24 June 2016. It measured max gauge of 9.37 inches at Maxwelton, WV. The Elk River high reached 33.37 ft. The consequence is 23 fatalities with 15 in Greenbrier Co. 44 of 55 WV counties were placed in State Emergency. The CAPS HMT phase did capture the entire episode during the regular operation period.

Figure 6 shows the Multi-Radar Multi-Sensor (MRMS) precipitation estimation (QPE) of the 12 h, and 24 h accumulated precipitation valid at 00 UTC June 24, 2016. Figures 7 and 8 plot the 24 h and 12 h QPF in the form of probability matching mean from CAPS HMT SSEF. The forecasted heavy 24 h precipitation maxima over WV in Figure 7 are 378 and 337 mm, respectively, compared to MRMS's 623 mm in Figure 6b. The PM forecast values are more close to the max gauge recorded (238mm) in Maxwelton, WV. Figures 9 and 10 are example neighborhood probabilities. They demonstrate great values for the CAPS SSEF's ability to predict the intensive flash flood occurrence 24 h or even 48 h in advance,

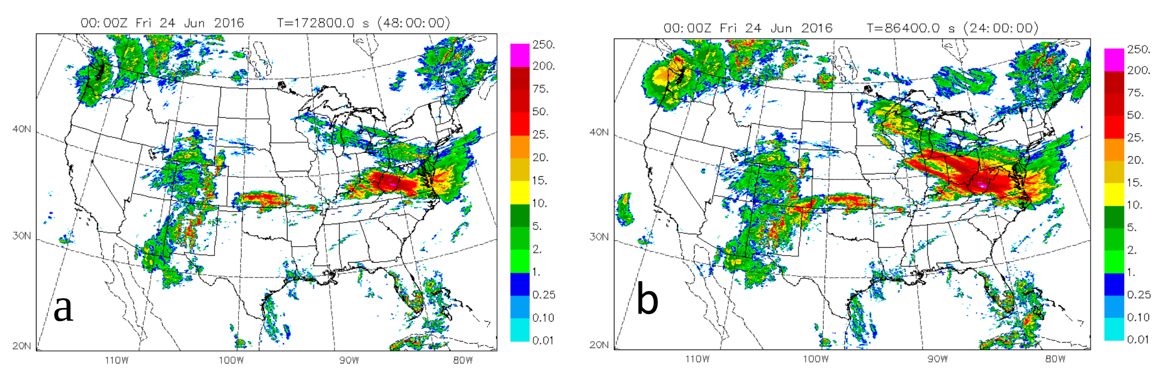

Figure 6. MRMS QPE: (a) 12 h accumulated precipitation, 12-00 UTC, (b) 24 h accumulated precipitation, 00-00 UTC, valid at 00 UTC June 24, 2016.

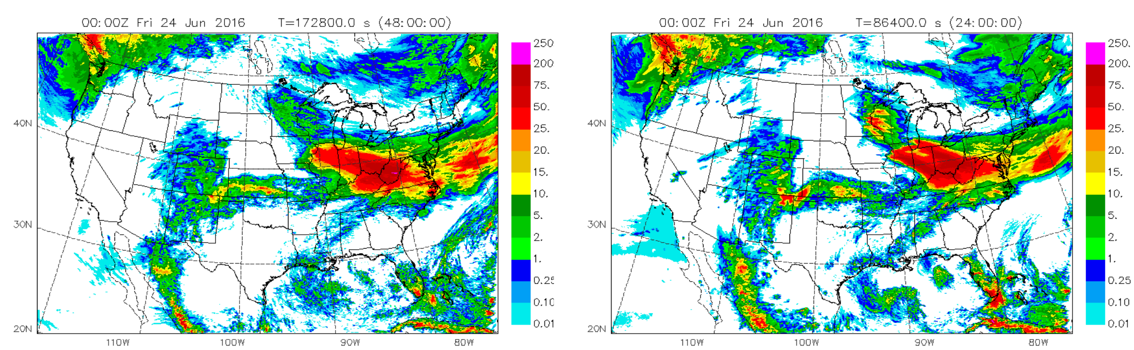

Figure 7.Probability matched mean forecast 24 h accumulated precipitation, valid at 00 UTC June 24, 2016. (a) 48 h forecast, (b) 24 h forecast

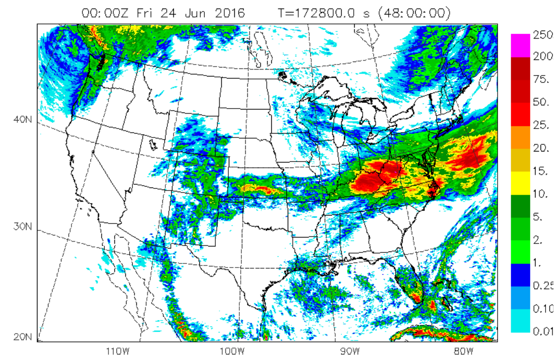

Figure 8. Same as Figure 7, except for 12 h accumulated precipitation.

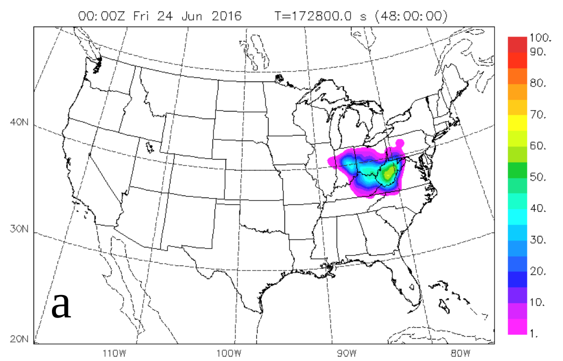

Figure 9. 48 h forecast of neighborhood probability of 24 h QPF exceeding (a) 24 h Flash Flood Guidance (FFG), and (b) exceeding 3 inches, valid at 00 UTC June 24, 2016.

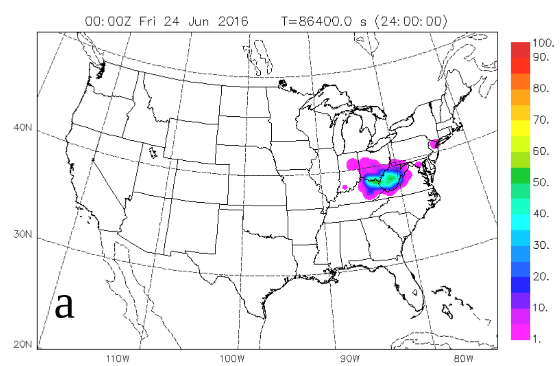

Figure 10. Same as Figure 9, except for 24 h forecast of 12 h QPF valid for12-00 UTC

5. 3D/4D Visualization Demonstration

Since 2015 SFE, 3D fields from the 00Z control run covering a 200x200 grid-point area (600 km x 600 km) region were extracted from the CONUS domain on Stampede at TACC and transmitted to the NWC in real-time. The domain was centered on the SPC-determined daily area of interest as set on the NSSL HWT web site the previous afternoon, as a default, or as manually set by one of the Co-PIs (KB). All 3D files generally arrived by 0800 CDT. Workflow for the 3D data processing is shown in Figure 11.

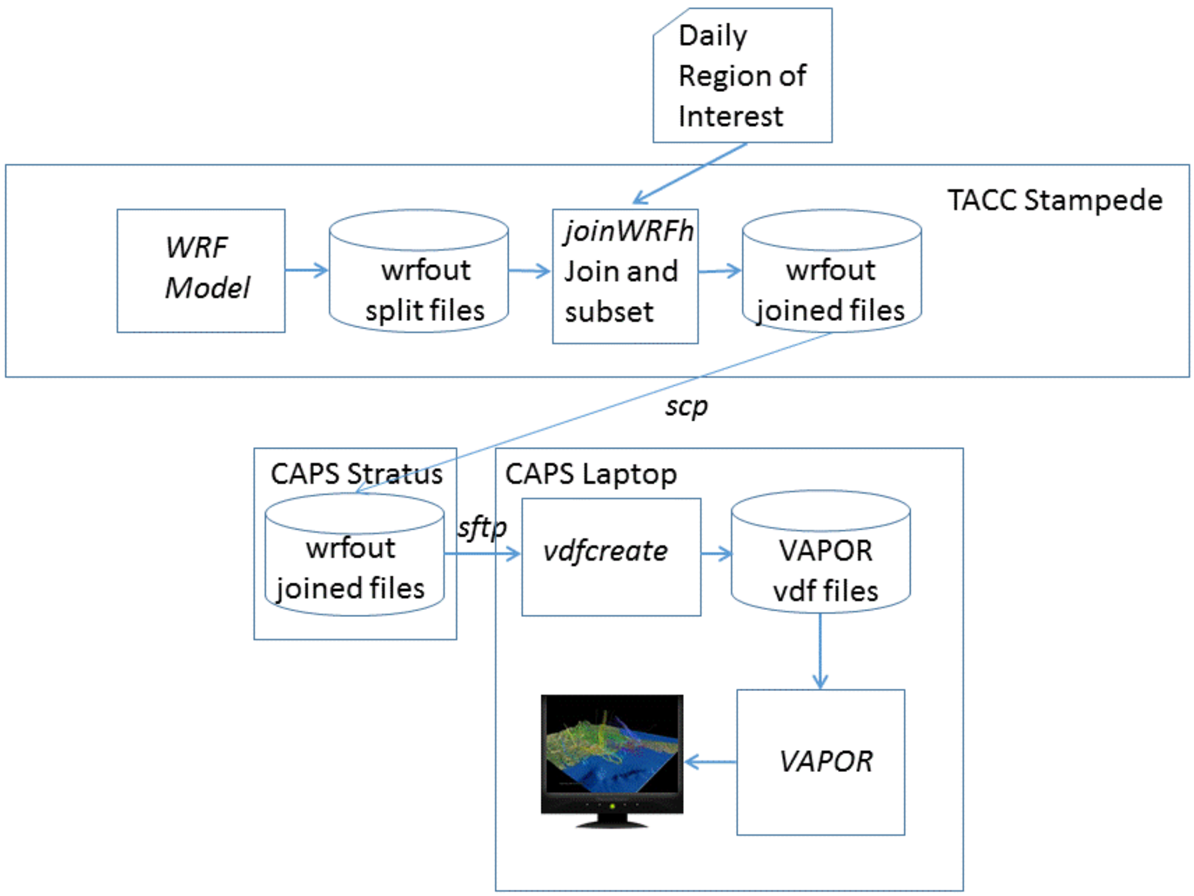

Figure 11. Workflow for 2016 3D data extraction, transmission and 3D visualization processing.

For 2016 the realtime SSEF system created 6-minute interval output for 3D visualization from 1800 UTC to 0600 UTC (forecast hours 18-30) on TACC Stampede for the following members: cn, m17, m18, m19, m20. The WRF subsetting and join program, joinwrfh, were queued on Stampede at 0530 CDT each morning to create joined wrfout files of a 600 x 600 km domain centered on the HWT centerpoint of the day or at an appropriate location of interest selected by one the Co-PIs (KB) based on prior day’s forecast. The joined wrfout files were feed into a local laptop where 3D fields were processed into VAPOR data format (vdf) files using the VDCWizard tool. The NCAR VAPOR software was then used to display relevant fields of the day in the form of mp4 movies for one or more members. The movies were created manually by one of the co-PIs and/or a scientist from NSSL (Robert Hepper).

The movies were presented at the HWT briefing once per week (Tuesdays) and every day on the CAPS HWT 3D visualization web site, http://www.caps.ou.edu/~kbrews/hwt_2016 . Sample static VAPOR demonstration images are shown in Figures 12 and 13, a tornadic storm case in the Texas Panhandle and a high wind case in North Carolina, respectively

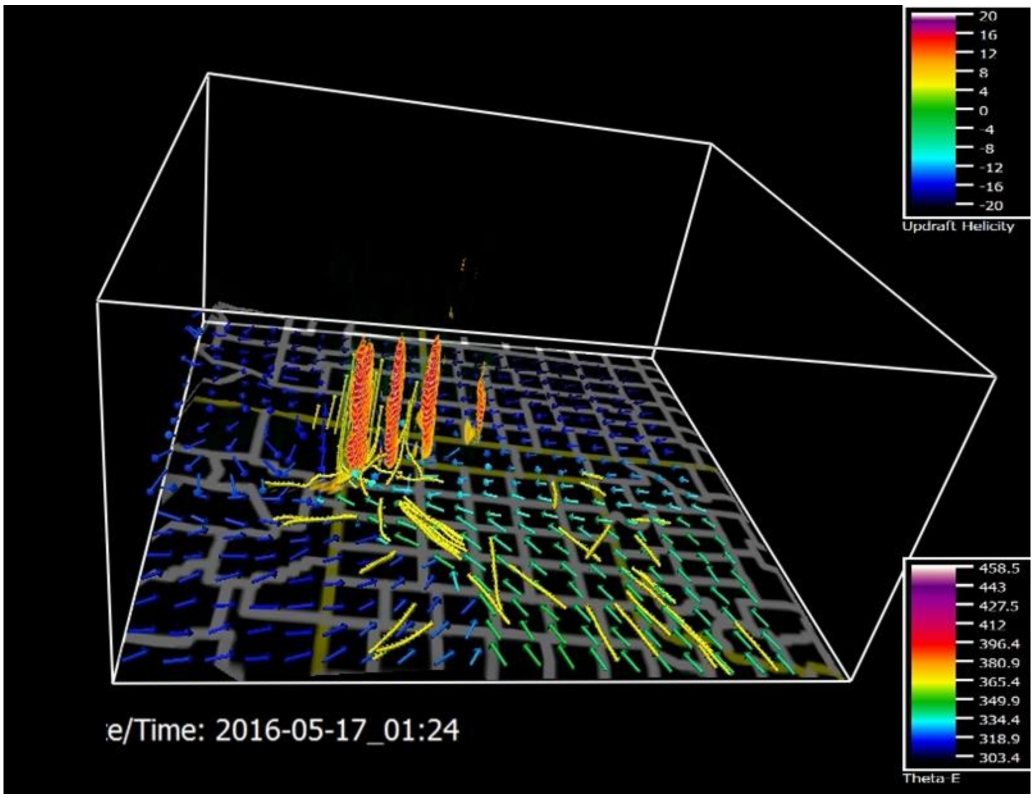

Figure 12. Example of VAPOR visualization of CAPS Control Run (WRF-ARW with 3DVAR-Cloud Analysis radar initialization) depicting near-surface wind (vectors), near-surface theta-e (vector colors, scale lower right) updraft helicity (3D shading, scale upper right), and updraft trajectory tracers (bright yellow lines) county boundaries (white) and state boundaries (yellow). It is for a 25-hour forecast valid 0124 UTC 17-May-2015. Domain shown is centered on the Texas Panhandle, with view point looking northeast. Tornadoes were reported near this time near Dalhart, TX in the northwest Texas panhandle.

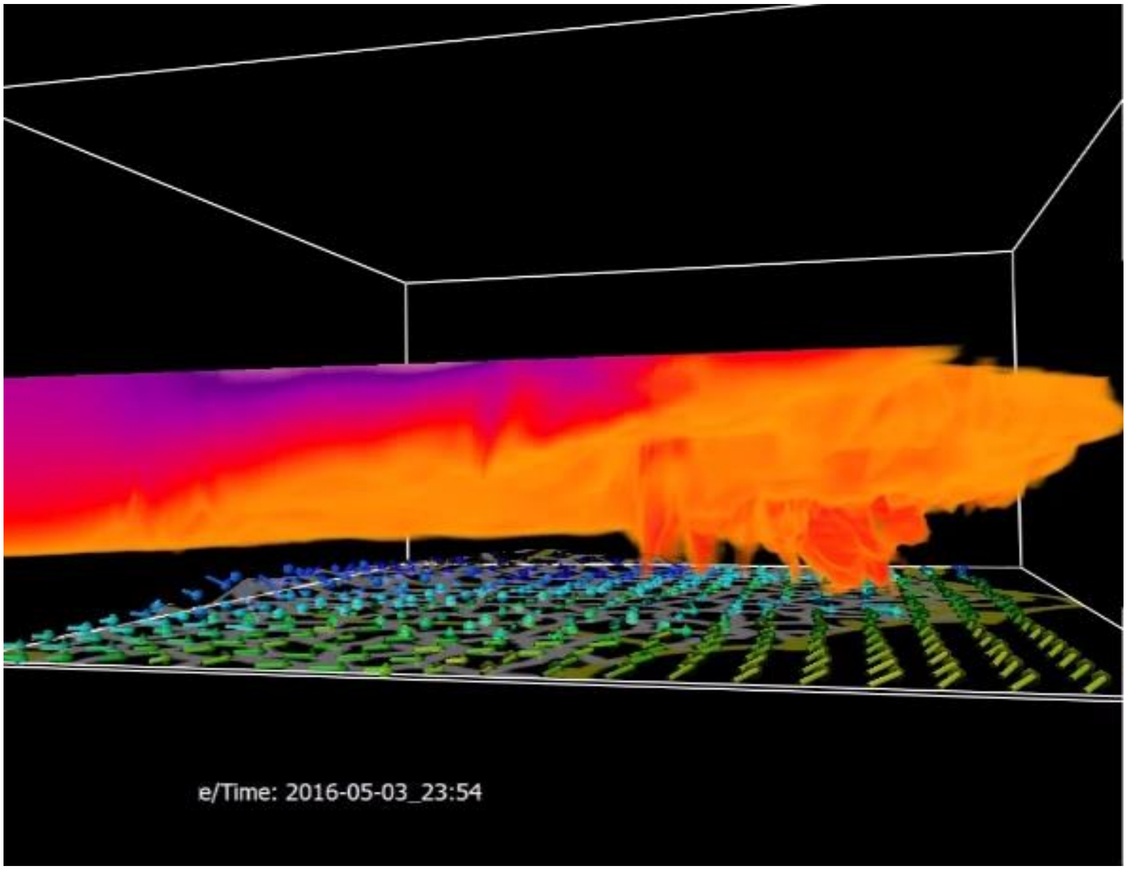

Figure 13. Sample VAPOR image illustrating mixing of high winds from aloft. Shown are wind speeds greater than 25 m s^{-1} (shaded), mid-level and low-level wind vectors for 3 May 2016 high wind case near the coast of North Carolina.

6. SSEF QPF Product and verifications

6.1 SSEF QPF Product

Figure 14 shows the example QPF/PQPF products CAPS SSEF provide to HMT from the 15 members SSEF along with the observation QPE, including the probability matched mean (PM), QPF exceedance, FFG exceedance, spaghetti map, and RI exceedance. All exceedance are in neighborhood probability. This case represents the June 23, 2016 West Virginia flash flood event.

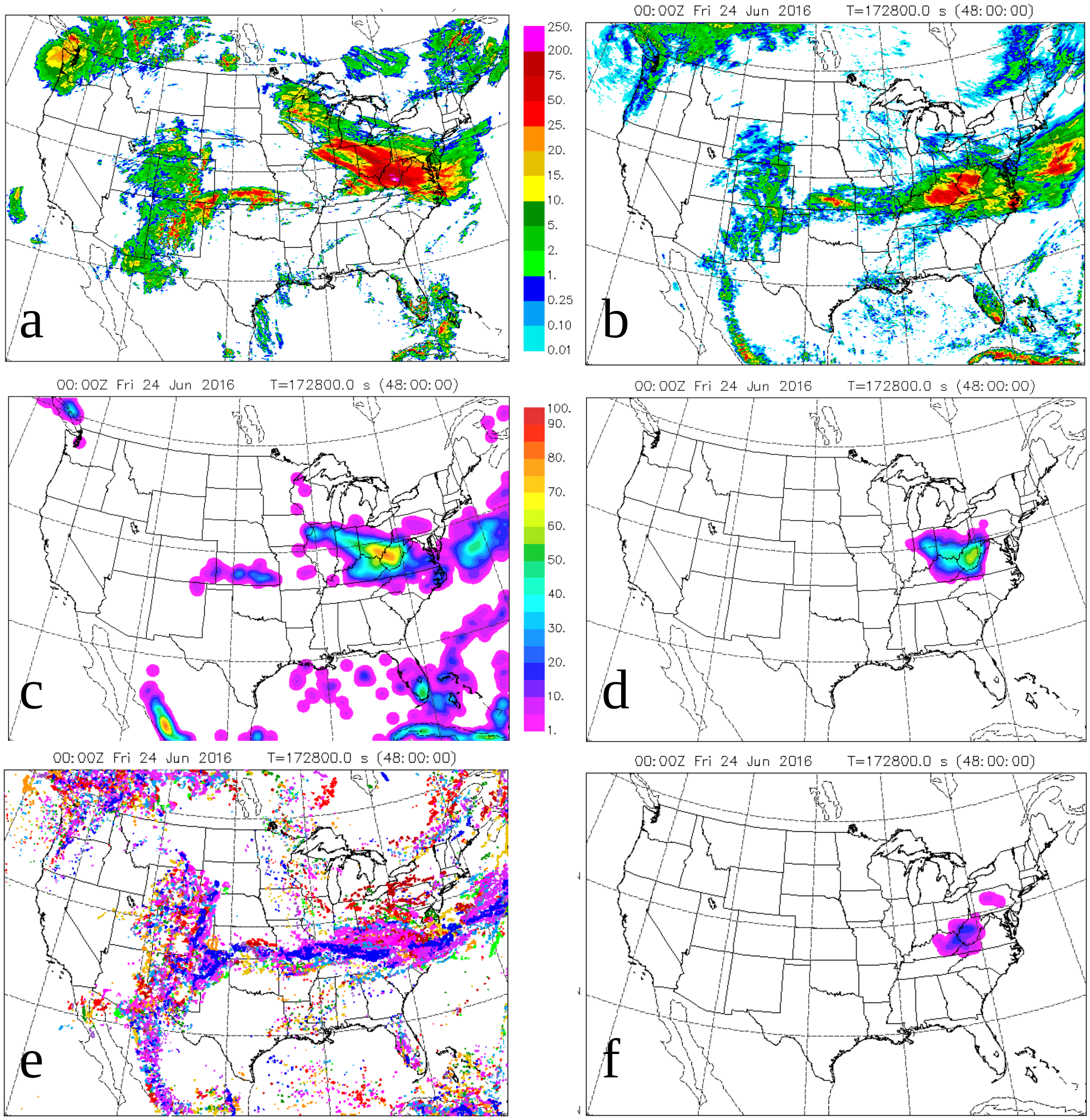

Figure 14. 48-h forecast products of 24-h (00-00Z) accumulated precipitation, valid 0000 UTC 24 June 2016. (a) MRMS QPE (observation), (b) ensemble probability matched mean, (c) neighborhood probability QPF ≥ 3", (d) neighborhood probability QPF ≥ 24h FFG, (e) Spaghetti of CREF=35 dBZ, and (f) neighborhood exceedance of 6-h QPF (18-00Z) ≥ 100-year RI

6.2 CAPS SSEF QPF evaluation

QPF verification was performed over a sub-domain marked in Figure 15. The NSSL National Multi-Radar/Multi-Sensor Quantitative Precipitation Estimation (QPE) or MRMS QPE (Zhang et. al. 2011) dataset was interpolated to the 3-km verification domain to serve as verification dataset for QPF and PQPF.

Figures 16 plots the ETS scores for the 1-h accumulated precipitation from the mixed sub-ensemble 3DVAR initiated SSEF runs in 2016 SFE, averaged over 32 dates. The initially higher scores reflect the benefit of radar data assimilation. This beneficial effect drops quickly as forecast proceeds. Low scores are seen over the convection active afternoon and evening hours for lighter rain. Overall, PM scores the highest compared with individual members and with ensemble mean excepting for the light rain threshold of 1-h accumulated precipitation in Figure 16a. PM outscores ensemble mean especially in heavier rain thresholds. Such performance features are indicated in every year's SFE.

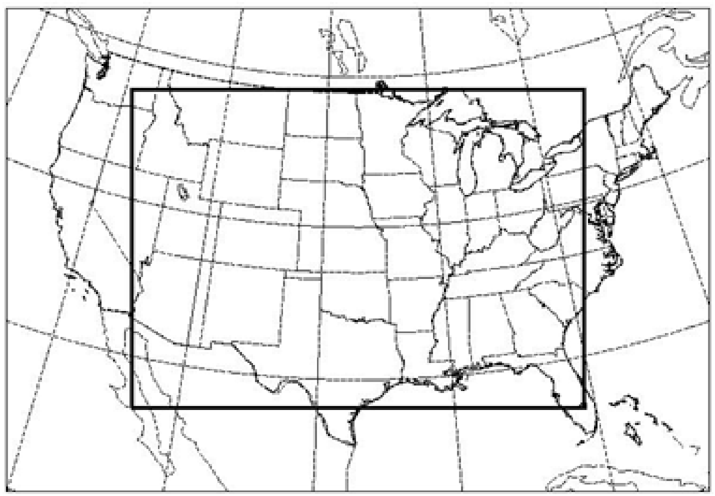

Figure 15. The small thick inner box (1080×760 horizontal grid points) is a sub-region used for the QPF verification.

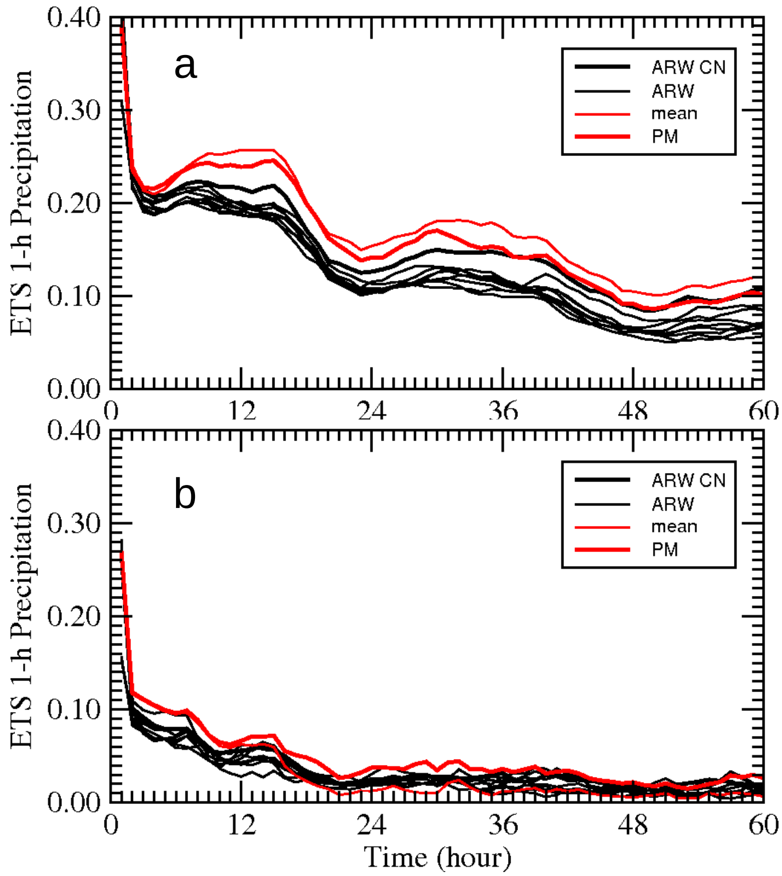

Figure 16. ETS of 1-h accumulated precipitation (a) ≥0.01 inch and (b) ≥0.25 inch, averaged over 32 dates in 2016 SFE over the verification domain.

Figure 17 shows the ETS scores of 3-hourly accumulated precipitation, averaged over 30 dates during 2016 SFE, among three sub-ensemble groups of the non-cycled 3DVAR-based SSEF. It shows that the single physics ARW sub-ensemble have comparable ETS scores to the mixed sub-ensemble; While NMMB members generally score lower in terms of QPF ETS scores. The one NMMB member with radar analysis outscores other non-radar NMMB members in the first 12 hours. This is also reflected in the probabilistic QPF as show in Figure 18 of the ROC areas (Note: For NMMB and single physics ARW members only 36 h forecasts are produced.)

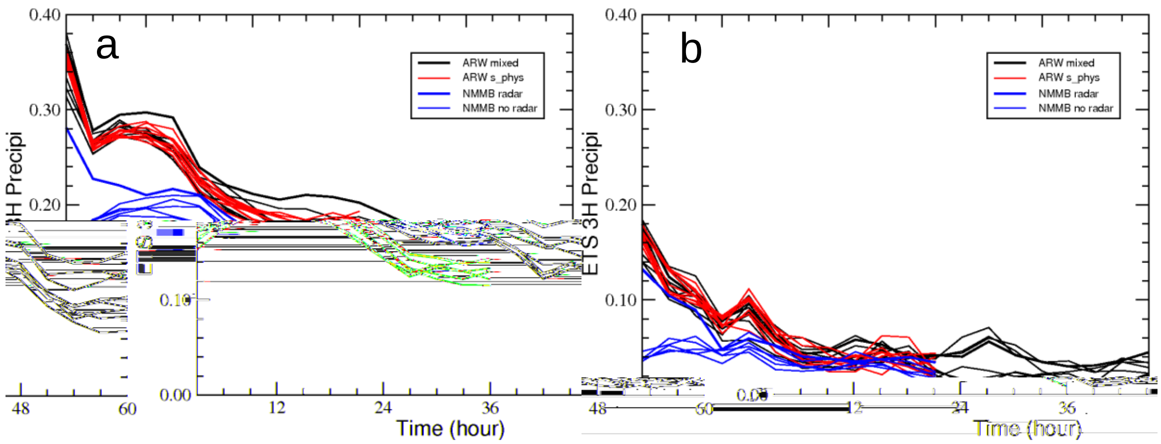

Figure 17. ETS scores of 3-hourly QPF ≥ 0.01" (a) and ≥ 0.5" (b).

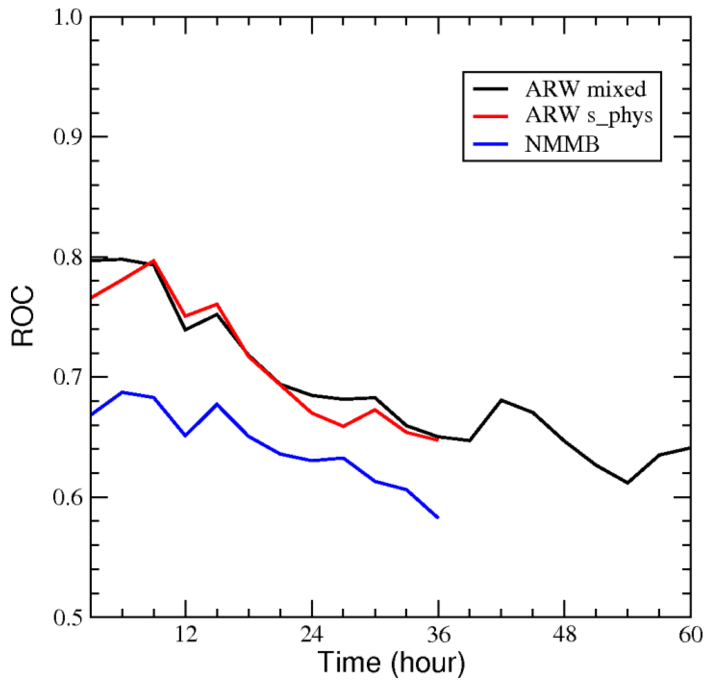

Figure 18. ROC areas for the 3-hourly accumulated precipitation ≥ 0.5" for the three sub-ensemble groups.

6.3 Extended effect of SSEF on QPF/PQPF

Starting in 2014, CAPS SSEF was extended to 60-h forecast to provide guidance for Day-2 outlook. CAPS collaborators at OU/CIMMS and NSSL (Iyer et al. 2016) compared the 3DVAR initiated SSEF generated in 2014 HWT Spring Forecast Experiment with the NCEP operational Short-Range Ensemble Forecast (SREF) to examine the extended effect (36-60 h) of high resolution SSEF (at 4-km) on QPF (and PQPF) over the lower resolution SREF (at 16-km). Figure 19 plots the ETS curves of 0.1 and 0.5 inch thresholds, for ensemble individual members and the probability matched mean. Figure 20 shows the Area under ROC curves (AUROC) for the 3-h accumulated precipitation of 0.5 inch threshold. It can be seen from both figures that the SSEF forecasts were clearly superior to the SREF forecasts through all the 60 h forecast period. Other findings from this study include:

- SSEF more closely represents the amount of precipitation that falls over the domain as a whole during the day 2 forecast period
- Despite the fact that the SSEF forecasts were not always significantly better than the SREF in the day 2 period, convection-allowing models very likely provide additional value to a QPF forecast out to 60 hours
- The difference is most evident in the mid to late morning (hours 36-42), which is evidenced by the hypothesis test results outlook.

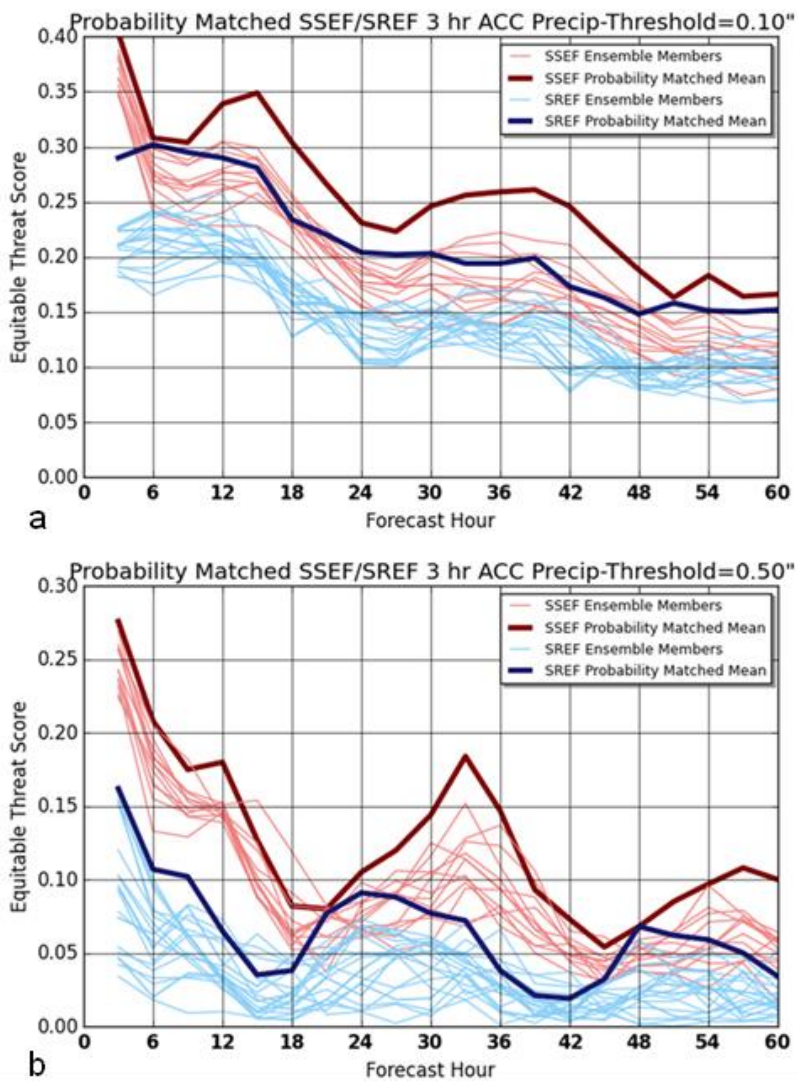

Figure 19. ETS scores of 3-h accumulated precipitation (a) ≥0.1 ich and (b) ≥0.5 inch from 2014 CAPS SSEF (red) and NCEP SREF (blue) datasets. Stage IV precipitation dataset was verified against. (Courtesy of Iyer et al. 2016)

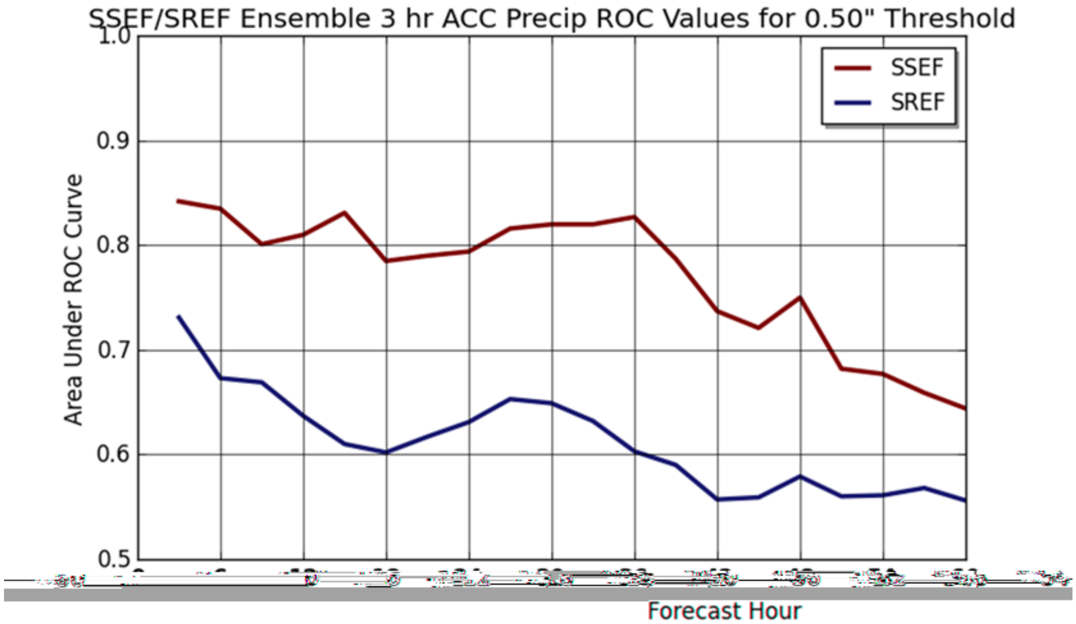

Figure 20. Area under ROC curves for the 3-h accumulated precipitation at 0.5 inch threshold. (Courtesy of Iyer et al. 2016).

6.4 Performance of CAPS SSEF relative to other CAM ensembles

CAPS collaborators at OU/CIMMS and NSSL compared five convection-allowing model ensembles that contributed to 2015 SFE (Gallo et al., 2016). In addition to CAPS SSEF, other four CAM ensembles are NCAR, NSSL, SSEO, and CAPS EnKF SSEF. The NCAR ensemble was EnKF based using DART community EnKF tool. The NSSL ensemble was a 10 member single physics cold start ensemble that utilized IC/LBC perturbations downscaled from SREF members. SSEO is also called Storm-Scale Ensemble Opportunity, which contains seven operationally available high resolution window forecasts from EMC and NSSL.

3-hourly accumulated precipitation in the form of probability matched mean was verified against Stage IV data. Figure 21 shows ETS scores for all five CAM ensembles for four thresholds at 0.10, 0.25, 0.50, and 0.75 in. CAPS SSEF clearly outperformed all other CAM ensembles for the 0.1 and 0.25 inch thresholds at all forecast hours, and outperformed all others for the 0.5 and 0.75 inch thresholds for the first 18 h.

Figure 22 shows areas under ROC curves for the same set of four thresholds. It reveals a similar trend at all thresholds but at a lesser degree.

Overall, CAPS SSEF scored the highest in the objective verification measures. A hybrid ensemble configuration that contain both IC/LBC perturbation and physics diversities, plus radar data analysis using 3DVAR and cloud analysis, could be the contributing factors for the high performance demonstrated by CAPS SSEF.

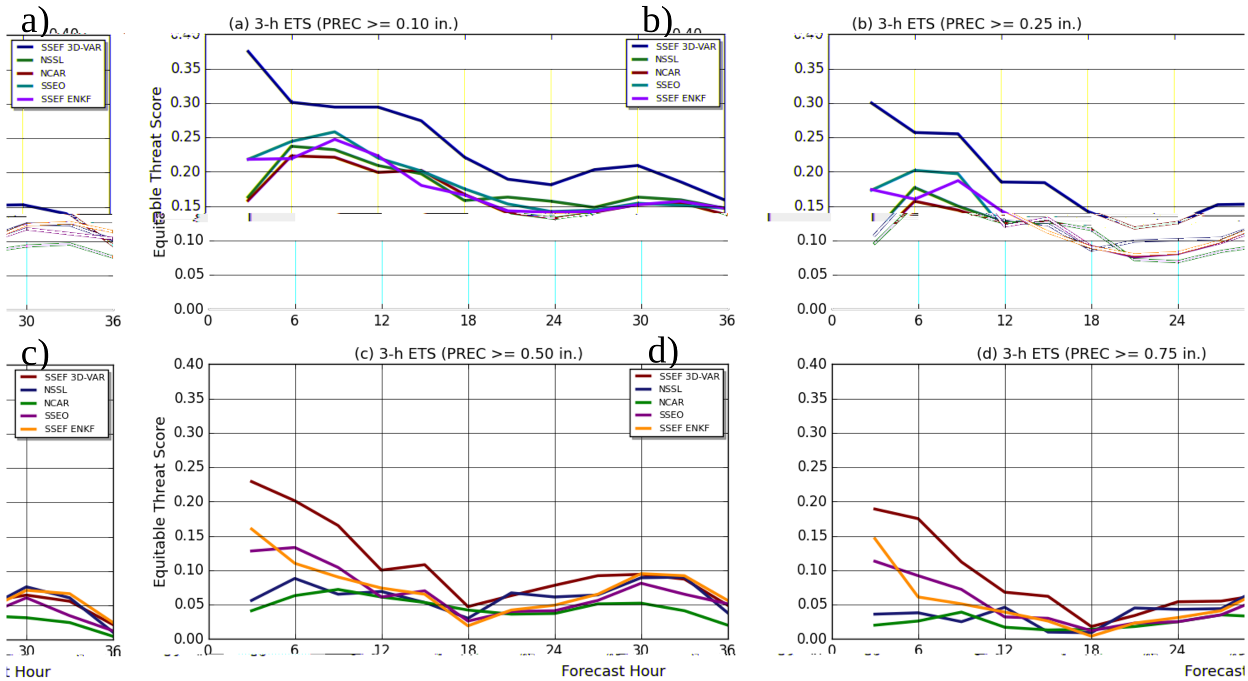

Figure 21. ETS scores for 3 h ensemble mean fields at four QPF exceedance thresholds: (a) 0.10 in; (b) 0.25 in; (c) 0.50 in; and (d) 0.75 in. (Courtesy of Gallo et al. 2016)

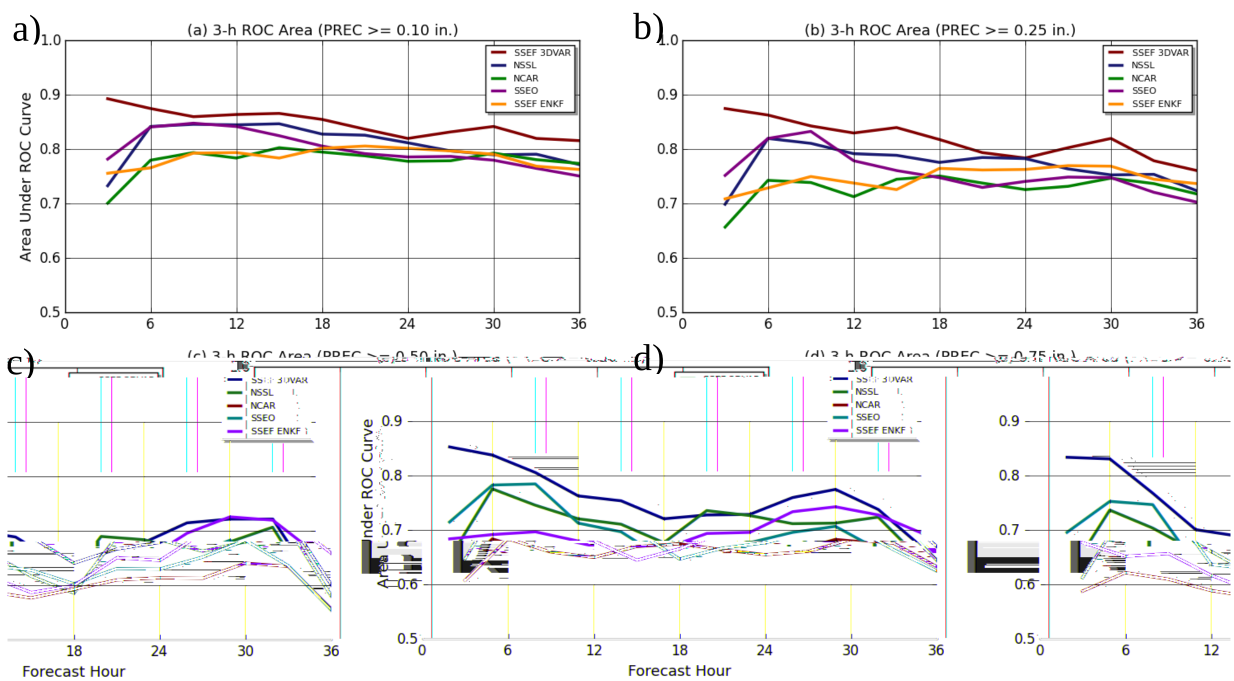

Figure 22. ROC area scores for 3 h ensemble mean fields at four QPF exceedance thresholds: (a) 0.10 in; (b) 0.25 in; (c) 0.50 in; and (d) 0.75 in. (Courtesy of Gallo et al. 2016)

6.5 GSI+EnKF vs 3DVAR based SSEFs

Different from the 2015 season, in NOAA/HWT SEF2016 the experimental cycled DA process features the combination of GSI and CAPS EnKF over the CONUS domain.

In-depth post season analysis is underway, but we present some preliminary results here. Focus is on the comparison between the forecasts initiated using GSI+EnKF final analysis ensemble and using a single 3DVAR analysis with complex cloud analysis at 00 UTC. Figure 23 shows a ETS scores of the ensemble mean and probability matched mean for both ensembles. For the light rain threshold, the GSI+EnKF based SSEF scores higher than or comparable to the 3DVAR based SSEF until 12 h into the forecast, are nearly identical for forecast hours 15-18 and are trailing afterward. The SSEF initialized with 3DVAR performs better at all forecast periods for higher threshold. This result comes is despite the huge cost of the 6-hour 40-member ensemble required to produce the GSI+EnKF initial analysis compared to the single 3DVAR and complex cloud analysis.

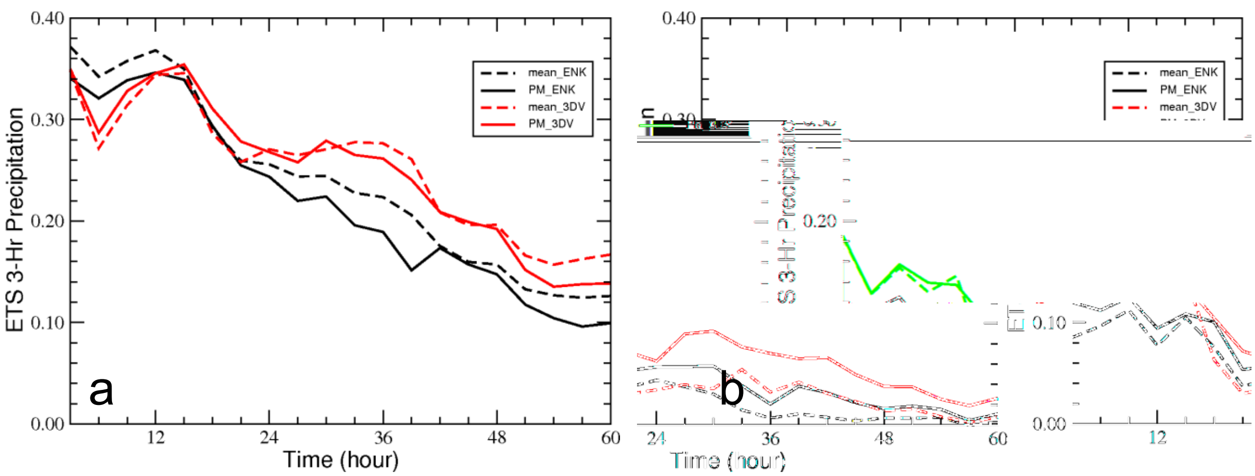

Figure 23. ETS scores of the 3-hourly accumulated precipitation ≥ 0.01" (a) and 0.5" (b), for the ensemble mean and probability matched mean, averaged over a 12-day period with complete ensemble dataset.

. Although the GSI+EnKF underperformed in the overall ETS metric there were some individual cases where it performed better. Figure 24 presents an example 6-h forecast valid at 0600 UTC 11 May 2016. A MCS in Texas is much weaker than observed radar echo in GSI+EnKF based ensemble and stronger than the observation in the 3DVAR based ensemble. In this particular case, GSI+EnKF is behaving little bit better with the storms in the north. Figures

25 and 26 are selected members with different microphysics from another case but 24-h forecast from GSI+EnKF based SSEF and 3DVAR based SSEF, respectively. They also suggest the GSI+EnKF initiated members can be qualitatively slightly better than the corresponding 3DVAR members in terms of location and structure of precipitation,

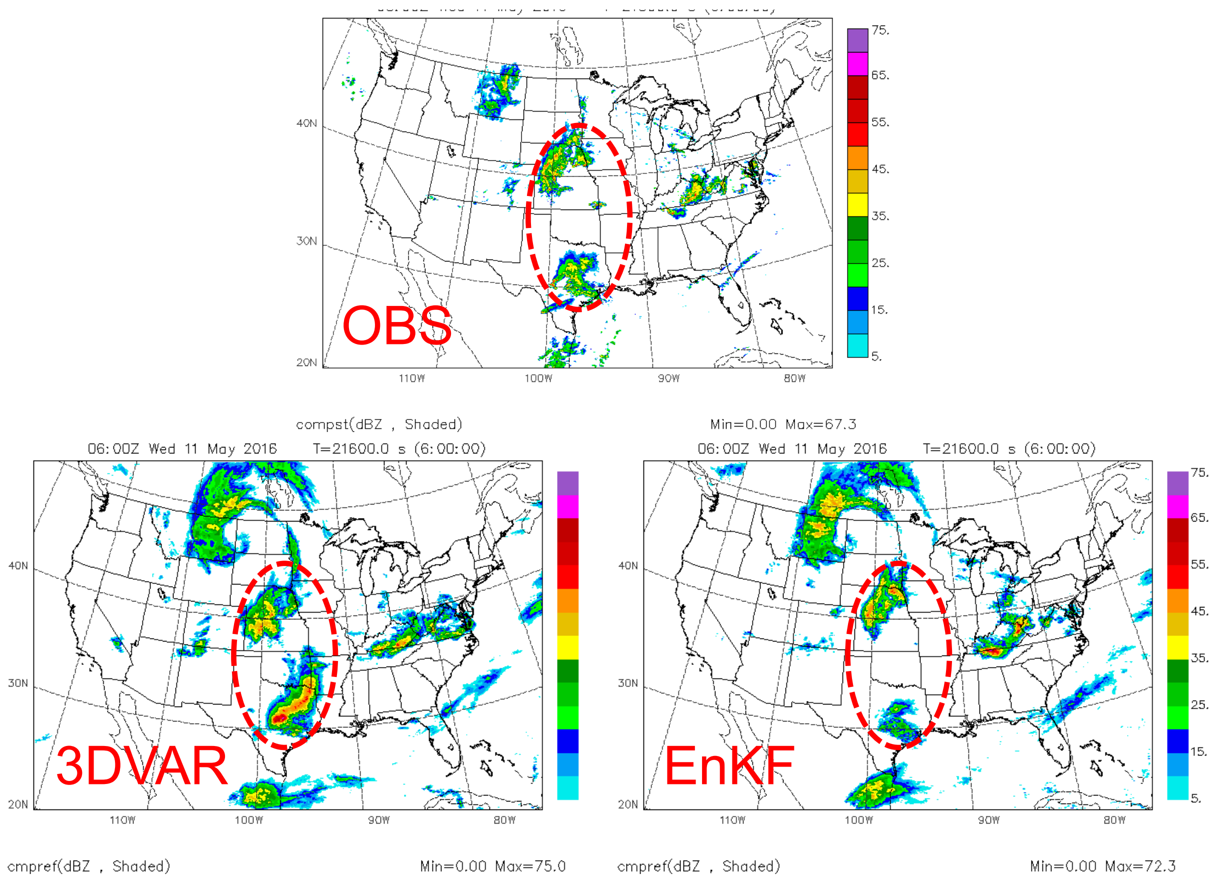

Figure 24. 6-h forecast composite reflectivity probability matched mean and MRMS radar mosaic, valid at 0600 UTC 11 May 2016, comparing the non-cycled 3DVAr-based SSEF and the cycled GSI+EnKF based SSEF.

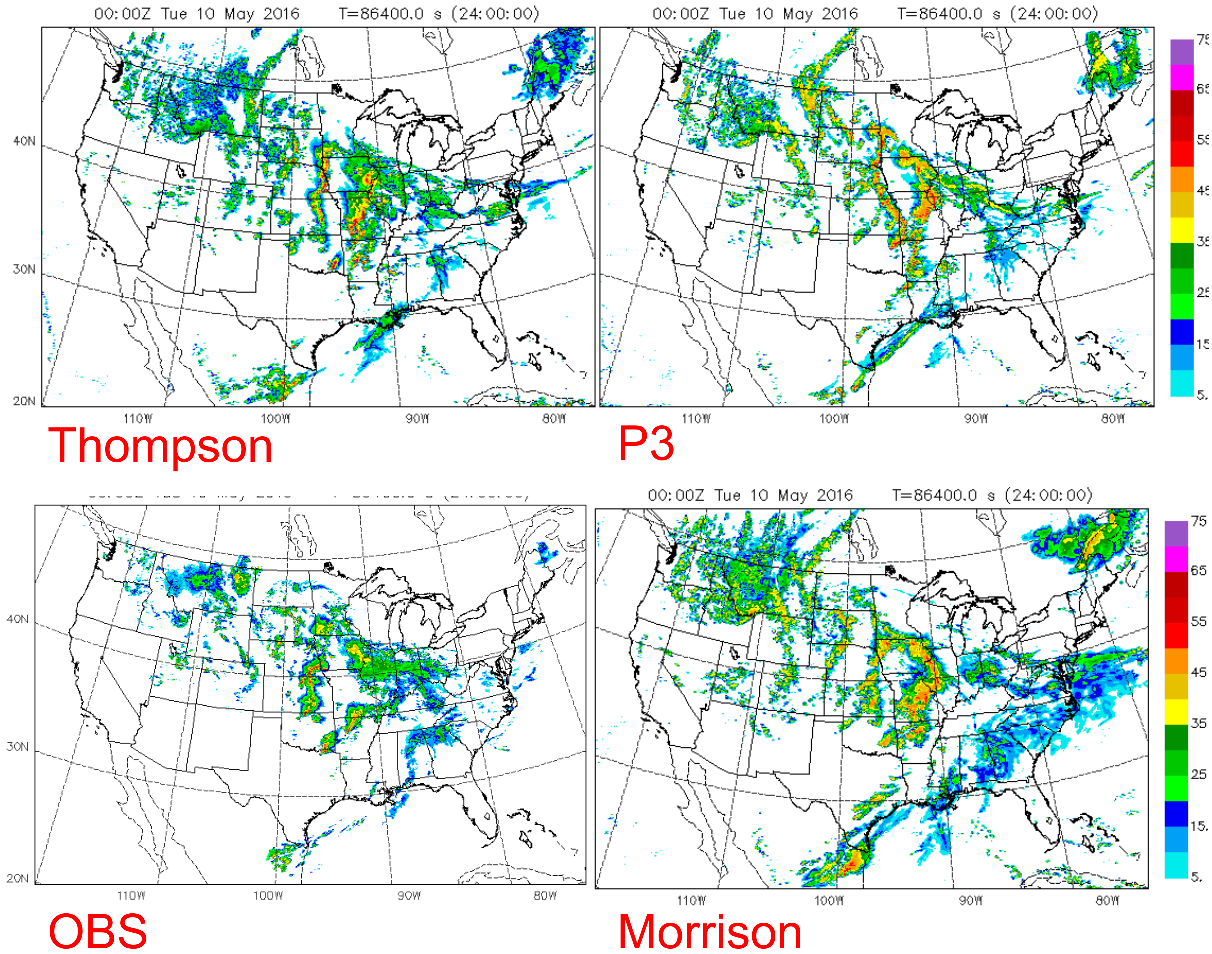

Figure 25. 24-h forecast composite reflectivity from the GSI+EnKF based ensemble members and MRMS radar mosaic, valid at 0000 UTC 10 May 2016.

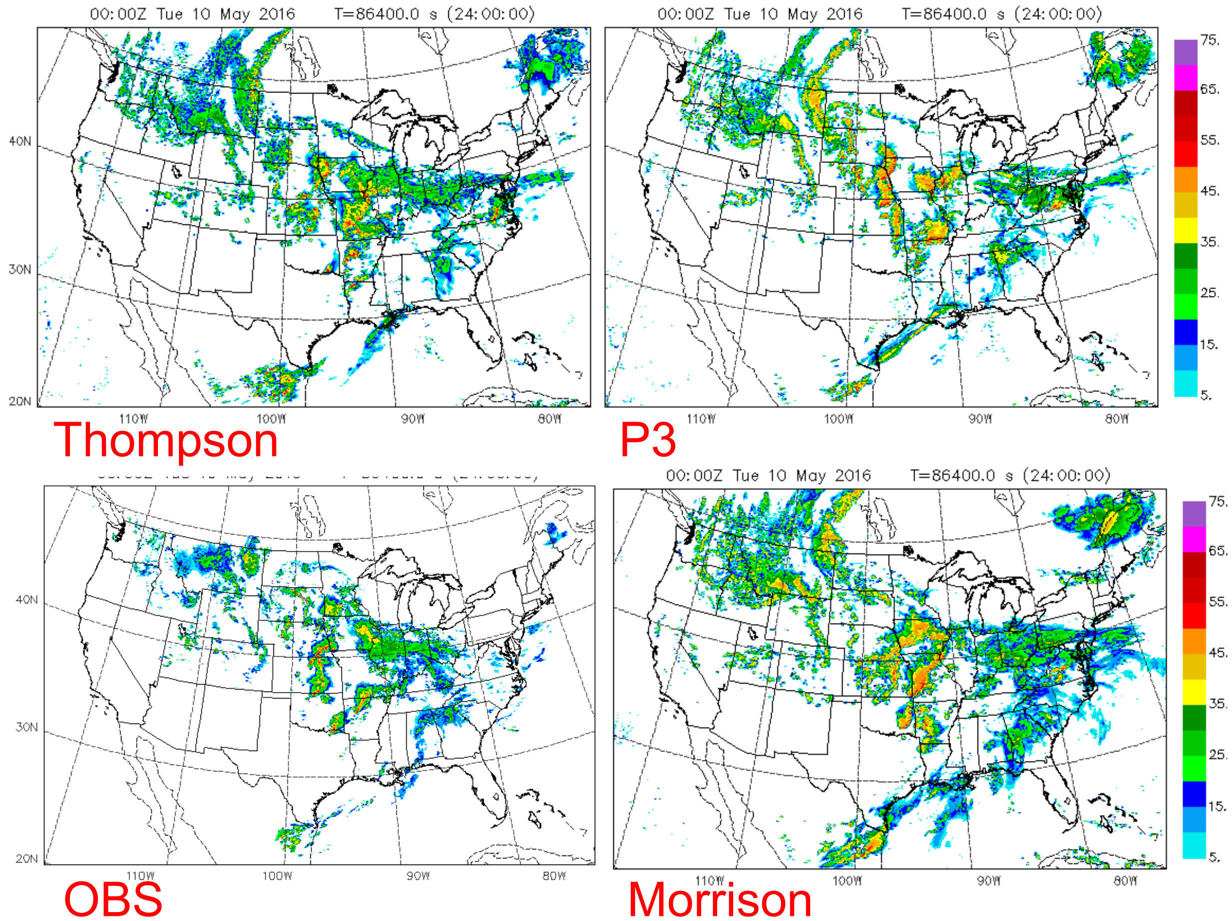

Figure 26. 24-h forecast composite reflectivity from the 3DVAR based ensemble members and MRMS radar mosaic, valid at 0000 UTC 10 May 2016.

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