NOAA Collaborative Science, Technology, and Applied Research (CSTAR) Final Report

Development of Probabilistic and Sensitivity-Based Forecast Tools to Improve High-Impact Forecasting Guidance at the NWS

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I. Overview and Statement of Primary Goals

The primary goal of this project was to further develop the use of ensemble sensitivity toward operational use at the Storm Prediction Center (SPC) and National Weather Service (NWS) forecast offices (WFOs). The main theme underpinning these activities is that ensemble sensitivity contains important information pertaining to the predictability of specific severe convective events, and this information can be extracted from the ensemble and used to improve the skill of forecasts of convection in an operational framework. The further development of ensemble sensitivity in this project builds on a previous CSTAR award to Texas Tech University (TTU; 2011-2015) that focused on the advancement of ensemble sensitivity analysis (ESA) at convective scales. Other goals of this project were to expand the operational TTU ensemble system, enhance the quality of the TTU ensemble system through the incorporation of physics uncertainty, and to export real-time TTU ensemble data into the current NWS Advanced Weather Interactive Processing System (AWIPSII). The specific project goals were to:

- **Expand the TTU operational ensemble system to a CONUS 12-km outer domain with a 4-km nest over the Plains and Midwest that encompassed much of the U.S. that experiences the most severe convective weather**
- **Develop convective-scale ensemble sensitivity toward a technique that selects the best ensemble members that improve probabilistic forecast skill of high-impact convective events (sensitivity-based subsetting)**
- **Evaluate new physics modeling configurations of the TTU operational ensemble**
- **Investigate the impact of ensemble sensitivity-based targeted observations on the prediction of severe convective events**
- **Create regular files from the TTU ensemble system that can be ported to and ingested by the AWIPSII at various NWS WFOs**

II. Research Achievements

A. Expansion of the Operational TTU Ensemble System

In order to effectively develop the ensemble sensitivity-based forecast tools described in this project, it was necessary to expand the convection-allowing domain within the TTU operational ensemble system from its limited Texas domain to one encompassing substantially more of the U.S. Funding was acquired external to the CSTAR project through the TTU Global

Laboratory for Energy Asset Management and Manufacturing (GLEAMM) project to support a larger computing cluster. This cluster, named Realtime2, is maintained at the TTU High Performance Computing Center (HPCC) and begun operation in December 2015. Realtime2 is roughly a 1000-core computing cluster that solely supports the TTU real-time ensemble and deterministic prediction systems. This enhanced computing capability allowed a larger ensemble domain configuration (Figure 1) to support the research-to-operations goals of this project. This 42-member ensemble system still utilizes the Data Assimilation Research Testbed (DART) ensemble Kalman filter assimilation system, ingesting hundreds of thousands of surface and upper-air observations on a continuous 6-hr cycle, producing 48-hr forecasts from each 0000 and 1200 UTC ensemble initialization. Data assimilation is performed on only the 12-km domain, with 4-km forecasts produced by downscaling the ensemble of 12-km analyses. Boundary conditions for the 12-km members are taken from the past two runs of the Global Forecast System Ensemble (GEFS), while the 12-km members themselves provide the boundary conditions for the 4-km forecasts.

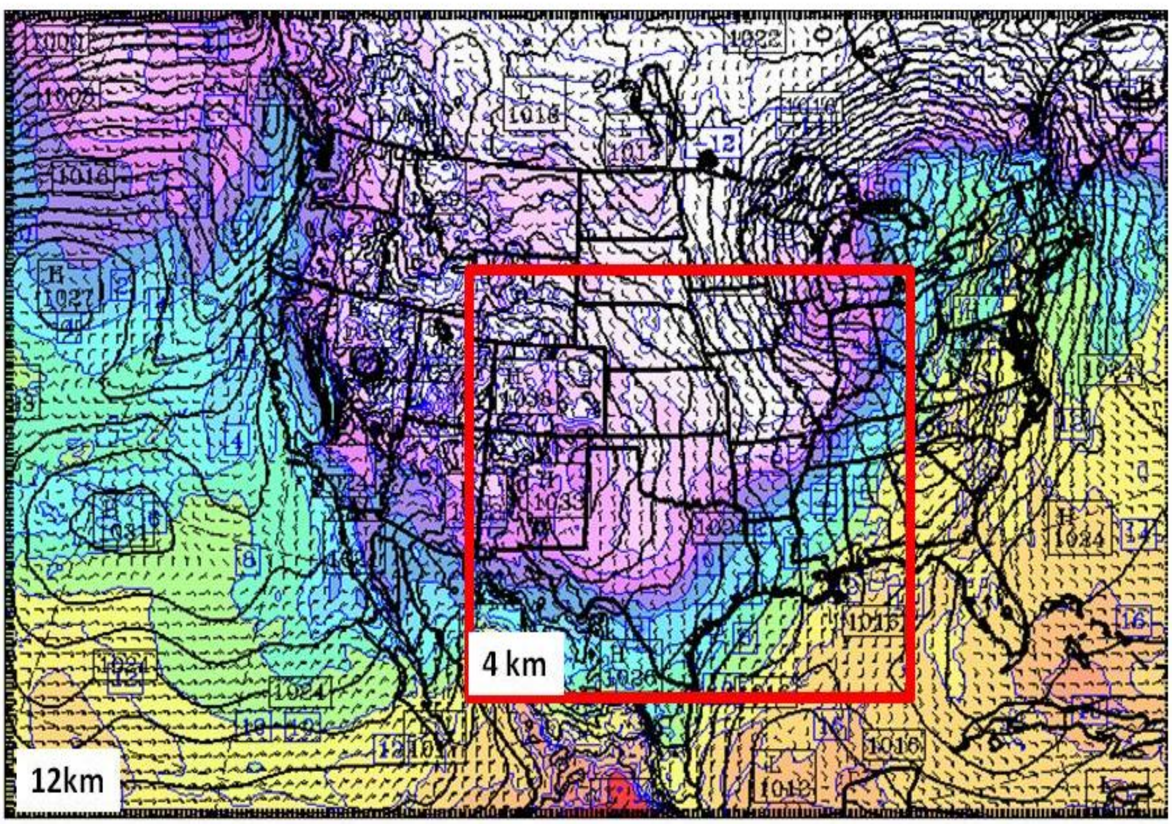

Figure 1 - The new configuration of the TTU ensemble 12-km and 4-km domains.

B. Further Development of Convective-Scale Ensemble Sensitivity toward Sensitivity-Based Subsetting

i. Thorough Examination of Convective-Scale Sensitivity Fields

Following the initial development of convective-scale ensemble sensitivity analysis from a prior TTU CSTAR award, efforts during this project first focused on determining whether sensitivity at convection-allowing scales was robust in the presence of substantial nonlinear ensemble perturbation evolution. It was found that response functions diagnosing convection and convective initiation indeed continued to reveal logical sensitivity features for additional cases of severe convection. For example, Figure 2 shows an area of negative sensitivity to 700-hPa temperature that propagates upstream backwards in time for a response function chosen as the maximum simulated reflectivity in a localized box. This strongly suggests the strength of the inversion plays a role in convection initiation - it reveals that members with colder 700-hPa temperatures in these areas of negative sensitivity are related to more pronounced convection. In the opposite sense, it reveals warmer 700-hPa temperatures in the region of large sensitivity (a stronger capping inversion) limits convection in the box.

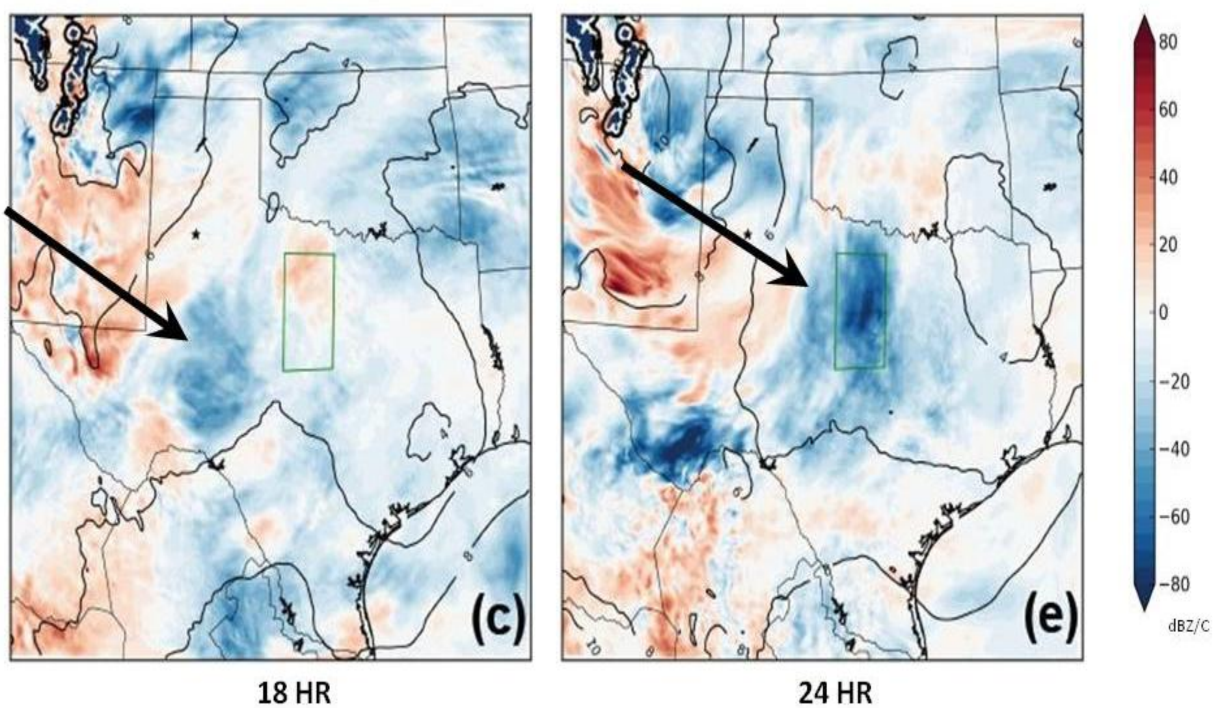

Figure 2 - Ensemble sensitivity of the maximum 24-hr simulated reflectivity in the green box with respect to 700-hPa temperature at both 24 hr and 18 hr. Arrows indicate the specific feature attributed to the capping inversion that influences convection in the box.

It was also found that ensemble sensitivity fields strongly resemble the difference field of the means of the different modes (e.g. convection vs. no convection) of bimodal response function distributions. This suggests that ensemble sensitivity, even though it is a linear regression applied in the presence of nonlinearity and non-Gaussian response function distributions, is able to recover the primary dynamical linkages between severe convection and the atmospheric state at earlier times. These results are found with more detail in Hill et al. (2016), and strongly motivated the day-to-day evaluation of ensemble sensitivity fields at the 2016 NOAA Hazardous Weather Testbed (HWT) Spring Forecasting Experiment.

ii. Evaluation of Convective-Scale Sensitivity at the 2016 NOAA HWT

The evaluation of real-time ensemble sensitivity fields at the 2016 NOAA HWT was primarily done to understand whether sensitivity fields exhibited day-to-day coherent signals relative to severe convection. If so, motivation would be significant to further develop sensitivity-based techniques such as those that chose ensemble subsets that improve probabilistic skill over that of the full ensemble, and those that target observations based on sensitivity fields. Ensemble sensitivity of response functions diagnosing severe convection - coverage and magnitude of localized high winds, updraft helicity, and simulated reflectivity - was calculated within the operational TTU ensemble system on a daily basis at the 2016 HWT. Response function locations were chosen by participants, and resulting sensitivities throughout the forecast window to atmospheric variables at both the surface and aloft were presented by TTU researchers for participant evaluation. It was generally found that sensitivity fields to lower-atmospheric variables like sea-level pressure, and 700-850hPa dewpoint and temperature were relatively noisy and difficult to interpret in an operational environment. Sensitivities aloft however, particularly those with respect to 500-hPa geopotential height and 300-hPa wind speed, revealed coherent signals nearly every day. These signals usually were tied to a trough, ridge, or jet streak - Figure 3 shows an example from May 2016 of a strong positional sensitivity to a jet streak position for severe convection in Oklahoma 30 hours later..

Another interesting result from this evaluation was that the sensitivity of different severe attributes were not always the same. Some days showed large sensitivity for updraft helicity but little sensitivity to simulated reflectivity or high winds (for the same response function area), and many cases showed that the most sensitive regions occurred in different locations for the various severe attributes. Figure 4 shows the maximum sensitivity magnitude for the maximum

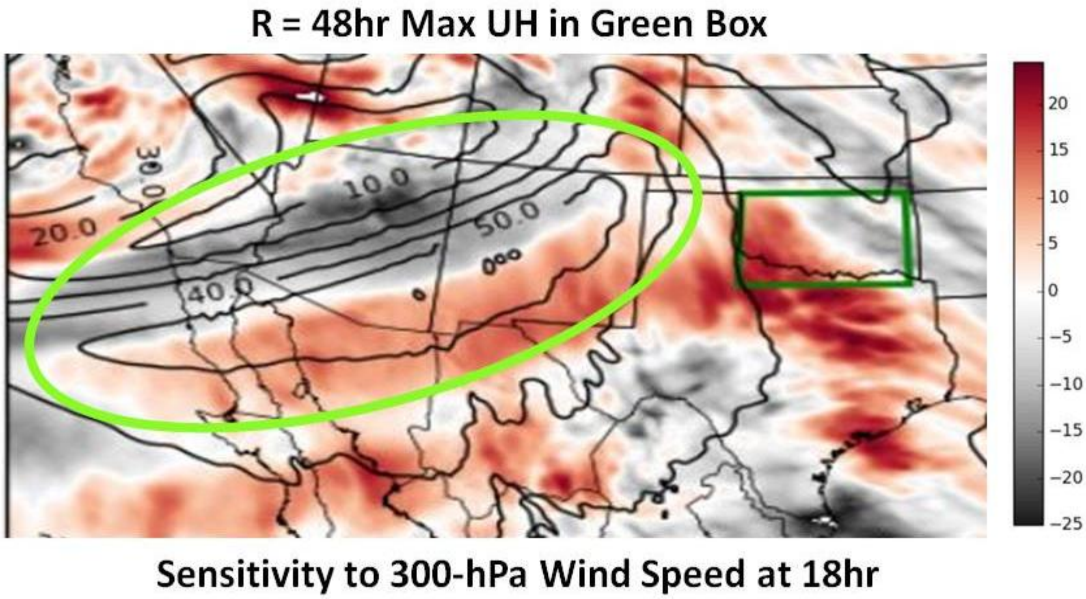

Figure 3 - Ensemble sensitivity of 48-hr maximum 2-5km updraft helicity in the green box with respect to 18-hr 300-hPa wind speed (black contours show mean wind speed). The green oval indicates a positional sensitivity feature to the 300-hPa jet core.

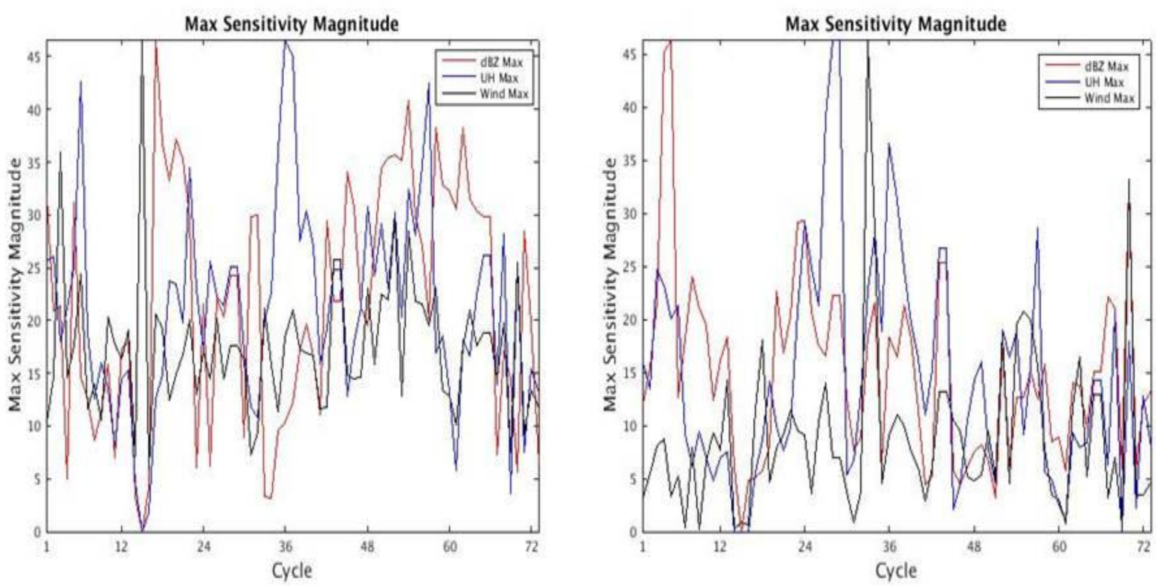

Figure 4 - Maximum magnitude of ensemble sensitivity for magnitude (left) and coverage (right) updraft helicity, surface wind speed, and simulated reflectivity response functions over all cases for the 2016 NOAA HWT.

magnitude (left panel) and coverage (right panel) responses with regard to updraft helicity, high wind, and simulated reflectivity. For both magnitude and coverage, it is clear the pattern of the three hazard response functions do not match, indicating that the hazards themselves are sensitive in different ways. One common example of how this manifested itself during the 2016 HWT is that simulated reflectivity coverage showed positive sensitivity in areas that showed negative sensitivity for updraft helicity magnitude (e.g. with respect to 300-hPa wind speed). This indicates that the members with the lowest 300-hPa wind speed values in those areas are associated with less coverage of simulated reflectivity, but larger updraft helicity values, potentially indicating a more supercellular mode. This has motivated subsequent work currently being performed that attempts to fully understand and utilize these interesting results.

Participants from the 2016 HWT were asked whether they thought the sensitivity fields presented provided value to the forecasting process. The results were as follows: Never - 3%, Always - 3%, Unsure - 34%, Sometimes - 60%. Written feedback revealed that participants were mostly concerned about the inability in an operational environment to interpret the complicated sensitivity patterns. Nonetheless, give the majority of responses that saw some value in ensemble sensitivity for improving forecasts, and the fact that sensitivity fields aloft exhibited day-to-day coherent signals, the groundwork was laid to continue development of sensitivity in subsequent work within the CSTAR program toward the creation of an operational sensitivity-based subsetting technique.

iii. Sensitivity-Based Subsetting at Synoptic Scales

An initial examination into the value of sensitivity-based subsetting was first performed at synoptic scales with regard to midlatitude cyclones. This was because the value of the subsetting technique must first be established at larger scales before the development of convective-scale sensitivity-based subsetting with all of the associated nonlinearity could be undertaken. WRF ensemble simulations of landfalling midlatitude cyclones on the west coast of North America were made, and the sensitivities of the 24-hr central cyclone pressure were calculated with respect to 6-hr forecast time. One ensemble member was considered truth, and the members with the smallest errors in sensitive regions were selected as the ensemble subset and compared against the full ensemble in terms of the 24-hr cyclone central pressure errors. The members were selected by both taking the smallest RMS value against truth in sensitive regions (the RMS method), as well as the smallest projected value using the product of the sensitivity field and the differences with truth (the PROJ method). Further, different ensemble subset sizes (from the original 80-member ensemble) and sensitivity thresholds (the cutoff for what defines the most sensitive regions) were tested. In general, ensemble subsets significantly improved upon the full ensemble (Figure 5), particularly when only the cases of largest ensemble spread were considered. Figure 6 shows that a clear optimal range of subset size exists (5-30 members), and that a sensitivity threshold of between 20-50% is optimal. More detail on this study and these results can be found in Ancell (2016), but most importantly the fundamental ability for sensitivity-based subsetting was established in this work. The optimal parameters from this synoptic-scale test served as the initial values for subsequent work currently being performed on ensemble sensitivity-based subsetting at convective scales.

iv. Ensemble Sensitivity Analysis at High Spatial and Temporal Resolution

A series of experiments has been carried out to assess the utility of ensemble sensitivity analysis techniques at very high resolution (1-km grid spacing) and at frequent time intervals within hours of severe convection. We view the benefits of sensitivity analysis in this framework as three-fold: 1) to gain a clearer understanding of the physics determining specific severe hazard outcomes near the times they are occurring, 2) to better understand the predictability of these outcomes at very short time scales, and 3) to assess the possible benefits of targeting observations just prior to severe events to improve forecasts of the associated hazards.

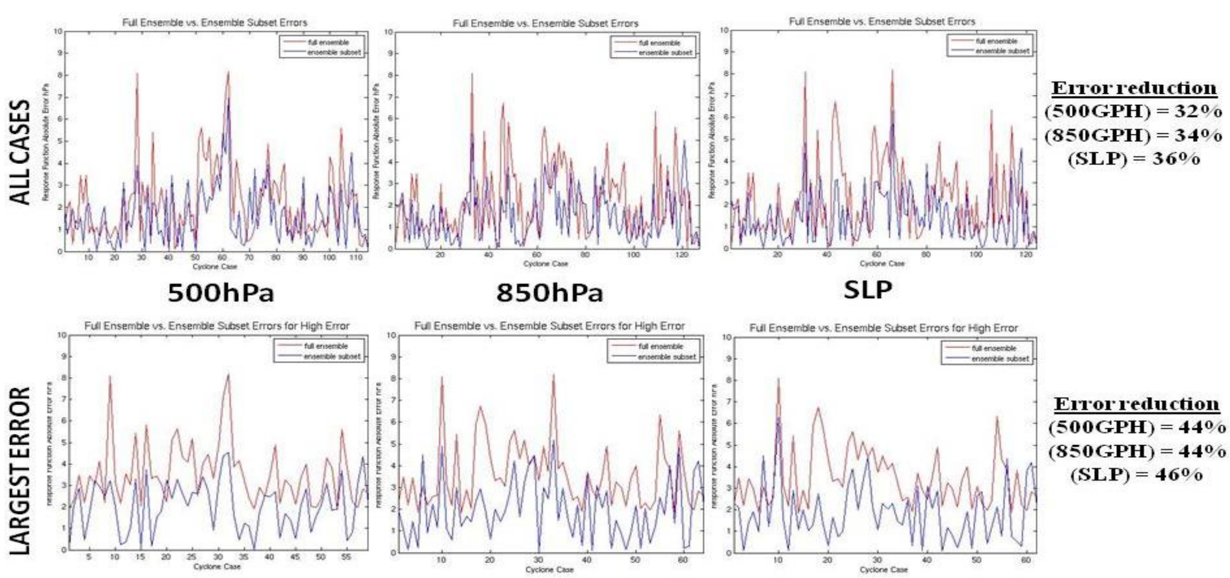

Figure 5 - Ensemble mean error for the full ensemble vs. the sensitivity-based subset

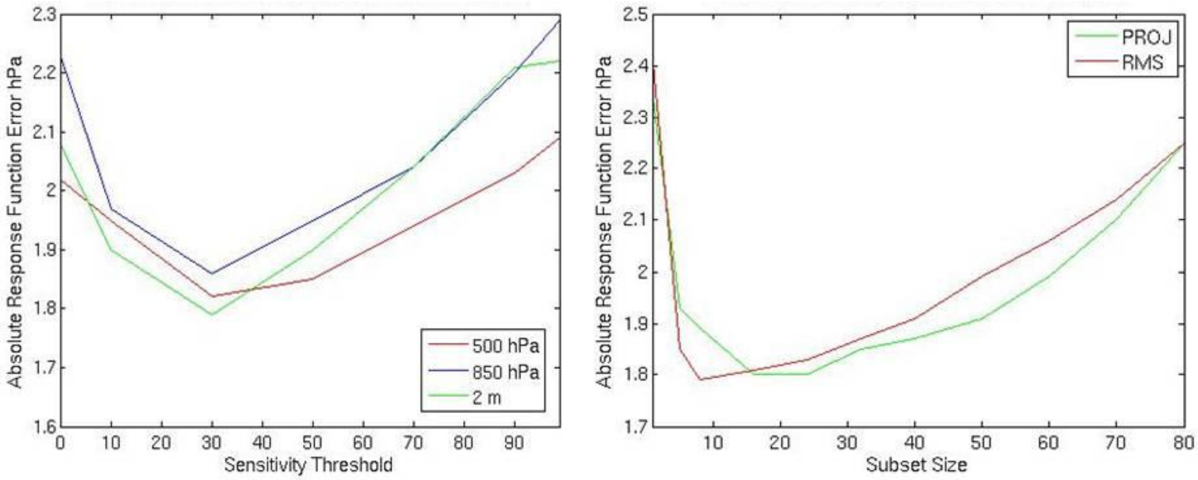

Figure 6 - Sensitivity-based subsetting performance for different sensitivity thresholds (left) and subset size (right).

Progress during this project has primarily involved retrospective WRF-ARW simulations of the 27 April 2011 tornado outbreak across the southeastern United States, with a focus on a supercell thunderstorm that produced a long-track EF4 tornado between Tuscaloosa and Birmingham, AL. The simulations were part of a 36-member ensemble, initialized using a multi-scale ensemble technique assimilating in situ, satellite and radar observations. Ensemble sensitivity code was developed at Texas Tech University to specifically handle this type of storm-scale application. In this particular case, we used near-surface circulation as a response metric, which was figured to be the best option available to associate with tornado production given the horizontal grid spacing of 1 km.

A variety of kinematic and thermodynamic state variables were considered in the analysis, which was carried out for 30 separate model output times at 2-min intervals. Though a number of these variables offer some interesting and complex associations with near-surface circulation, the clearest signal we have identified is tied to the cold pool production within the storm itself. Recurring negative sensitivity signals (e.g., Figure 7) affirm that instances of colder downdraft regions within the storm, particularly within the left and rear flanks, best associated with strong low-level circulation. Our interpretation is that this result signals the importance of baroclinic vorticity production within the target storm, and provides hope that measurements of downdraft thermodynamic characteristics, perhaps in real-time, can improve the prediction of tornadoes.

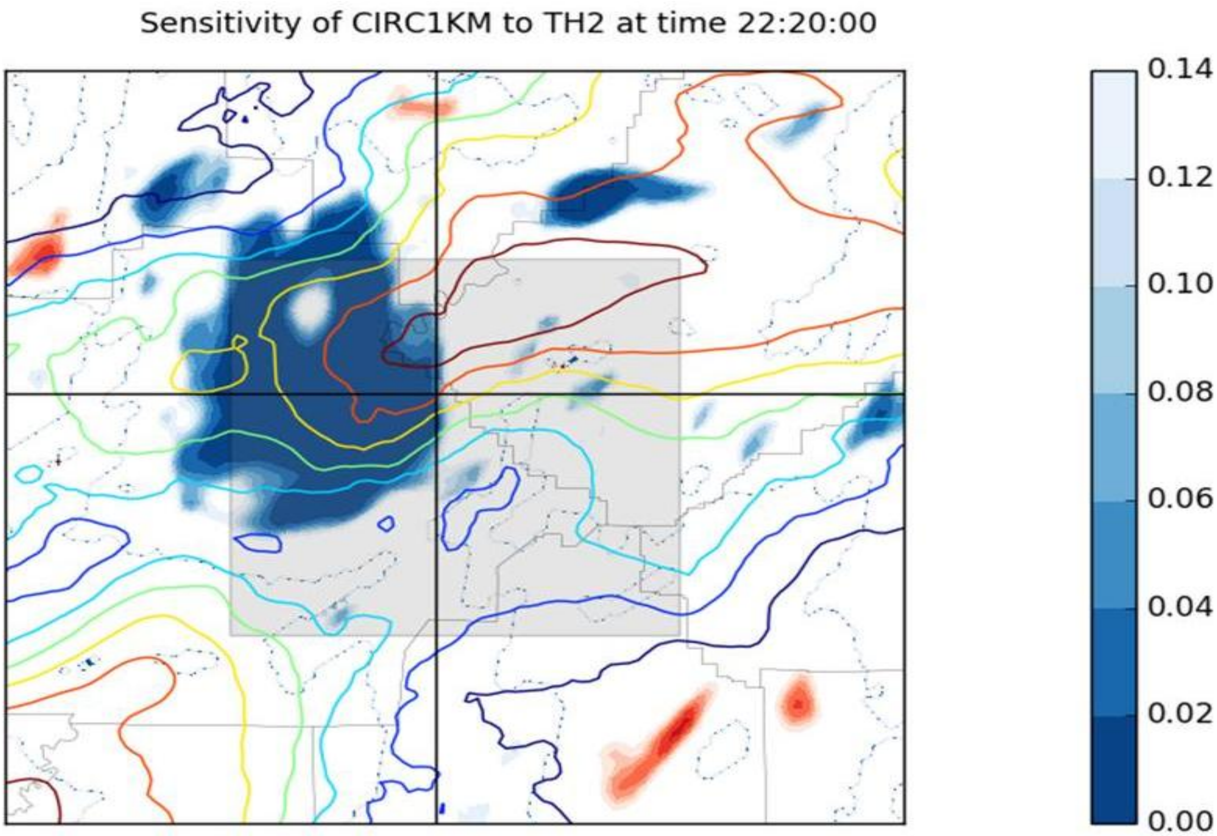

Figure 7 - P-value of regression slope (~sensitivity) for lowest model level circulation vs. virtual potential temperature, valid for a 10-min lead time prior to 2230 UTC on 27 April 2011. Line contours represent the simulated radar reflectivity (every 10 dBZ) and the crosshairs represent the location of maximum lowest model level circulation. Blue (red) shading denotes negative (positive) sensitivity, with the scale for negative sensitivity to the right.

C. Incorporation of Physics-Based Uncertainty for Forecasts of Convection

The configuration of the operational TTU ensemble has always used a static, single physics configuration with regard to the model parameterizations used. Although adaptive inflation is used in the EnKF process, the ensemble is underdispersive, particularly near the surface. This underdispersiveness may extend to convection, and a goal of this work was to assess the spread-skill relationships of forecasts of convection from an object-oriented perspective. The planetary boundary layer, surface layer, and microphysics schemes were varied on both the 4-km and 12-km grids independently, as well as concurrently, and spread-skill relationships were examined for both standard domain-wide variables and metrics defining the convective objects. These relationships were compared for the fixed physics and varied physics ensembles, and the contribution from both error and spread was examined. It was found that the varied physics configuration improves the spread-skill ratio (e.g. it is closer to 1), but at the expense of error. In other words, a large increase in spread accompanied by larger errors improved the spread-skill ratio. Interestingly, this is similar to the behavior of the Storm Scale Ensemble of Opportunity run by the Storm Prediction Center (informal communication with Israel Jirak) in that various ensemble members may produce large errors, but overall the spread-skill relationship is favorable. This has motivated both the inclusion of 10 additional physics members into the TTU ensemble system that employ varied physics parameters (for a total of 52 members), and the examination of using an adaptive physics configuration that uses the best-performing schemes for a given upcoming flow situation. More details on this work can be found in Burghardt and Ancell (2018).

D. Ensemble Sensitivity-Based Observation Targeting

In order to examine the utility of targeted observations for nonlinear mesoscale forecasts of severe convection along the dryline, experiments were strategically designed to investigate individual components of the targeting process. First, it was necessary to remove the influence of model error, which can complicate results. We constructed simulations where the model had the same error characteristics as the assimilated observations by configuring Observing System Simulation Experiments (OSSEs) in which observations are gathered from an independent simulation of a model nature run. Second, it was vitally important to analyze a suite of convective cases so that our results could be considered to represent the behavior of targeted observations generally. Therefore, ten convective events in the Southern Plains from April-June were chosen, spanning 2011-2013. These events were chosen through an examination of once-daily, cold-start initialized deterministic forecasts. If the forecast produced a reasonable depiction of dryline convection in the southern plains, it was preliminarily selected and compared against storm reports. The chosen ten cases represent a random assortment of the available cases from the three years.

Finally, a step-by-step approach was employed to evaluate the impacts of targeted observations as a function of time and location, as well as the influence of the assimilation process on observation impacts. The time of assimilation, height of observation, filter type, and assimilation characteristics (e.g. localization and inflation) were varied to analyze their respective impacts. Observations were assimilated at five distinct height levels: 300, 500, 700, and 850 hPa, as well as the surface. Observations were also assimilated at forecast hours 6, 12, and 18 to evaluate the role of nonlinearity on forecast impacts (nonlinearity should increase with increasing lead time). The ensemble Kalman filter and ensemble adjustment Kalman filter were used, which differ with respect to how the Posterior ensemble is augmented to match statistical definitions. Inflation and localization are turned on and off to further understand their importance in the targeting methodology. In this manner, each experiment permutation could be individually compared to the control forecast to determine what factors influence the observation impacts. In total, 75 target experiments are generated per convective case. An additional 75 experiments were carried out for non-targeted observations to determine the value of targeted observations over randomly choosing a location to observe where the sensitivity-based targeting algorithm predicts small impacts.

The Advanced Research Core of the Weather Research and Forecasting model v3.8.1 was used to generate the nature run as well as the ensemble forecasts. The nature run was begun six hours prior to the first data assimilation cycle and integrated through the event of interest (~90 hours). Ensemble data assimilation with 50 ensemble members occurred six-hourly for 48 hours prior for forecast integration. Both the nature run and ensemble forecast utilized the same suite of parameterization schemes, which was required in order to remove model error during analysis. After a forecast was complete, the location and time of the response function was selected that both diagnosed convection and would be used in the sensitivity-based observation targeting algorithm. Targeted observations, at the varying levels and times describes above, were then selected from the ensemble sensitivity-based targeting algorithm for assimilation toward testing of impacts.

Initial results for one case suggest that predicted observation impacts do not correlate with actual impacts for mesoscale targeting experiments, a result that deviates from more traditional synoptic-scale targeting experiments using the same sensitivity-based algorithm. Observations assimilated at different height levels, with different assimilation configurations, and at varying lead times have impacts on composite reflectivity that don't correlate with predicted impacts (Figure 8). In particular, reducing lead time between the response and assimilation times (i.e. 2011052206 to 2011052218) produces similar impacts on reflectivity variance. This result would suggest nonlinearity is impacting results even at short lead times, an important result for the applicability of mesoscale targeting. Targeted observations do produce larger impacts compared with non-targeted observations, suggesting they provide more value

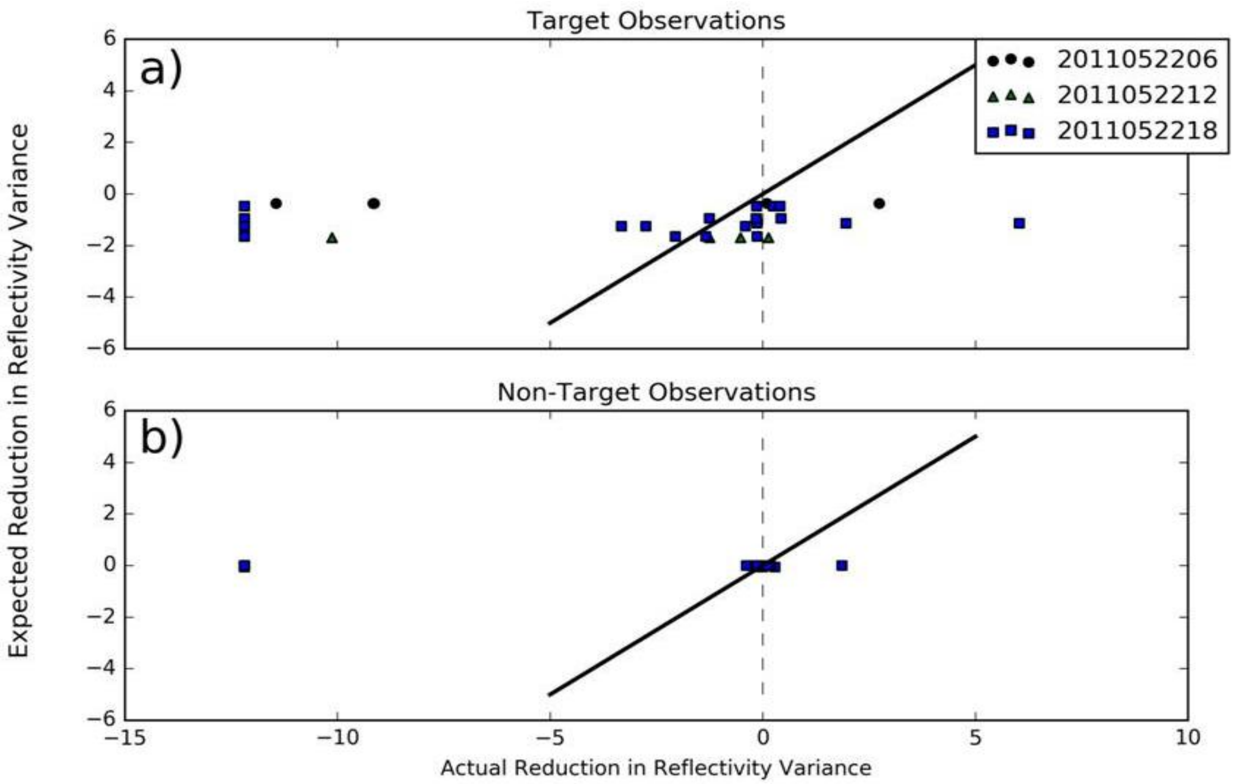

Figure 8 - Expected reduction of variance in composite reflectivity compared to actual reduction for a) targeted and b) non-targeted observations assimilated at varying times. Black line indicates a one-to-one relationship and dashed line demarcates a reduction in variance (negative) from an increase (positive).

even if the impacts are not predictable. Given that reflectivity forecasts are highly nonlinear, it was also important to investigate another response function with the sensitivity-based targeting algorithm. The change in variance of sea level pressure is similarly complex and random in nature, with many observations increasing the variance of the response. This is notable since the targeting methodology suggests any additional observation should reduce variance of the response.

E. Integration of TTU Prediction System into the NWS AWIPSII

TTU prediction system products are now being ingested into the NWS AWIPSII system. The obstacle to achieving this task was to create GRIB2 files that were configured correctly such that local NWS WFOs could ingest them without error, and several attempts to do this were unsuccessful. In turn, bi-weekly meetings were conducted with the Lubbock WFO to modify the ingestion process, and after many attempts at modifying a number of configuration settings on the local AWIPSII server, data was ingested properly. A stream of output files from the TTU deterministic system (a single WRF run forced by the initial and boundary conditions of the GFS) was created in real time via the Local Data Manager to NWS Southern Region from which individual WFOs can grab the data. Both the Lubbock and Austin/San Antonio WFOs have begun ingesting this data into AWIPSII in real time. The initial set of files from the deterministic system sent to NWS Southern Region contained only surface wind speed and direction, near-surface simulated reflectivity, and 500-hPa geopotential height for testing. However, given the success of AWIPSII ingestion and the conclusion of testing, these files are currently being populated with several additional variables from both the deterministic and ensemble system for wider use at NWS.

III. Synergistic Activities Performed with NOAA

TTU researchers directly collaborated with the following offices in transitioning probabilistic and sensitivity-based products into operations:

- The Storm Prediction Center (creation and evaluation of 2016 HWT ensemble sensitivity product)
- The Lubbock WFO (development of new TTU prediction system products, creation of sensitivity evaluation website for 2016 HWT, AWIPSII ingestion)
- The Austin/San Antonio WFO (seminar to update the WFO on the TTU prediction system,
- The Amarillo WFO (seminar to update the WFO on the TTU prediction system, development of new TTU prediction system products)
- The Houston WFO (seminar to update the WFO on the TTU prediction system, AWIPSII ingestion)
- The Norman WFO (seminar to update the WFO on the TTU prediction system, AWIPSII ingestion)
- NWS Southern Region Headquarters (AWIPSII ingestion)

IV. Dissemination of Results and Graduate Student Involvement

This project resulted in 4 publications, 22 presentations, and the involvement of 3 graduate students (listed below).

Publications

1) Ancell, B.C., 2016: **Improving High-Impact Forecasts through Sensitivity-Based Ensemble Subsets: Demonstration and Initial Tests.** *Weather and Forecasting*, Vol. 31, No. 3, pages 1019-1036.
2) Hill, A.J., C.C. Weiss, and B.C. Ancell, 2016: **Ensemble Sensitivity Analysis for Mesoscale Forecasts of Convection Initiation**. *Monthly Weather Review*, Vol. 144, No. 11, pages 4161-4182.
3) Burghardt, B., 2017: **Performance Characteristics of Convection-Allowing Ensemble Forecasts with Varied Physics Parameterizations**", PhD Dissertation, Texas Tech University.
4) Burghardt, B. and B.C. Ancell, 2018: **Performance Characteristics of Convection-Allowing Ensemble Forecasts with Varied Physics Parameterizations**", *Monthly Weather Review*, submitted, in review.

Presentations

1) "**The Impact of Observation Localization on South Plains Convective Forecasts**", Brock Burghardt and Brian C. Ancell, the 6th EnKF Workshop, Buffalo, NY, May 18-22, 2014.
2) **"Ensemble Sensitivity Analysis of Multiple Great Plains Convective Events",** Brock Burghardt and Brian C. Ancell, 27th Conference on Severe Local Storms, Madison, WI, Nov. 2-7, 2014.
3) **"Mesoscale Ensemble Sensitivity of Dryline Convective Initiation",** Aaron J. Hill, Christopher C. Weiss, and Brian C. Ancell, 27th Conference on Severe Local Storms, Madison, WI, Nov. 2-7, 2014.
4) **"The Use of Ensemble-Based Sensitivity with Observations to Improve Predictability of Severe Convective Events",** Brian C. Ancell**,** Aaron J. Hill, and Brock Burghardt, Non-Gaussian and Nonlinear Techniques for Data Assimilation/Fusion, Predictability, and Uncertainty Quantification (American Geophysical Union Fall Meeting), Dec. 15-19, 2014.
5) **"The Use of Ensemble-Based Sensitivity with Observations to Improve Predictability of Severe Convective Events",** Brian C. Ancell**,** Aaron J. Hill, and Brock Burghardt, 19th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), Phoenix, AZ, Jan. 4-8, 2015.
6) "**Mesoscale Ensemble Sensitivity and Observation Targeting of Dryline Convection",** Aaron J. Hill, Christopher C. Weiss, and Brian C. Ancell, 19th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface (IOAS-AOLS), Phoenix, AZ, Jan. 4-8, 2015.
7) **"The Use of Ensemble-Based Sensitivity with Observations to Improve Predictability of Severe Convective Events"**, Brian C. Ancell, A.J. Hill, and Brock Burghardt, 27th Conference on Weather Analysis and Forecasting/23rd Conference on Numerical Weather Prediction, American Meteorological Society, Chicago, IL, July 1, 2015.
8) **"The Use of Ensemble-Based Sensitivity with Observations to Improve Predictability of Severe Convective Events"**, Brian C. Ancell, A.J. Hill, and Brock Burghardt, 10th Adjoint Workshop, Roanoke, WV, June 1, 2015.
9) **Presentations by Aaron J. Hill and Brock Burghardt regarding operational TTU ensemble products**, 2015 Workshop on Storm-Scale Ensembles, Boulder, CO, July 23, 2015.

10) "**Ensemble Sensitivity-Based Observation Targeting OSSEs for Southern Plains Dryline Convection**", Aaron Hill, C.C. Weiss, and B. Ancell, 20th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface, 2016 AMS Annual Meeting, New Orleans, LA., January 10-14, 2016.
11) "**Quantifying Accuracy and Dispersion of Ensemble Forecasts of Severe Convection Using and Object-Based Technique**", Brock Burghardt and B. Ancell, 20th Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface, 2016 AMS Annual Meeting, New Orleans, LA., January 10-14, 2016.
12) "**The Use of Forecast Sensitivity to Improve High-Impact Ensemble Forecasts**", Brian Ancell, 2016 Texas Weather Conference, Austin, TX, February 5-6, 2016.
13) "**The TTU WRF Deterministic/Ensemble Prediction System**", Brian Ancell, Austin/San Antonio WFO seminar, February 9, 2016.
14) "**The TTU WRF Deterministic/Ensemble Prediction System**", Brian Ancell, NWS SOO ConWest meeting, March 1, 2016.
15) "**The TTU WRF Ensemble Prediction System**", Brian Ancell, Aaron Hill, and Brock Burghardt, The 2nd Storm-Scale Ensemble Workshop, College Park, MD, August 29, 2016.
16) "**The TTU WRF Deterministic/Ensemble Prediction System**", Brian Ancell, Norman WFO seminar, May 10, 2016.
17) "**Improving Spread Characteristics in a Convection Allowing Ensemble**", B. Burghardt and B.C. Ancell, 28th Conference on Severe Local Storms, American Meteorological Society, November 7-11, 2016, Portland, OR.
18) "**Ensemble Sensitivity-Based Observation Targeting Experiments for Southern Plains Dryline Convection**", A.J. Hill, C.C. Weiss, and B.C. Ancell, 28th Conference on Severe Local Storms, American Meteorological Society, November 7-11, 2016, Portland, OR.
19) "**Ensemble Sensitivity Analysis of Controls on Updraft Rotation for the 27 April 2011 Tornado Outbreak**", C.C. Weiss, D.C. Dowell, A.J. Hill, and N. Yussouf, 28th Conference on Severe Local Storms, American Meteorological Society, November 7-11, 2016, Portland, OR.
20) "**Ensemble Sensitivity Analysis of Controls on Updraft Rotation for Two Southeastern U. S. Tornado Events"**, C.C. Weiss, D.C. Dowell, A.J. Hill, and N. Yussouf, 21st Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface., American Meteorological Society Annual Meeting, January 23-27, 2017, Seattle, WA.
21) "**Ensemble Sensitivity-Based Observation Targeting Experiments for Southern Plains Dryline Convection**", A.J. Hill, C.C. Weiss, and B.C. Ancell, 21st Conference on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface, American Meteorological Society Annual Meeting, January 23-27, 2017, Seattle, WA.
22) "**Initial Results from the Evaluation of Convective Ensemble Sensitivity at the 2016 HWT Spring Forecast Experiment**", B.C. Ancell and B. Burghardt, 28th Conference on Weather Analysis and Forecasting / 24th Conference on Numerical Weather Prediction, American Meteorological Society Annual Meeting, January 23-27, 2017, Seattle, WA.

Graduate Student Involvement

1) Aaron Hill (Ensemble sensitivity analysis, observation targeting)
2) Brock Burghardt (Varied ensemble physics)
3) Jon Madden (AWIPSII ingestion)