a small project request for NSF Lower Atmospheric Observing Facilities

The Mesoscale Predictability Experiment (MPEX)

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1. Project Summary

This proposal outlines our request for the use of the NCAR GV, along with the new Airborne Vertical Atmospheric Profiling System (AVAPS) dropsonde system and the Microwave Temperature Profiling (MTP) system, for a field project named the Mesoscale Predictability Experiment (MPEX) to be conducted within the U.S. intermountain region and high plains during the late spring/early summer of 2013 (Fig. 3.2). MPEX is motivated by the basic question of whether experimental, sub-synoptic observations can extend convective-scale predictability and otherwise enhance skill in regional numerical weather prediction over a roughly 6 to 24 hour time span. Our experimental plan is guided by the following two scientific hypotheses:

Hypothesis 1: Enhanced synoptic and sub-synoptic scale observations and their assimilation into convection-permitting models over the intermountain region during the early morning will significantly improve the forecast of the timing and location of convective initiation as well as convective morphology and evolution during the afternoon and evening to the lee of the mountains and over the High Plains.

Hypothesis 2: Enhanced sub-synoptic scale observations in the late afternoon, over regions where the atmosphere has been/is being convectively disturbed, will significantly improve the 6-24 hr forecast of convection evolution and perhaps initiation in downstream regions. Enhanced observations of convective storm-environmental feedbacks will correspondingly improve the synoptic-scale forecast.

Basic operations involve two missions a day: an early morning mission (~3:00 am – 10:00 am) primarily over the intermountain region, and a late-afternoon and early evening mission to the lee of the mountains. A project of 4 weeks duration, from 15 May to 15 June 2013, is proposed. This time period is preferred due to the known high frequency of widespread, severe convective outbreaks over the Great Plains region during this period (an average of 15 per year, based on a survey of radar composites and official Storm Prediction Center storm reports over the previous 6 years), and also due to the fact that such outbreaks are still often associated with synoptic and sub-synoptic scale forcing features moving eastward from the nominally poorly sampled intermountain regions. Ten intensive observation periods (IOPs) are requested.

Our proposed observational strategy will be to release 28 to 32 dropsondes each mission from an altitude of about 40,000 ft over a grid of spacing ~ 75-200 km. MTP observations will continuously sample the temperature structure through the mid- and upper troposphere in conjunction with the dropsonde data, enhancing the representation of any mesoscale or sub-synoptic scale features along the plane's path. The dropsonde and MTP data will be incorporated into both realtime and retrospective data assimilation experiments using a variety of techniques (3DVAR, ENKF, etc.) to establish the potential benefits of such enhanced observations.

Intellectual Merit: The morning dropsonde and MTP data will offer us an unprecedented opportunity to examine the regional-scale predictability of severe convective storms on the high plains later in the day. The observations in the evening will additionally provide us with documentation/verification of the evolution of key mesoscale and subsynoptic features to the lee of the mountains as well as offer unique insight into how different storm types modify their nearby environments and influence subsequent forecasts.

Broader Impacts: MPEX will produce unprecedented observations for model initialization and forecast verification that can be used by the broad research and forecast community to address the predictability of severe convective storms over a region of the country that is especially prone to widespread severe weather outbreaks. The subsequent research will contribute to improved forecast guidance of the timing and location of severe convective weather, to help enhance public response for potentially damaging and life threatening weather conditions. The results of this research will also help inform decisions as to needed improvements in observing systems for convective weather forecasting.

2. Science Overview

The Mesoscale Predictability Experiment (MPEX) is a field program that aims to investigate the predictability of convective storms on the mesoscale. In particular, it seeks to address the basic question of whether experimental, sub-synoptic observations can extend convective-scale predictability and otherwise enhance skill in regional numerical weather prediction over a roughly 6 to 24 hour time span.

There are two complementary research foci for MPEX:

Regional-scale numerical weather prediction (NWP) of convective storms. Analysis and prediction of the upstream, pre-storm mesoscale and sub-synoptic scale environment for regional scale convective forecasting.

The feedbacks between deep convective storms and their environments. The upscaling effects of deep convective storms on their environment, and how these feed back to the convective-scale dynamics and predictability.

Theoretical studies clearly suggest a decrease in predictability for decreasing scale of the phenomena in question, with predictability possibly extending out to several days for synoptic scale disturbances, perhaps 12 to 24 hours for mesoscale or sub-synoptic disturbances, down to mere hours for convective storms (e.g., Lilly 1990). Indeed, data assimilation studies to date suggest that the value of adding convective scale details to the initial forecast state, via the direct incorporation of radar data, the indirect use of diabatic heating to represent ongoing convection, and the like, is largely lost in the first six hours of a forecast. However, to the degree that convective storms are forced and constrained by larger-scale phenomena such as fronts, dry lines, jet streaks, etc., improving the representation of these forcing elements has the potential to significantly improve the predictability of the more regional aspects of convective weather as well. It is in this regard that we intend to use the dropsonde and MTP data to address the predictability of convective weather.

A. Regional analysis and numerical weather prediction

Explicit predictions of convective weather with numerical models that assimilate high-resolution observations are recognized as essential for improving warnings of hazardous weather associated with convective storms (tornadoes, other damaging winds, hail, lightning, and floods) and improving quantitative precipitation forecasts in general (Fritsch et al. 1998; Droegemeier et al. 2000; Dabbert et al. 2000; U.S. Dept. of Commerce 1999). Various real-time experiments during the last decade have demonstrated that explicit prediction of convective storms (Lilly 1990; Droegemeier 1990; Droegemeier 1997) has now become a reality (e.g., Droegemeier et al. 1996; Xue and Martin 2006ab; Sun and Crook 2001; Crook and Sun 2002; Done et al. 2004; Kain et al., 2005, 2006, 2008; Weisman et al. 2008; Clark et al. 2012). Since 2003, experimental daily 24 to 48 h real-time explicit convective forecasts employing grid spacings between 1 and 4-km horizontal over the central U.S. have been evaluated as part of the NSSL-SPC Hazardous Weather Testbed (HWT) spring experiments, whereby forecasters and researchers from a variety of backgrounds have evaluated the applications of such high resolution guidance for operational severe storm forecasting (e.g., Weiss et al. 2004, 2007; Kain et al. 2005, 2006, 2008). These forecast exercises have demonstrated that increasing horizontal grid resolutions into the convectively-explicit regime leads to significant improvements in convective forecast guidance. Such forecasts often realistically represent the structure and evolution of mesoscale convective phenomena, such as supercells, squall lines, bow echoes, and mesoscale convective vortices (e.g., Weisman et al. 2008). On the other hand, significant errors in the timing and location of significant convective events are also frequently encountered. An example of such a forecast is presented in Fig. 2.1 from 5 May 2007, the day of the devastating Greensburg, KS tornado. A 3 km WRF-ARW simulation successfully forecast an intense, isolated supercell storm over central Kansas between 21 UTC and 01 UTC, nearly 24 h in advance, but was off in timing and location by 3 h and 150 km, respectively. Although we generally cannot count on accurately forecasting individual convective storms 24 h in advance, we would hope to be able to improve on the overall timing, location and coverage of storms for such episodes.

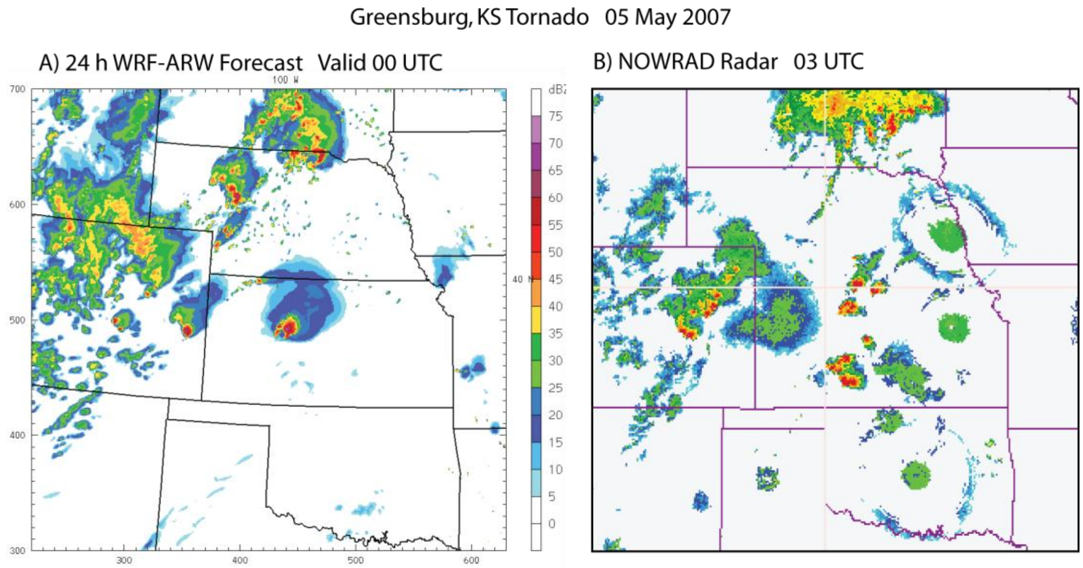

Fig. 2.1. a) 24 h WRF-ARW reflectivity forecast, using a 3 km horizontal grid resolution, valid 00 UTC on 5 May 2007. b) Observed composite NOWRAD radar reflectivity, valid 03 UTC 5 May 2007.

Numerous issues could contribute to these forecast errors, including errors in physical parameterization schemes, coarse horizontal and vertical resolution, poor representation of atmospheric features crucial to storm initiation and evolution, and so on. While sensitivity studies considering resolution and model physics (e.g., PBL and microphysics) have generally not been able to explain errors in mesoscale convective organization, far more forecast sensitivity on the 6 to 48 h timescale is generally observed by varying initial conditions (e.g., initializing with the RUC versus NAM versus GFS), providing a larger spread of possible outcomes that seems to offer a better chance of encompassing the correct forecast (e.g., Weisman et al. 2008).

In an attempt to improve forecasts of a severe derecho-producing convective system, Gallus et al. (2005) suggest, “It thus appears that useful forecasts of systems such as this one may require a much better observation network than now exists, or better methods of including additional information from radar and satellites.” A recent simulation study of the 3 May 1999 Oklahoma tornado outbreak by Roebber et al. (2002) suggests that 24-h forecast errors of order several hundred km and/or several hours (similar to the more significant forecast errors noted in the real-time experiments) can indeed be related to resolvable-scale observational errors in the initial upstream conditions.

Figure 2.2 provides an example of the type of upstream features that can have a significant impact on convective forecasts later in the day. In this case, from June 10, 2003 during BAMEX, a series of small-scale waves (labeled A and B in Fig. 2.2) were moving eastward within the subtropical jet stream. Of particular interest, wave A was not accurately represented in the initial analyses for either the operational NAM or an experimental WRF-ARW forecast, at either 00 UTC or 12 UTC. This wave subsequently initiated a large mesoscale convective system (MCS) with an associated mesoscale convective vortex (MCV) later that evening over central Oklahoma (not shown). Neither the NCEP operational regional model (ETA) or the WRF-ARW forecasts initialized from the ETA were able to capture this significant MCS. Although the precursor was apparent in satellite imagery, higher resolution upstream soundings on this day may have been critical for properly representing the dynamical structure of this feature in the initial analyses and improving the subsequent convective forecasts.

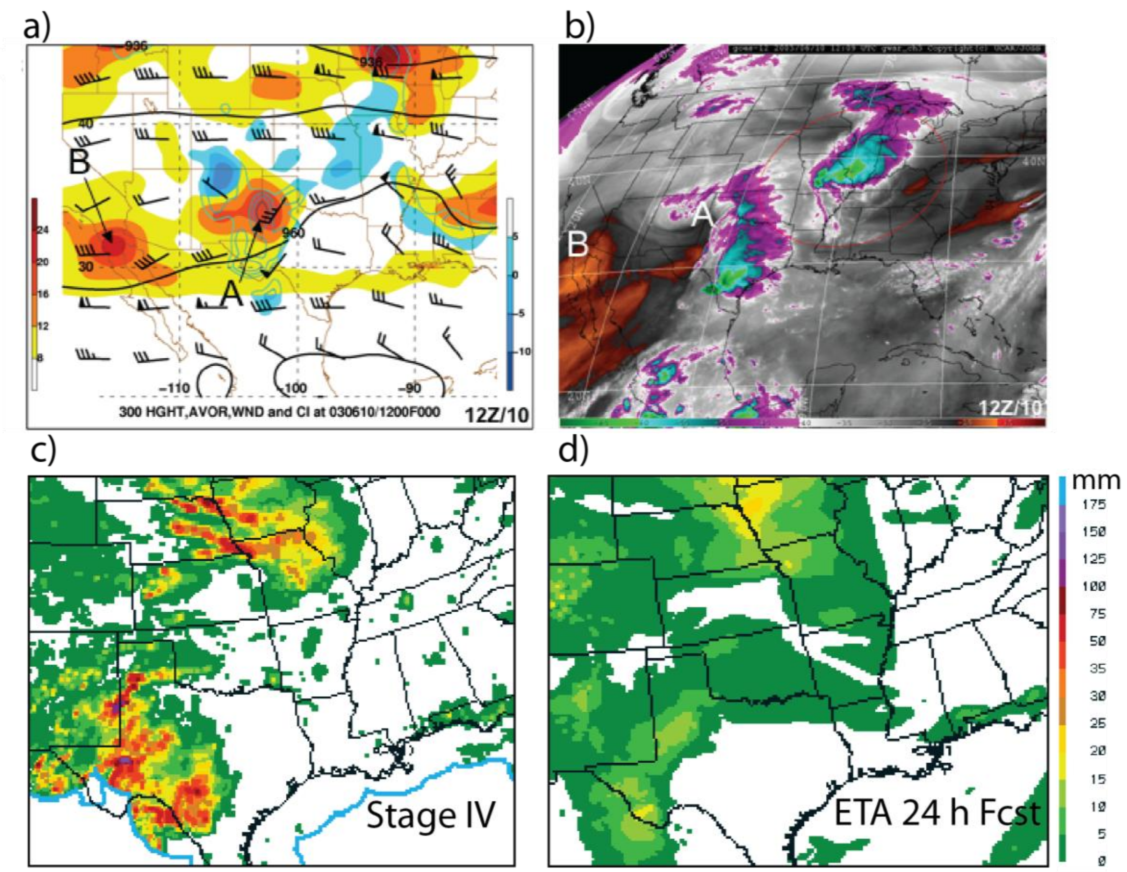

Fig. 2.2. (a) 300 hPa geopotential height (dam; solid contours), absolute vorticity (10-5 s-1; shaded warm colors), and wind (knots; standard barbs), and coupling index (shaded cool colors < 5 K) at 1200 UTC 10 June 2003. Data source: 1.0 degree GFS final analyses. (b) GOES-12 water vapor imagery at 1200 UTC 10 June 2003. Data source: BAMEX field catalog. Letters A, B, denote subtropical jet disturbances. Also 24 h rainfall totals from c) Stage 4 observations and d) 24 h ETA forecast ending 12 UTC on June 10 2003.

Indeed, one of the greatest challenges facing mesoscale and cloud-scale weather prediction is analysis uncertainty. While large-scale analysis uncertainty can be estimated by calculating the differences between global analyses from operational modeling centers, mesoscale analysis uncertainty is much harder to define, owing largely to a lack of data with sufficient spatial and temporal resolution to define mesoscale atmospheric features accurately. Fig. 2.3 presents an example of how analysis uncertainties can have an impact on convective forecasts. In this case, a significant convective system in Oklahoma on 20 June 2007 was forecast quite successfully using the GFS analysis from 12 UTC, but is significantly misrepresented when using the North American Model (NAM) analysis at 12 UTC. Sensitivity testing with model microphysics and PBL schemes failed to improve the NAM-based forecast. The improved Global Forecast System (GFS) forecast for this case was likely related to the enhanced 700 hPa theta-e and accompanying cyclonic circulation analyzed in northwestern Kansas at 12 UTC (Fig. 2.4b), which resulted in stronger initial convection in that region.

The observational strategy proposed in Section 3 would provide an unprecedented data set for use in data assimilation to capture mesoscale features upstream from the MPEX area of forecast interest. Comparisons with operational analyses would allow us to determine better the analysis uncertainty on the mesoscale, which can then be used to guide ensemble initial condition perturbation strategies and in predictability studies.

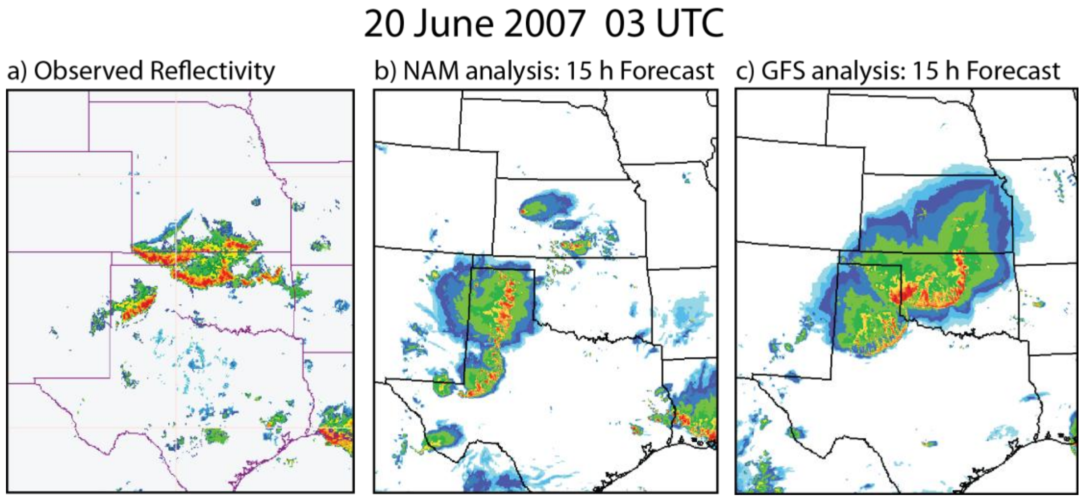

Fig. 2.3. (a) Observed composite reflectivity at 03 UTC on 20 June 2007. (b) 15 h reflectivity forecast from 3 km WRF-ARW simulation initialized 19 June at 12 UTC using a NAM analysis. (c) 15 h reflectivity forecast from 3 km WRF-ARW simulation initialized 19 June at 12 UTC using a GFS analysis.

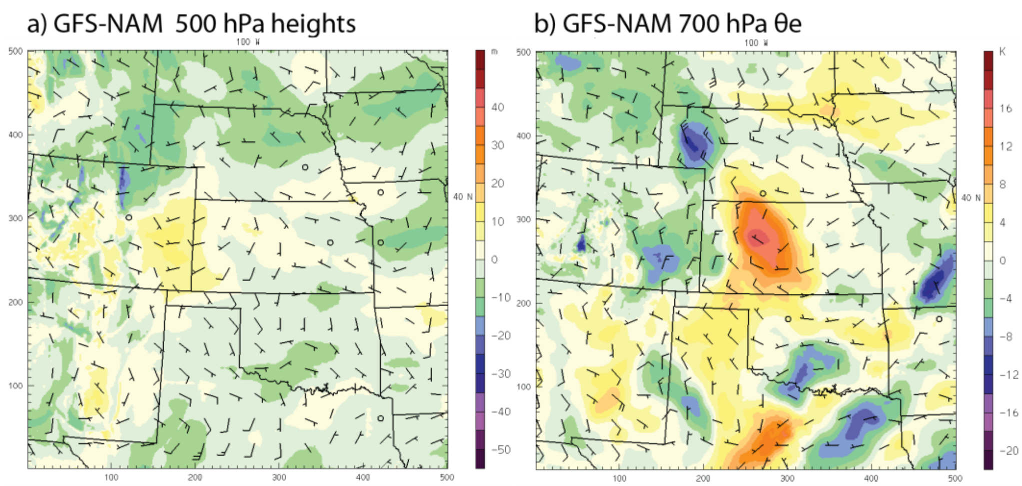

Fig. 2.4. Difference fields for GFS versus NAM analyses on 19 June 2007 at 12 UTC. (a) 500 hPa height (m) and wind (kts) differences. (b) 700 hPa theta-e (k) and wind (kts) differences. Positive (negative) values denote higher values in the GFS (NAM) analyses for both fields.

The potential value of enhanced upstream observations for short term forecasting of hazardous weather is highlighted in several recent studies. For instance, Benjamin et al. (2004) discuss the value of the enhanced wind observations offered by NOAA Profiler Network (NPN) in improving short-term forecasts within a 20 km version of the Rapid Update Cycle (RUC) model. Benjamin et al. (2010) further discuss the relative value of a variety of observational data sets, including aircraft, profilers, radiosondes, mesonets, etc., in improving short-term (3-12 h) forecasting in the RUC, noting especially the value of radiosondes for improving 12 h forecasts. Roebber et al. (2008) note for 15 km forecasts of precipitation over the NW United States that predictability at the mesoscale is strongly linked to the quality of the synoptic information feeding the mesoscale grid. Schumacher (2011) similarly noted that an ensemble forecast of a long-lived mesoscale convective system was sensitive to relatively small differences in the upstream height and wind field. Wandishin et al. (2008, 2010) further note the need for improved mesoscale observations to improve the predictability of mesoscale convective systems.

It seems clear that the proper representation of subsynoptic and synoptic scale features crossing the intermountain regions (e.g., fronts, jet streaks, subtropical waves), especially at mid-tropospheric levels, is critical to properly forecasting key mesoscale features to the lee of the mountains (e.g., lee troughs, dry lines, low-level jets). It also seems clear that many of the features that end up being critical to subsequent severe weather outbreaks are at scales below those which can be represented by our current set of observations over the intermountain regions, and, as such, are often absent from or misrepresented within the available model guidance. Thus, severe weather forecasters continuously monitor for such features during the day using profilers, satellites, etc., to help modify the available numerical guidance. While dropsonde observations have been demonstrated for a variety of applications as they are anticipated to aid here as well, previous experiments have generally spaced dropsondes too sparsely to resolve the mesoscale details. This project aims to provide enhanced observation density at the location of features of interest through both increased dropsonde drop rates and additional temperature profile cross-sections using the Microwave Temperature Profiler (MTP, Denning et al. 1989). The MTP is particularly useful for representing horizontal fluctuations of temperature on spatial scales of 10-100 km within roughly 6 km of the aircraft altitude with a vertical resolution of a few hundred meters.

These upstream tropospheric measurements will be used to produce enhanced synoptic and subsynoptic analyses for incorporation into explicit convective forecast models, for both realtime and retrospective studies. The potential benefits of the enhanced upstream tropospheric observations will be tested using a variety of data assimilation techniques (e.g., 3DVAR, ensemble Kalman filter (EnKF)), through the use of data denial experiments. The variety of techniques/methodologies currently being considered is described below.

The Data Assimilation Research Testbed (DART; Anderson et al. 2009) is an ensemble-based data assimilation system that provides interfaces to a number of models including WRF-ARW (Skamarock et al. 2008). Used as a cycled data assimilation system, DART provides periodic analysis and initial conditions for deterministic or probabilistic forecasts. Further, diagnostics generated by DART provide key feedback on model system deficiencies in representing observed features. We will utilize the WRF-DART system for the proposed project to address aspects of targeting, model error and observation impact from special observations as detailed below.

MPEX aims to improve the forecast by sharpening the analysis with additional observations in regions where synoptic and subsynoptic features may not be sufficiently represented by the operational observational network as well as where forecast errors are sensitive to analysis (initial condition) errors (e.g. Berliner et al. 1999; Aberson 2003; Bergot 1999, Buizza et al. 2007, Szunyogh et al. 2000; Bishop and Toth 1998).

For the present experiment, subjective forecaster based methods will be used to identify features (e.g. short waves projected by operational and/or experimental forecast models, cloud or moisture bands in satellite imagery, etc.) that will be targeted during the campaign. These forecaster identified features can then be evaluated against formal targeting techniques and subsequent retrospective assimilation experiments can test the impact of the enhanced data on subsequent forecasts. Supplemental observations have historically posed some challenges toward improving model forecasts when mesoscale features are inadequately sampled, such as with hurricane core observations (Aberson 2008). We will address such issues by evaluating the model representation of these mesoscale features against the special dropsonde and Microwave Temperature Profile (MTP) observations, identifying opportunities for improved model representation.

In addition, the predictability and growth of initial condition errors will be evaluated using ensemble sensitivity analysis. This technique allows for an objective estimate of how initial condition errors at a particular location, field or feature would impact a forecast metric that is a function of the model variables, similar to how these methods are used for winter storms in the Winter Storm Reconnaissance Program for winter weather (e.g., Szunyogh et al. 2000) and tropical cyclones during the THORPEX

Pacific Asian Regional Campaign (T-PARC; Elsberry and Harr 2007). In particular, sensitivity analysis can be used to evaluate the optimal location for the G-V to sample with dropsondes during the field phase and test hypotheses about what particular features or fields lead to the lack of predictability during particular cases. Ensemble forecasts initialized from the WRF-DART analyses will be integrated to 48 h, whereby an ensemble of forecast metrics related to convection, such as precipitation rate, area coverage of precipitation, convective inhibition, etc., will be calculated over regions believed to be convectively active during that period. The ensemble estimates of the forecast metric will be used to objectively determine sensitive regions for comparison with the forecaster identified features believed to be limiting the predictability of convection (e.g., Ancell and Hakim 2007, Torn and Hakim 2008). Following the field phase, additional experiments will be undertaken to evaluate the hypothesis that reducing initial condition errors in particular locations can improve forecasts.

Finally, the dropsonde data will also be incorporated into both the operational Rapid Refresh (RAP) hourly assimilation system, as well as the High-Resolution Rapid Refresh (HRRR) experimental convection permitting forecast model, run by the Assimilation and Modeling Branch of the Global Systems Division, Earth System Research Lab of NOAA. Both the RAP (13km horizontal grid spacing, North American domain) and HRRR (3km over CONUS, initialized from the RAP assimilation cycle, including a diabatic initialization) are run in real time. Assuming the dropsonde data are available in near real time, this additional data will be incorporated into one of the parallel RAP/HRRR cycles to conduct both subjective and objective evaluation of the HRRR convection-permitting model's forecasts of convection onset, mode and upscale growth into mesoscale convective systems. This evaluation will then suggest other experiments involving treatment of the drop data and perhaps other model and assimilation configurations that will be carried out retrospectively.

B. Storm-environment feedbacks

The influence of organized regions of deep convection on the large-scale environment in both space and time has been recognized for many years. Upper tropospheric meso-α scale anticyclones commonly are associated with cloud clusters, tropical storms, and hurricanes in the tropics (Riehl 1959; Yanai 1964; Houze and Betts 1981) and mesoscale convective systems (MCSs) in the midlatitudes (Ninomiya 1971a,b; Maddox 1980; Fritsch and Maddox 1981; Anabor et al. 2009; Trier and Sharman 2009; Metz and Bosart 2010). These anticyclones can have significant amplitudes, with perturbations in wind speeds of over 20 m s^{-1} and in geopotential heights of over 80 m at 200 hPa (Leary 1979; Fritsch and Maddox 1981; Perkey and Maddox 1985; Smull and Augustine 1993). They typically develop during the mature stage of a convective system and dissipate during the decay stage (Houze 1977; Leary 1979; Gamache and Houze 1982; Wetzel et al. 1983; Menard and Fritsch 1989). This yields a relatively short lifetime of approximately 6 to 24 h for these features produced by storm-environment interactions.

The bulk upscale effects of convection in baroclinic cyclones noticeably impact the downstream synoptic-scale and immediate mesoscale environment. This includes: downstream ridging in the upper troposphere associated with diabatically driven outflow from convection (e.g., Dickinson et al. 1997); convection-assisted vorticity generation along occluded fronts in rapidly intensifying oceanic cyclones and resulting vorticity accumulation near the cyclone centers (e.g., Shapiro et al. 1999); enhanced differential cyclonic vorticity advection ahead of weak upstream troughs resulting from convection-generated enhanced downstream ridging and jet development with landfalling and recurving tropical cyclones (e.g., Bosart and Lackman 1995; Atallah et al. 2007); vorticity accumulation and amalgamation in vortical hot convective towers during incipient tropical cyclogenesis (e.g., Reasor et al. 2005); and mesoscale ridging in the upper troposphere ahead of convection associated with mesoscale convective vortices (e.g., Galarneau and Bosart 2007).

Further evidence of the ability of midlatitude MCSs to produce longer-lived effects on the environment is given by Keyser and Johnson (1984) and Wolf and Johnson (1995a,b), who illustrate the ability of organized deep convective regions to enhance upper-level jet streaks through modification of the direct mass circulation in jet entrance regions by diabatic heating. Stensrud (1996) and Stensrud and Anderson (2001) further show that long-lived regions of deep convection can act as a Rossby wave source region and produce significant upper-level perturbations to the large-scale flow (Fig. 2.5). Long-lived regions of deep convection also tend to increase the low-level inflow of warm, moist air that helps sustain the convection (Stensrud 1996). Similarly, buoyancy bores emanating from deep convection act to further enhance nearby low-level vertical motion, making new convection initiation more likely (Mapes 1993), although interactions between nearby convection also can occur within several vertical layers and actually suppress convection (Stensrud and Maddox 1988). Bretherton (1993) further indicates that the gravity wave response near the heat source region can be quite complex, with mean flow and wind shear capable of altering the propagation of the long gravity waves that produce adjustment (Lin 1987).

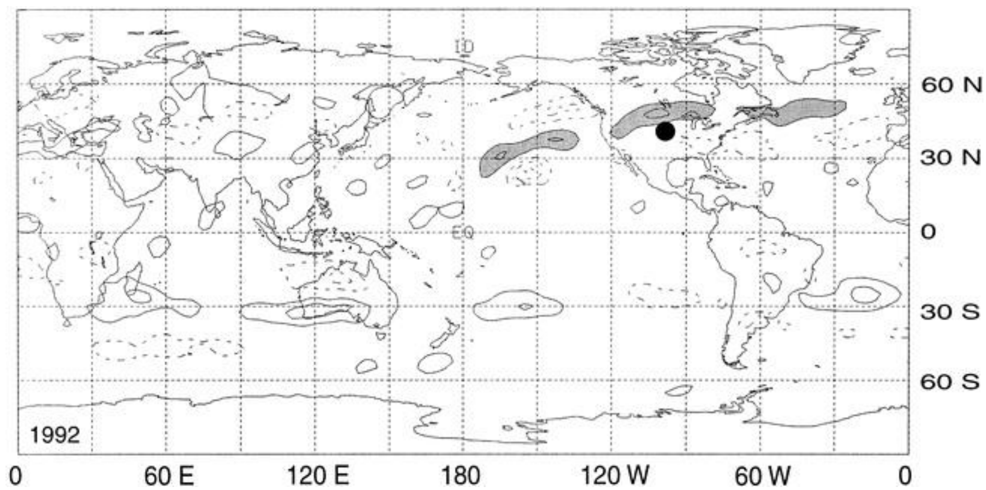

Fig. 2.5. Anomalies in 200-hPa vertical vorticity during July 1992. The black dot represents the Rossby-wave source region. Shaded anomalies are those that lie within the Rossby waveguides. Contour interval is 1×10^{-5} s^{-1}. From Stensrud and Anderson (2001).

On the smaller scale, closer to the region of deep convection in both space and time, Brooks et al. (1994) show changes in the convective available potential energy (CAPE) and storm-relative environmental helicity surrounding a simulated supercell thunderstorm. The supercell enhances both CAPE and helicity in the inflow region within 2 hours after initiation, with the changes extending out 10-20 km from the storm core. These changes likely assist supercell maintenance and may increase storm severity. Thus, even isolated, short-lived thunderstorms influence the nearby environment.

While these past studies clearly document the influences of thunderstorms and MCSs on the large-scale environment, both nearby the convection and more distant, a careful comparison of the upscale response to convection from model simulations with environmental observations has not been conducted. It is plausible to propose that a large region of deep diabatic heating due to convection would lead to the production of an upper-level anticyclone while simultaneously strengthening the low-level flow around the convective region. This is a first-order effect and it is expected that numerical models with even crude approximations of convective processes would be able to reproduce this behavior. With the improved capability of NWP models at convection-allowing grid spacing (1 – 4 km), however, it is time to examine the details of how deep convection modifies the surrounding environment in much greater detail.

The improvements in NWP models at convection-allowing grid spacing also provides an opportunity to examine the predictability of convective forecasts. Current convection-allowing NWP models can be quite skillful in predicting convection, but their forecast skill generally decreases rapidly within a few hours (Weygandt et al. 2004, Kain et al. 2010, Stratman et al. 2012). One important reason for this rapid degradation in skill is analysis error in the environment. It is well known that the characteristics of convective storms are strongly tied to the environment in which they develop, thus it is important to represent the initial environment accurately to be able to forecast convection accurately (Benjamin et al. 2010, Wandishin et al. 2010).

Recent studies show this may be true even for convection-allowing grids and when observations of precipitation and radial wind from Doppler radar data are assimilated. For example, Fabry (2010) shows that radiosonde temperature, wind and humidity observations (midlevel humidity in particular) all have a large positive impact on 0 – 6 h forecasts of precipitation on 4-km grids. Stensrud and Gao (2010) show that a horizontally inhomogeneous background environment derived from an assimilation of surface observations drastically improves 1-h forecasts of a tornadic thunderstorm on 1 - 3-km grids over those provided by horizontally homogeneous initial conditions. For the successful prediction of a squall line on a 4-km grid, Sun and Zhang (2008) show that assimilation of wind observations from a nearby environmental sounding are very important. Schenkman et al. (2011) show that 1 – 2 h forecasts of a MCS on a 2-km grid and an embedded vortex are impacted positively and significantly by the assimilation of surface mesonet data. Although the abovementioned studies show the importance of representing the environment accurately for short-term convective forecasts, they are limited in scope. A careful examination of the impact of multiple radiosonde observations at mesoscale space and time scales on the short-term (0 – 6 h) prediction of convection has not been done.

As a way of summarizing the preceding review of storm-environment feedbacks, we ask the following:

- How does the upscale feedback relate to the mode of convection, and to other characteristics, such as the numbers and relative sizes of the convective cells?
- Are simulations with convection-permitting models able to produce the environmental warming/cooling due to convection over the same vertical depths as indicated by observations? How well do these model simulation reproduce the moisture and wind structures nearby deep convection?
- Is the rapid decrease in the skill of convective forecasts influenced by the accuracy of model environmental forecasts in regions just outside of active deep convection?

Accordingly, these and related research questions under Hypothesis 2 can be divided into three complementary parts to be pursued during MPEX:

QUANTIFICATION OF OBSERVED UPSCALE FEEDBACKS FROM DEEP CONVECTION

To diagnose the 3D structure of the upscale effect, we will use a methodology that basically follows Davis and Trier (2007). This includes a time-space correction of the dropsonde data to the mean time of the dropsonde deployment, and then an application of the "triangle method" (Bellamy 1949; Doswell and Caracena 1988; Davies-Jones 1993; Spencer et al. 1999) to compute spatial derivatives of the horizontal wind vector components (divergence, vorticity); justification for this use of the triangle method is provided by Spencer and Doswell (2001). Application of this technique will result in analyses akin to the diagnosed MCV structure determined by Davis and Trier (2007).

It will be important for us to relate the structure of this environmental perturbation back to the characteristics of the associated convective storm(s). Single-Doppler radar data from the proximate WSR-88D will suffice for this purpose. The number, size, intensity, and other attributes of storms will be quantified using the Baldwin Object-Oriented Identification Algorithm (BOOIA; Baldwin et al. 2005) applied to fields of radar reflectivity. We will also exploit the 5-min analyses produced via assimilation of WSR-88D radar data and other standard observations (Yussouf and Stensrud 2010; see below). In particular, these analyses will provide us with additional information about the 3D airflow and storm structure.

Finally, following Gallus and Johnson (1991) and others, diagnostic equations for heat and moisture budgets (Q_1 and Q_2) will be analyzed using all available data. This will provide information about the diabatic heating, and moisture processing and transport by the storms, and again will be related back to the storm characteristics.

All of the analyses will be supplemented, when possible, by the airborne MTP measurements. These will provide a continuous vertical profile of atmospheric temperature (or potential temperature), extending roughly 6 km above and below the aircraft's altitude, along the aircraft's path.

MODEL SIMULATIONS OF UPSCALE FEEDBACKS FROM DEEP CONVECTION

The MPEX soundings will be used to study how well the upscale influence of deep convection on the environment is simulated by numerical weather prediction models. This study will be based on the development of high-quality, model-based ensemble analyses that will be constructed every 5 minutes throughout the lifetime of the convective complex. The WRF model will be used in an ensemble with ~50 members and with a convection-allowing horizontal grid spacing of ~3 km and more than 50 vertical levels with the model top at 50 hPa or less.

Observations will be assimilated into the ensemble using an EnKF approach using DART. Initially only standard observations (surface, aircraft, rawinsondes as in Wheatley and Stensrud 2010) and WSR-88D radar observations of reflectivity and radial velocity (see Yussouf and Stensrud 2010 for details) will be assimilated. This assimilation system will ensure that the evolution of deep convection in the analyses reproduces the observed evolution, while simultaneously constraining the large-scale environment to match the large-scale observations. The resulting 5-minute ensemble mean analyses will provide the best high-resolution analyses possible with current modeling and data assimilation approaches. However, with the dearth of standard environmental observations in regions surrounding deep convection, the numerical model will largely determine the analyses in the regions surrounding the deep convection. Comparisons between the model ensemble mean and the MPEX dropsonde and MTP observations will be conducted to see how well the model reproduces the environmental changes nearby convection.

The ensemble data assimilation system will also be rerun with the addition of the MPEX dropsondes to produce more accurate analyses of the upscale feedback associated with deep convection. Comparisons between the ensemble means with and without special MPEX observations should be very useful in documenting regions where the model is not producing a reasonable simulation and in answering questions regarding upscale feedbacks listed above. The ensemble assimilation system also will be rerun with different parameterizations for microphysics (i.e., single and double moment schemes) and radiation to document any model sensitivities. It is believed that these comparisons will lead to a better understanding of the upscale influence of deep convection on the environment and perhaps identify deficiencies in current model parameterization schemes.

PREDICTABILITY OF CONVECTIVELY DISTURBED ATMOSPHERE

The MPEX dropsonde observations will provide an unprecedented opportunity to define the sensitivity of explicit convective forecasts (and hence the changes in predictability) to environmental uncertainty. Predictability will be examined in two ways, 1) as the change in skill (both scale and variable dependent) as the convective event is forecast with sequentially greater lead time, and 2) as the change in forecast skill as the MPEX dropsondes are added sequentially to the assimilation and (presumably) the local analysis error is reduced. The WRF-DART system with an ensemble adjustment Kalman filter will be used to assimilate the observations into a ~50 member ensemble from which 6 h forecasts of a selected MPEX case (or cases) will be performed. Similar assimilation/forecast systems have shown much promise in providing accurate short-term forecasts of severe convection (Stensrud and Gao 2010, Dawson et al. 2011).

For each MPEX case examined, a baseline ensemble analysis and forecast will be produced on a CONUS-sized domain with mesoscale horizontal grid spacing (~18 km) by assimilating standard operational data over a 2 – 3 day period. In addition, reflectivity and radial velocity observations from the

WSR-88D network will be assimilated into an ensemble of WRF simulations nested inside the mesoscale ensemble at 2 – 3 km horizontal grid spacing during the 1-hour period before the start of the forecast. A 6-h ensemble of WRF forecasts will then be launched from the final analysis on the convection-allowing domain.

The skill of the ensemble of model analyses and forecasts will be assessed based on the model representation of the convective evolution compared to Doppler radar observations. The skill will be assessed out to 6 h, thus a one-to-one correspondence between forecast and observations on convective scales is not likely to be obtained beyond a few hours because of inherent predictability limits (Zhang et al. 2007, Stensrud et al. 2009). Therefore, this study will use objective techniques that examine the scale dependency of the forecast errors to quantify the skill of the forecasts (Ebert 2008). The improvement in predictability will then be assessed through a comparison of the skill scores between the many experiments. It is believed that these comparisons will lead to a better understanding of the potential for in situ observations of the atmospheric profile in the nearby environment to improve our current capability of predicting convective storms

3. Experimental Design and Deployment Strategies

Our experimental design requires observations that are sufficiently dense (typical spacing ~75 to 200 km) to sample short-wave troughs and ridges, low-level jets, dry intrusions, potential vorticity streamers, and other mesoscale phenomena in the pre-storm environment, as well as the modification of environment proximate to active and decaying storms. Operational full-tropospheric kinematic and thermodynamic measurements are too sparse, especially over the intermountain regions, to resolve many of these features thought to be critical for convective forecasting (e.g., Fig. 3.2). Although satellite-derived profiles are a promising mesoscale data source, these profiles do not yet have the vertical resolution thought to be necessary for convective forecasting.

Therefore, an observational strategy involving in situ (dropsondes) and MTP measurements is proposed. GPS dropsondes deployed from aircraft represent the best technology available for targeting different geographical regions from day-to day, and obtaining the required horizontal and vertical resolution of observations throughout the troposphere to meet the MPEX scientific objectives. The successful use of dropsondes during BAMEX (e.g., Davis et al., 2004; Davis and Trier, 2007; Trier and Davis, 2007; Storm et al., 2007) and PREDICT (Montgomery et al., 2012; Davis and Ahijeviych, 2012) demonstrates the value and feasibility of this observational strategy.

Airborne MTP measurements offer an additional capability of obtaining a continuous vertical profile of atmospheric temperature (or potential temperature), extending roughly 6 km above and below the aircraft's altitude, along the aircraft's path. This technique has been quite useful in identifying the height of the tropopause as well as identifying mid-tropospheric baroclinic zones (e.g., Fig. 3.1). During PREDICT, it was shown that MTP observations could also identify more subtle (e.g., 1-2 K) temperature variations (Chris Davis, personal communication), as might be critical for identifying the type of weaker mid- and upper-tropospheric mesoscale features thought to be important for convective triggering. As such, MTP data will likely be able to significantly enhance the characterization of atmospheric structure between dropsondes, thereby increasing the effective resolution of the observational data set even further. In conjunction with this, we also hope to take advantage of d-value mapping of the difference between pressure altitude and GPS, to provide further fine scale measurements of the pressure field along the flight path. Accessing MTP and the d-value data in realtime would be especially useful for identifying and refining regions for enhanced dropsonde density during flights, as described further below.

The NSF/NCAR Gulfstream V (GV) is the requested platform for deploying dropsondes and MTP during MPEX. Since two major deployments of the dropsonde aircraft, separated by 3-4 h, are being requested, a double crew will likely be needed to support dropsonde deployments.

The nominal daily schedule for data collection is as follows:

- Early morning (~09-17 UTC): Pre-convective dropsonde (**D-R**) and MTP deployment to establish upstream conditions for anticipated later convection. (See Fig. 3.2)
- Late afternoon and evening (~21-03 UTC): pre-storm and post-storm dropsonde (**C-A, C-B**) and MTP deployment to resample the upstream storm environment in the lee of the mountains, and to sample the modified mesoscale environment surrounding existing storms or storm systems. (See Figs. 3.3, 3.4)

The dropsonde and MTP deployments will occur for all days for which widespread (severe) convection with an identifiable upstream precursor is forecast, based on operational and experimental convectively explicit forecast guidance as well as the Storm Prediction Center convective outlooks. Dedicated dropsonde coordinators will guide the various deployment efforts from an MPEX operations center at JEFFCO. The various deployment strategies are described in detail below.

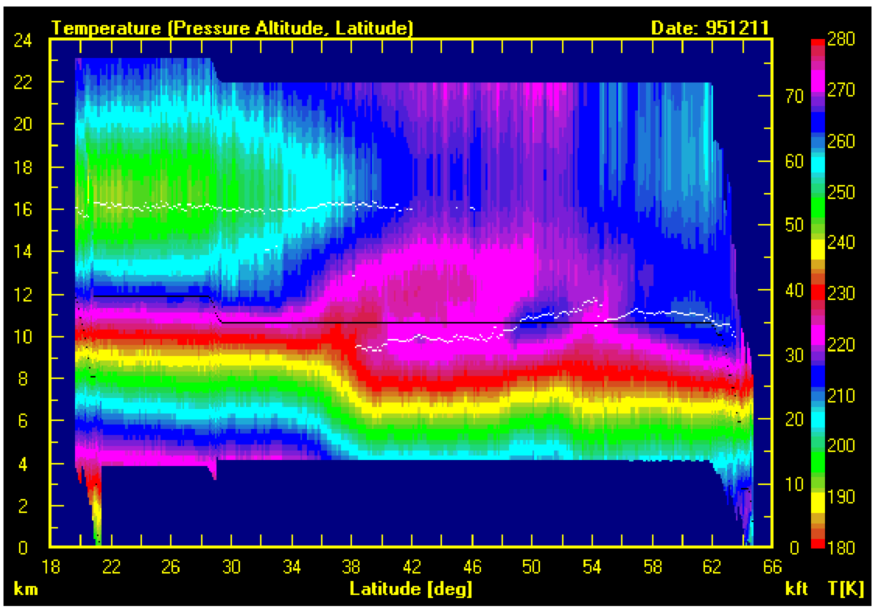

Figure 3.1. Sample altitude temperature profile vertical cross section from the Microwave Temperature Profiler (MTP). The solid black line on the display represents the aircraft altitude, and the white dotted line represents the tropopause altitude.

<u>Type **D-R** (regional)</u>

The goal of deployment (**D-R**) is to establish upstream early morning conditions for anticipated later convection. Observations will be taken between 09 and 17 UTC to enhance the standard NWS operational 12 UTC analysis. This strategy supports Hypothesis 1.

The full domain of interest for this deployment is depicted on Fig. 3.2, and primarily includes eastern Utah, eastern Arizona, Wyoming, Colorado, New Mexico, Texas, along with Nebraska, Kansas and Oklahoma. A sub-domain of roughly 600 by 1000 km will be chosen for each typical one day Intensive Observing Period (IOP) depending on the meteorological scenario (mean flow direction and speed, moisture source, etc.) as well as specific features of interest (e.g., regions of enhanced upper tropospheric PV, persistent cloud bands evident from satellites, etc.). Given a mean motion for a sub-synoptic feature of 10-15 m s^{-1}, observations would be needed 400 to 600 km upstream of the anticipated region of convective initiation for a 12-h forecast. Thus, features as far west as eastern Utah and Arizona could be candidates for the enhanced observations.

The Type **D-R** strategy (Fig. 3.2) involves dropping 28-32 sondes on a variable grid covering the specified sub-domain, with the drop spacing ranging between 75 and 250 km, with the highest density of dropsonde observations being centered on a targeted subsynoptic feature of interest. A 75-km grid spacing for dropsondes will nominally be able to resolve features with a scale of 300 km or greater, which is much finer than is allowed by the existing observational NWS sounding network over the region of interest (e.g., Fig. 1). The addition of MTP data will help to further refine the thermodynamic structure of any features of importance along the aircraft path (e.g., Fig. 3.1). Such a density of full tropospheric observations has never been available for such purposes upstream of the high and central Plains of the US. This observing strategy will be able to document the suspected role of poorly observed and/or initialized sub-synoptic features over the intermountain region on subsequent severe convective outbreaks.

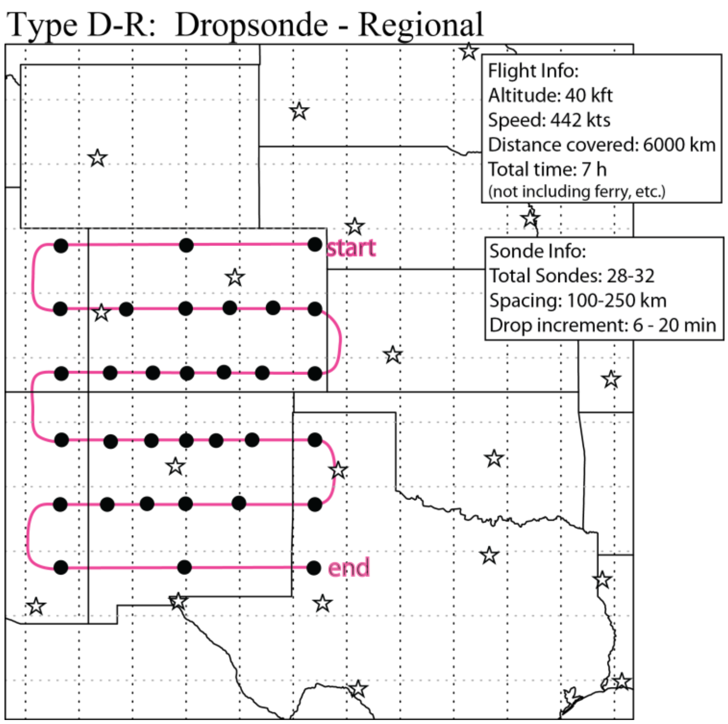

Figure 3.2. Example flight pattern and GPS dropsonde locations for the Type D-R deployment strategy. Although the depicted pattern is a grid, actual sonde locations can be shifted to account for local factors (population centers, airports, etc.). Stars indicate locations of National Weather Service soundings. MTP observations would be requested continuously along the aircraft path.

Although a uniform and or nested grid of dropsondes at this scale is preferable, the investigators understand that adjustments may be necessary in identified no-drop zones based on population, military, or domestic en route or approach air traffic flow constraints without significantly compromising the value of the dataset. We will work with EOL RAF flight personnel to identify the key no-drop zones ahead of time to ease with project planning and feasibility assessments. Also, drop sites will be chosen so as to not overlap with existing NWS sites to maximize the value-added of the deployment strategy. We have read the RAF policy on dropping objects from aircraft and will work with the RAF to make sure the policy and procedures are followed for MPEX.

A flight altitude of 12 km (40000 ft) is requested for all drops to allow for the sampling of deep-layer shear, stability, and moisture, as well as to characterize upper/mid tropospheric features that may be important for subsequent convective initiation. Given a 600 x 1000 km grid and an aircraft speed of 440 kt, the proposed distance covered would be about 5000 km, and would take approximately 6.5 h to complete (plus approximately 2 hours for takeoff, ferry, and landing). The requested drop increment would generally range from 6 min for specific targeted features to 20 min for the coarser drop regions, as noted above. MTP observations would be taken continuously along the aircraft track to help characterize the atmospheric structure between dropsonde locations, and to help make in-flight modifications of droposonde density.

Go-no go decisions for day 2 Type **D-R** deployments will be based on 24-36 h forecasts from the 12 UTC operational and experimental forecast models, and will be decided by 18 UTC on day 1. An initial grid of requested specific east-west legs and drop locations will be available by 21 UTC, but it would be beneficial to be able to further adjust the drop density on the pre-specified east-west legs in the morning, to account for updated observations for any specific features of interest. A nowcaster and PI will continuously monitor the weather during the morning flight, to adjust dropsonde locations within any predetermined constraints and also to avoid any potentially hazardous flight conditions. Since convective activity tends to be minimal over the intermountain region at that time of the day, weather-related hazards are generally not expected to be a significant concern during these early morning flight patterns. IOP days will be selected based on a moderate/high expectation of significant convective weather to the lee of the mountains and on the High Plains later in the afternoon and evening.

Type **C-A** (pre-storm-environment)

The goal of the Type **C-A** deployment is to sample the mesoscale environment in the mid-to-late afternoon on the plains to the lee of the mountains over a region targeted for anticipated convective initiation. This strategy supports Hypotheses 1-2.

The Type **C-A** strategy (Fig. 3.3) would request the dropsonde aircraft to fly at 12 km (40000 ft) AGL, to observe the nearly full tropospheric structure prior to convective initiation. However, a flight level of 29000 ft or slightly lower could be considered to avoid conflicts with en route air traffic. The MPEX investigators will work with the RAF pilots to consider viable options for dropsonde releases supporting this objective.

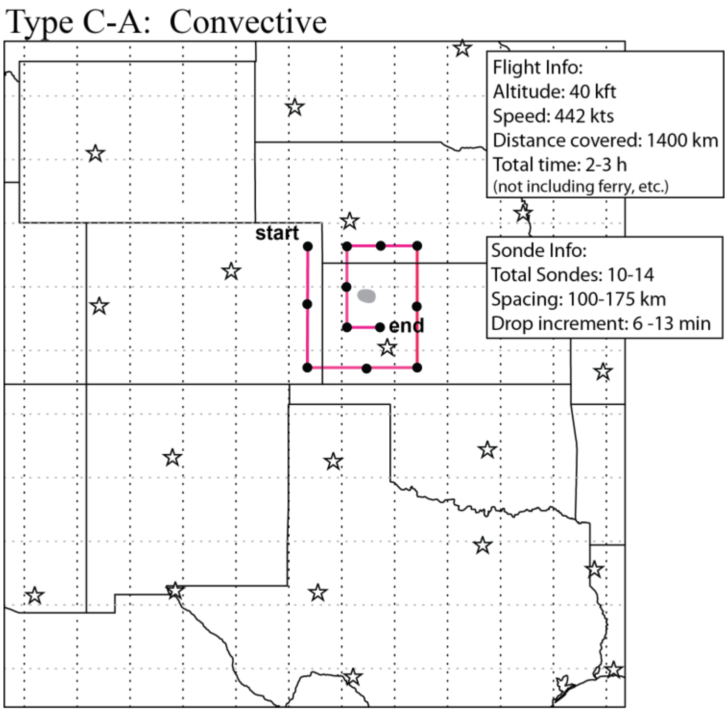

Figure 3.3. Example flight path and GPS dropsonde locations for the Type C-A strategy, which focuses on documenting the pre-storm environment for a targeted region during the mid- to late-afternoon observational period. The small shaded region indicates the anticipated location for initial convective development. Actual sonde drop locations can be adjusted to take into account local factors (e.g. population centers, airports, etc.).

The flight pattern would consist of a roughly square spiral focusing in towards the expected location of convective initiation. Approximately 12 sondes would be dropped using a nominal spacing of 100 - 175 km and drop increment of 8 - 13 min. The total distance covered by the spiral would be approximately 1400 km. Assuming an airspeed of 440 kt, it is anticipated that this pattern would take about 2 h to complete, not including ferry time, etc.

Targeted regions for this afternoon flight could be located anywhere within the regional domain included in Fig. 2.1, in the lee of the mountains, but will generally be located downwind of the morning observational domain. An initial target, with proposed dropsonde locations, will be identified by 9:00 am, but it would be beneficial to be able to update this plan just prior to aircraft takeoff, to account for evolving weather conditions. Anticipated takeoff time for this flight would generally be between 1:00 and

2:00 pm, but could be delayed to as late as 3:00 pm. Nowcasting support will be critical for monitoring and avoiding developing convection.

Type **C-B** (storm-environment modification)

The goal of the Type **C-B** deployment is to sample the mesoscale environment in the mid-to-late afternoon or evening surrounding storms once they develop. This strategy supports Hypothesis 2 and related questions regarding storm-environment feedbacks.

The Type **C-B** strategy (Fig. 3.4) represents a continuation of Type C-A plan, once convection has begun to develop and is considered appropriate for further sampling (e.g., relatively isolated, etc.). A flight level of 40000 ft AGL would again be considered optimal for observing the nearly full tropospheric modifications produced by the convection. However, a flight level of 29000 ft could again be considered if air traffic issues were a concern. The basic flight pattern would consist of an outward square spiral surrounding the developing and maturing convective cells. Approximately 18 sondes would be dropped using a nominal spacing of 75-125 km and drop increment of 6 - 12 min. Nowcasting support will be critical for monitoring and avoiding active convective regions. In flight strategy adjustments would likely be needed to avoid electrically active regions and newly developing convective cells. The total distance covered by the spiral would be approximately 1400 km. Assuming an airspeed of 440 kt, it is anticipated that this pattern would take about 2 h to complete, not including ferry time, etc. If convection does not develop as anticipated in the targeted region, or becomes too widespread for observational purposes, then the C-B plan will be aborted, and the G-V will return to base. Flight operations will all be completed before sunset.

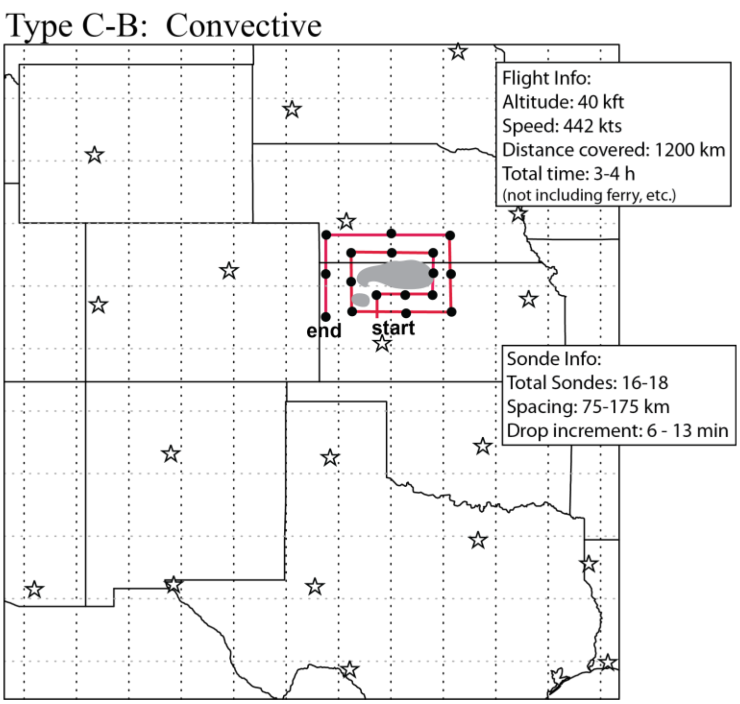

Figure 3.4. Example flight path and GPS dropsonde locations for the Type C-B strategy, which focuses on storm-environment feedbacks for the targeted region identified in Fig. 2, once convection begins to develop. The shaded regions depict a hypothetical maturing convective storm, with a new storm developing to its southwest. Actual sonde drop locations can be adjusted to take into account local factors (e.g. population centers, airports, etc.).

Total number of dropsondes and flight hours required

We are requesting 10 IOPs for the **D-R** deployment. Assuming 30 dropsondes per deployment, this would require 300 dropsondes. At 8 hours per mission, a total of 80 flight hours is requested for the 10 IOPs

We are requesting 10 IOPs for the **C-A, C-B** deployments. Assuming 25 dropsondes per deployment (given that several of the C-B missions may be aborted due to either a lack or excess of convective development), this would require approximately 250 dropsondes. At 6 hours per mission, a total of 60 flight hours is requested for the 10 IOP

Total Dropsonde Request: (Type **D-R**, **C-A and C-B** deployments)

Flight Hours: 140
Dropsondes: 550

Finally, as with all field campaigns, there is some uncertainty in our deployment strategies, and therefore we will conduct a pre-field phase exercise. This real-time dry run exercise will be used to help build experience in dropsonde domain identification and otherwise refine the strategies.

4. MPEX Modeling and Analysis Activities

The MPEX modeling and analysis activities are detailed in Section 2. Summarizing here, the dropsonde and MTP data will be used in a host of realtime and post-field phase analysis and prediction studies, involving investigators from the National Center for Atmospheric Research, Purdue University, University of Oklahoma, and the National Severe Storms Laboratory. Explicit 0-48 hr Weather Research and Forecasting (WRF) model forecasts of convective storms (deterministic and ensemble forecasts), initialized from operational analyses at 00 and 12 UTC and employing horizontal grid spacings of 3 km or less, will be provided for guidance in project planning.

5. MPEX Program Management

We will request FPS support for data cataloguing and program management.

6. Relevance and Significance of MPEX to NSF and the Broader Community

The mesoscale density of wind and thermodynamic observations being proposed herein has never been available for such research or application purpose. For instance, recent field studies, such as BAMEX (Davis et al., 2004) and IHOP (Weckwerth et al. 2004) used dropsondes and upsondes to sample the environment and structure of convective systems such as bow echoes and mesoscale convective vortices (MCVs), or specific features such as the dry line, respectively, but did not obtain the regional coverage, especially upstream of anticipated convection, as proposed here. A similar density of observations was indeed proposed in association with the Storm-Central phase of the National Storm (Stormscale Operational and Research Meteorology) Program in 1984 (Zipser et al., 1984), but was never deployed. Such a dataset would contribute immensely to ongoing convective storm predictability research.

MPEX datasets will foster the development of a research testbed for regional-scale deep, moist convection prediction experiments. Unprecedented observations will be available for model initialization and forecast verification, enabling one to determine the optimal mix of observations, adaptive observing strategies, data-assimilation methods, and forecast models needed for successful regional-scale numerical prediction of convective weather in future operational systems. The MPEX data will also allow for an exploration of storm-environment feedbacks in unprecedented detail, representing an important and novel contribution to our understanding of such feedbacks and associated short-term predictability. Indeed, because vertical sounding profiles surrounding a region of deep convection have not been available previously, it is very likely that we will learn a great deal even with less than optimal sampling.

7. Educational and Outreach Activities

Graduate students will be involved in the pre-field phase exercise, including data collection, analysis, and subsequent model experimentation. In addition, components of this research will be incorporated by the university PIs into courses at the undergraduate level to the graduate level. K-12 and public outreach activities centered about the G-V will be coordinated through UCAR Communications.

References:

Aberson, Sim D., 2003: Targeted Observations to Improve Operational Tropical Cyclone Track Forecast Guidance. Mon. Wea. Rev., 131, 1613–1628.

Aberson, Sim D., 2008: Large Forecast Degradations due to Synoptic Surveillance during the 2004 and 2005 Hurricane Seasons. Mon. Wea. Rev., 136, 3138–3150.

Anabor, V., D. J. Stensrud, 2009 and O. L. L. de Moraes: Simulation of a serial upstream-propagating mesoscale convective system event over southeastern South America. *Mon. Wea. Rev.,* **137,** 2144-2163..

Ancell, B., and G. J. Hakim, 2007: Comparing adjoint- and ensemble-sensitivity analysis with applications to observation targeting. Mon. Wea. Rev., 135, 4117–4134.

Anderson, J. L., T. Hoar, K. Raeder, H. Liu, N. Collins, R. Torn, and A. Avellano, 2009: The Data Assimilation Research Testbed: A community facility. *Bull. Amer. Meteor. Soc.,* **90,** 1283-1296.

Atallah, E., L. F. Bosart, and A. R. Aiyyer, 2007: Precipitation Distribution Associated with Landfalling Tropical Cyclones over the Eastern United States. Mon. Wea. Rev., 135, 2185-2206.

Baldwin, M. E., J. S. Kain, and S. Lakshmivarahan, 2005: Development of an automated classification procedure for rainfall systems. *Mon. Wea. Rev.*, **133**, 844-862.

Benjamin, S.G., B.E. Schwartz, E.J. Szoke, and S.E. Koch, 2004: The value of wind profiler data in U.S. weather forecasting. Bull. Amer. Meteor. Soc., 85, 1871-1886.

Benjamin, S.G., B.D. Jamison, W.R. Moninger, S.R. Sahm, B.E. Schwartz, and T.W. Schlatter, 2010: Relative short-range forecast impact from aircraft, profiler, radiosonde, VAD, GPS-PW, METAR, and mesonet observations via the RUC hourly assimilation cycle. Mon. Wea. Rev., 138, 1319-1343.

Bergot, T., 1999: Adaptive observations during FASTEX: A systematic survey of upstream flights. Q. J. R. Meteorol. Soc., 125, 3271–3298.

Berliner, L. Mark, Zhan-Qian Lu, Chris Snyder, 1999: Statistical Design for Adaptive Weather Observations. J. Atmos. Sci., 56, 2536–2552.

Bishop, C. H., Z. Toth, 1999: Ensemble transformation and adaptive observations. J. Atmos. Sci., 56, 1748-1765.

Bosart, L.F. and G. M. Lackmann, 1995: Postlandfall Tropical Cyclone Reintensification in a Weakly Baroclinic Environment: A Case Study of Hurricane David (September 1979). Mon. Wea. Rev., 123, 3268-3291.

Bretherton, C. S., 1993: The nature of adjustment in cumulus cloud fields. *The Representation of Cumulus Convection in Numerical Models of the Atmosphere*, K. A. Emanuel and D. J. Raymond, Eds., Meteor. Monogr., vol 24, No. 46, Amer. Meteor. Soc., 63-74.

Brooks, H. E., C. A. Doswell III, J. Cooper, 1994: On the Environments of Tornadic and Nontornadic Mesocyclones. *Wea. Forecasting*, **9**, 606–618.

Buizza, R., C. Cardinali, G. Kelly, and J. Thepaut, 2007: The value of targeted observations - Part II: the value of observations taken in singular vectors-based target areas. Q. J. R. Meteorol. Soc., 133, 1817–1832

Clark, A. J. and Coauthors, 2012: An overview of the 2010 hazardous weather testbed experimental forecast spring experiment. Bul. Amer. Meteor. Soc., in press.

Crook, N. A., and J. Sun, 2002: Assimilating radar, surface, and profiler data for the Sydney 2000 Forecast Demonstration Project. J. Atmos. Oceanic Technol., 19, 888--898.

Dabbert, W. F., and Coauthors, 2000: Forecast issues in the urban zone: Report of the 10th Prospectus Development Team of the U.S. Weather Research Program. Bull. Amer. Meteor. Soc., 81, 2047--2064.

Davis, C., et al., 2004: The bow echo and MCV experiment (BAMEX): Observations and opportunities. Bul. Amer. Meteor. Soc., 85, 1075-1093.

Davis, C. A., and S. B. Trier, 2007: Mesoscale Convective Vortices Observed During BAMEX, Part I: Kinematic and Thermodynamic Structure. Mon.Wea. Rev., 135, 2029–2049.

Davis, C. A., and D. A. Ahijevych, 2012: Mesoscale Structural Evolution of Three Tropical Weather Systems Observed during PREDICT. J. Atmos. Sci., In press.

Dawson, D. T, L. J. Wicker, E. R. Mansell, and R. L. Tanamachi, 2012: Impact of the environmental low-level wind profile on ensemble forecasts of the 4 May 2007 Greensburg, KS tornadic storm and associated mesocyclones. *Mon. Wea. Rev*., 140, 696-712.

Denning, R. F., S. L. Guidero, G. S. Parks, and B. L. Gary, 1989: Instrument description of the airborne microwave temperature profiler. *J. Geophys. Res.*, **94,** 16757–16765.

Dickinson, M.J., L. F. Bosart, W. E. Bracken, G. J. Hakim, D. M. Schultz, M. A. Bedrick, and K. R. Tyle, 1997: The March 1993 Superstorm Cyclogenesis: Incipient Phase Synoptic- and Convective-Scale Flow Interaction and Model Performance. Mon. Wea. Rev., 125, 3041-3072.

Done, J., C. A. Davis, and M. Weisman, 2004: The next generation of NWP: Explicit forecasts of convection using the Weather Research and Forecasting (WRF) model. Atmos. Sci. Let., 5, 110--117.

Doswell, C. A. III, and F. Caracena, 1988: Derivative estimation from marginally-sampled vector point functions. *J. Atmos. Sci*., **45**, 242-253.

Droegemeier, K.K., 1990: Toward a science of storm scale prediction. Preprints, 16th Conf. on Severe Local Storms. Amer. Meteor. Soc., Kananaskis Park, Alberta, Canada, 256-262.

Droegemeier, K.K., 1997: The numerical prediction of thunderstorms: Challenges, potential benefits and results from real-time operational tests. WMO Bull, 46, 324-336.

Droegemeier, K. K., and Coauthors, 1996: Realtime numerical prediction of storm-scale weather during VORTEX ,Äô95: Goals and methodology. Preprints, 18th Conf.~on Severe Local Storms, San Francisco, CA, Amer. Meteor. Soc., 6--10.

Droegemeier, K. K., and Coauthors, 2000: Hydrological aspects of weather prediction and flood warnings: Report of the Ninth Prospectus Development Team of the U.S. Weather Research Program. Bull. Amer. Meteor. Soc., 81, 2665--2680.

Ebert E. E., 2008: Fuzzy verification of high-resolution gridded forecasts: A rreview and proposed framework. *Meteor. Appl*., 15, 51-64.

Elsberry, R. L. and P. A. Harr, 2008: Tropical cyclone structure (TCS-08) field experiment science basis, observational platforms, and strategy. Asia-Pacific J. Atmos. Sci., 44, 209–231.

Fabry, F., 2010: For How Long Should What Data Be Assimilated for the Mesoscale Forecasting of Convection and Why? Part II: On the Observation Signal from Different Sensors. *Mon. Wea. Rev.*, **138**, 256–264.

Fritsch, J.M., and R.A. Maddox, 1981: Convectively-driven mesoscale pressure systems aloft. Part I: Observations. *J. Appl. Meteor.*, **20**, 9-19.

Fritsch, J. M., and Coauthors, 1998: Quantitative precipitation forecasting: Report of the Eighth Prospectus Development Team, U.S. Weather Research Program. Bull. Amer. Meteor. Soc., 79, 285--299.

Galarneau, T., Jr and L. F. Bosart, 2007: The long-lived MCV of 10-13 June 2003: A possible example of an incipient tropical disturbance over land? 12th Conference on Mesoscale Processes, American Meteorological Society, 6-9 August 2007, Waterville Valley, NH.

Gallus, W. A., Jr., and R. H. Johnson, 1991: Heat and moisture budgets of an intense midlatitude squall line. *J. Atmos. Sci.*, **48**, 122-146.

Gallus, W.A. Jr., J. Correia Jr., I. Jankov, 2005: The 4 June 1999 derecho event: A particularly difficult challenge for numerical weather prediction. Wea. Forecasting, 20, 705-728.

Gamache, J.F., and R.A. Houze, Jr., 1982: Mesoscale air motions associated with a tropical squall line. *Mon. Wea. Rev.*, **110**, 118-135.

Houze, R.A., Jr., 1977: Structure and dynamics of a tropical squall line system. *Mon. Wea. Rev.*, **105**, 1540-1567.

_____, and A.K. Betts, 1981: Convection in GATE. *Rev. Geophys. Space Phys.*, **19**, 541-576.

Kain, J. S., S. J. Weiss, M. E. Baldwin, G. W. Carbin, D. A. Bright, J. J. Levit, and J. A. Hart, 2005: Evaluating high-resolution configurations of the WRF model that are used to forecast severe convective weather: The 2005 SPC/NSSL Spring Program. Preprints, 21st Conference on Weather Analysis and Forecasting/17th Conference on Numerical Weather Prediction, Washington, D. C., Amer. Meteor. Soc., CD-ROM, 2A.5.

Kain, J.S., S.J. Weiss, J.J. Levit, M.E. Baldwin, and D.R. Bright, 2006: Examination of convective allowing configurations of the WRF model for the prediction of severe convective weather: The SPC/NSSL spring program 2004. Wea. Forecasting, 21, 167-181.

Kain, J.S., S.J. Weiss, D.R. Bright, M.E. Baldwin, J.J. Levit, G.W. Carbin, C.S. Schwartz, M. Weisman, K.K. Droegemeier, D. Weber, and K.W. Thomas, 2008: Some practical considerations for the first generation of operational convection allowing NWP: How much resolution is enough? Wea. and Forecasting, 23, 931–952.

Kain, J. S., and Coauthors, 2010: Assessing Advances in the Assimilation of Radar Data and Other Mesoscale Observations within a Collaborative Forecasting–Research Environment. *Wea. Forecasting*, **25**, 1510–1521.

Keyser, D.A., and D.R. Johnson, 1984: Effects of diabatic heating on the ageostrophic circulation of an upper tropospheric jet streak. *Mon. Wea. Rev.*, **112**, 1709-1724.

Leary, C.A., 1979: Behavior of the wind field in the vicinity of a cloud cluster in the intertropical convergence zone. *J. Atmos. Sci.*, **36**, 631-639.

Lilly, D. K., 1990: Numerical prediction of thunderstorms---has its time come? Quart. J. Roy. Meteor. Soc., 116, 779--798.

Lin, Y.-L., 1987: Two-dimensional response of a stably stratified shear flow to diabatic heating. *J. Atmos. Sci.*, **44**, 1375–1393.

Maddox, R.A., 1980: Mesoscale convective complexes. *Bull. Amer. Meteor. Soc.*, **61**, 1374-1387.

Mapes, B.E., 1993: Gregarious tropical convection. *J. Atmos. Sci.*, **50**, 2026-2037.

Menard, R.D., and J.M. Fritsch, 1989: A mesoscale convective complex-generated inertially stable warm core vortex. *Mon. Wea. Rev.*, **117**, 1237-1261.

Metz, N. D., and L. F. Bosart, 2010: Derecho and MCS development, evolution, and multiscale interactions during 3–5 July 2003. *Mon. Wea. Rev.*, **138**, 3048–3070.

Montgomery, M. T. et al., 2012: The pre-depression investigation of cloud systems in the tropics (PREDICT) experiment: Scientific basis, new analysis tools and some first results. Bull. Amer. Meteor. Soc., (in press).

Ninomiya, K., 1971a: Dynamical analysis of outflow from tornado-producing thunderstorms as revealed by ATS III pictures. *J. Appl. Meteor.*, **10**, 275-294.

_____, 1971b: Mesoscale modification of synoptic situations from thunderstorm development as revealed by ATS III and aerological data. *J. Appl. Meteor.*, **10**, 1103-1121.

Perkey, D.J., and R.A. Maddox, 1985: A numerical investigation of a mesoscale convective system. *Mon. Wea. Rev.*, **113**, 553-566.

Reasor, P.D., M. T. Montgomery, and L. F. Bosart, 2005: Mesoscale Observations of the Genesis of Hurricane Dolly (1996). J. Atmo. Sci., 62, 3151-3171.

Riehl, H., 1959: On the production of kinetic energy from condensation heating. *The Atmosphere and the Sea in Motion*, Rossby Memorial Vol., B. Bolin, Ed., Rockefeller Institute Press, 509 pp.

Roebber, P. J., D. M. Schultz, and R. Romero, 2002: Synoptic regulation of the 3 May 1999 tornado outbreak. Wea. Forecasting, 17, 399-429.

Roebber, P. J., K. L. Swanson and J. K. Ghorai, 2008: Synoptic control of mesoscale precipitating systems in the Pacific Northwest. Mon. Wea. Rev., 136, 3465-3476.

Schenkman, A. D., M. Xue, A. Shapiro, K. Brewster, J. Gao, 2011: Impact of CASA Radar and Oklahoma Mesonet Data Assimilation on the Analysis and Prediction of Tornadic Mesovortices in an MCS. *Mon. Wea. Rev.*, **139**, 3422–3445.

Shapiro, M. A., and Collaborators, 1999: A Planetary-scale to Mesoscale Perspective of the Life Cycles of Extratropical Cyclones: The Bridge Between Theory and Observations. In The Life Cycles of Extratropical Cyclones, edited by M. A. Shapiro and S. Gronas, American Meteorological Society , 139-186.

Schumacher, R. S., 2008: Ensemble-based analysis of factors leading to the development of a multiday warm-season heavy rain event. Mon. Wea. Rev., 139, 3016-3035.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, M. G. Duda, X-Y. Huang, W. Wang, and J. G. Powers, 2008: A description of the Advanced Research WRF version 3. NCAR Tech Note NCAR/TN-475+STR, 113 pp. [Available from UCAR Communications, P. O. Box 3000, Boulder, CO 80307.]

Smull, B.F., and J.A. Augustine, 1993: Multiscale analysis of a mature mesoscale convective complex. *Mon. Wea. Rev.*, **121**, 103-132.

Spencer, P.L., P.R. Janish and C.A. Doswell III (1999): A 4-dimensional objective analysis scheme and multi-triangle technique for wind profiler data. *Mon. Wea. Rev.*, **127**, 279-291.

_____, and C. A. Doswell III, 2001: A quantitative comparison between traditional and line integral methods of derivative estimation. *Mon. Wea. Rev.*, **129**, 2538-2554.

Stensrud, D. J. and J. L. Anderson, 2001: Is midlatitude convection an active or a passive player in producing global circulation patterns. J. Climate, 14, 2222-2237.

Stensrud, D.J., 1996: Effects of a persistent, midlatitude mesoscale region of convection on the large-scale environment during the warm season. *J. Atmos. Sci.*, **53**, 3503-3527.

_____, and R.A. Maddox, 1988: Opposing mesoscale circulations: A case study. *Wea. Forecasting*, **3**, 189-204.

_______, and Coauthors, 2009: Convective-Scale Warn-on-Forecast System. *Bull. Amer. Meteor. Soc.*, **90**, 1487–1499.

_____, and J. Gao, 2010: Importance of Horizontally Inhomogeneous Environmental Initial Conditions to Ensemble Storm-Scale Radar Data Assimilation and Very Short-Range Forecasts. *Mon. Wea. Rev.*, **138**, 1250–1272.

Storm, Brandon A., M. D. Parker, and D. P. Jorgensen, 2007: A Convective Line with Leading Stratiform Precipitation from BAMEX. Mon. Wea. Rev., 135, 1769–1785.

Stratman, D. R., M. C. Coniglio, S. E. Koch, and M. Xue, 2012: Use of multiple verification methods to evaluate forecasts of convection from hot- and cold-start convection-allowing models. Manuscript submitted to *Wea. Forecasting*.

Sun, J., and N. A. Crook, 2001: Real-time low-level wind and temperature analysis using single WSR-88D data. Wea. Forecasting, 16, 117--132.

Sun, J., and Y. Zhang, 2008: Analysis and Prediction of a Squall Line Observed during IHOP Using Multiple WSR-88D Observations. *Mon. Wea. Rev.*, **136**, 2364–2388.

Szunyogh, I., Z. Toth, K. A. Emanuel, C. H. Bishop, C. Snyder, R. E. Morss, J. Woolen and T. Marchok, 1999: Ensemble-based targeting experiments during FASTEX: The effect of dropsonde data from the Lear jet. Q. J. R. Meteorol. Soc., 125, pp. 3189-3217.

Szunyogh, I., Z. Toth, R. E. Morss, S. J. Majumdar, B. J. Etherton, C. H. Bishop, 2000: The Effect of Targeted Dropsonde Observations during the 1999 Winter Storm Reconnaissance Program. Mon. Wea. Rev., 128, 3520–3537.

Torn, R. D., and G. J. Hakim, 2008: Ensemble-Based Sensitivity Analysis. Mon. Wea. Rev., 136, 663-677.

Trier, S. B., and C. A. Davis, 2007: Mesoscale Convective Vortices Observed During BAMEX, Part II: Influences on Secondary Deep Convection. Mon.Wea. Rev., 135, 2051-2075.

Trier, S. B., and R. D. Sharman, 2009: Convection-permitting simulations of the environment supporting widespread turbulence within the upper-level outflow of a mesoscale convective system. *Mon. Wea. Rev.*, **137**, 1972–1990.

U.S. Dept. of Commerce, 1999: Vision 2005: National Weather Service strategic plan for weather, water, and climate services 2000--2005. Available at http://www.noaa.gov.

Wandishin, Matthew S., David J. Stensrud, Steven L. Mullen, Louis J. Wicker, 2008: On the Predictability of Mesoscale Convective Systems: Two-Dimensional Simulations. Wea. Forecasting, 23, 773–785.

Wandishin, Matthew S., David J. Stensrud, Steven L. Mullen, Louis J. Wicker, 2010: On the Predictability of Mesoscale Convective Systems: Three-Dimensional Simulations. Mon. Wea. Rev., 138, 863–885.

Weckwerth, T. M., D. B. Parsons, S. E. Koch, J. A. Moore, M. A. Lemone, B. B. Demoz, C. Flamant, B. Geerts, J. Wang, and W. F. Feltz, 2004: An overview of the international H2O project (IHOP_2002) and some preliminary highlights. Bull. Amer. Meteor. Soc., 85, 253-277.

Weisman, M. L., C. A. Davis, W. Wang, K. W. Manning, and J. B. Klemp, 2008: Experiences with 0-36 h explicit convective forecasts with the WRF-ARW model. Wea. and Forecasting, 23, 407–437.

Weiss, S.J., J.S. Kain, J.J. Levit,M.E. Baldwin, and D.R. Bright, 2004: Examination of several different versions of the Weather Research and Forecasting (WRF) model for the prediction of severe convective weather: The SPC/NSSL Spring Program 2004. 22nd Conf. On Severe Local Storms.

Weiss, S.J., J.S. Kain, D.R. Bright, J.J. Levit, G.W. Carbin, M.E. Pyle, Z.I. Janjic, B.S. Ferrier, J.Du, M.L. Weisman and M. Xue, 2007: The NOAA Hazardous Weather Testbed: Collaborative testing of ensemble and convection-allowing WRF models and subsequent transfer to operations at the Storm Prediction Center. Preprints, 22nd Conf. on Weather analysis and Forecasting/18th Conf. on Numerical Weather Prediction, Park City, Utah, Amer. Meteor. Soc., CD-ROM 6B.4.

Wetzel, P.J., W.R. Cotton, and R.L. McAnelly, 1983: A long-lived mesoscale convective complex. Part II: Evolution and structure of the mature complex. *Mon. Wea. Rev.*, **111**, 1919-1937.

Weygandt, S.S., A.F. Loughe, S.G. Benjamin, and J.L. Mahoney, 2004: **S**cale sensitivities in model precipitation skill scores during IHOP**.** Preprints, 22th Conf. Severe Local Storms, Hyannis, MA.

Wheatley, D. M., and D. J. Stensrud, 2010: The impact of assimilating surface pressure observations on severe weather events in a WRF mesoscale ensemble system. *Mon. Wea. Rev.,* **138,** 1673-1694.

Wolf, B.J., and D.R. Johnson, 1995a: The mesoscale forcing of a midlatitude upper-tropospheric jet streak by a simulated convective system. Part I: Mass circulation and ageostrophic processes. *Mon. Wea. Rev.*, **123**, 1059-1087.

_____, and _____, 1995b: The mesoscale forcing of a midlatitude upper-tropospheric jet streak by a simulated convective system. Part II: Kinetic energy and resolution analysis. *Mon. Wea. Rev.*, **123**, 1088-1111.

Xue, M. and W. J. Martin, 2006: A high resolution modeling study of the 24 May 2002 dryline case during IHOP. Part 1: Numerical simulation and general evolution of the dryline and convection. Mon. Wea. Rev., 134, 149-171.

Xue, M. and W. J. Martin, 2006: A high resolution modeling study of the 24 May 2002 dryline case during IHOP. Part II: Horizontal convective rolls and convective initiation. Mon. Wea. Rev., 134, 172-191.

Yanai, M., 1964: Formation of tropical cyclones. *Rev. Geophys.*, **2**, 367-414.

Yussouf, N., and D. J. Stensrud, 2010: Impact of high temporal frequency phased array radar data to storm-scale ensemble data assimilation using observation system simulation experiments. *Mon. Wea. Rev.*, **138,** 517-538.

Zhang, F., N. Bei, R. Rotunno, C. Snyder, C. C. Epifanio, 2007: Mesoscale Predictability of Moist Baroclinic Waves: Convection-Permitting Experiments and Multistage Error Growth Dynamics. *J. Atmos. Sci.*, **64**, 3579–3594.

Zipser, E.J., et al., 1984: The National Storm Program: Storm-Central Phase, Preliminary Program Design. National Center for Atmospheric Research, Boulder, CO., 147 pp.

Appendix Collaborations:

1) Robert J. Trapp (Purdue), Davis Stensrud, Mike Coniglio, Mike Baldwin (NSSL), Charles Doswell (CIMMS): "Improved understanding of convective-storm predictability and environment feedbacks from observations during the Mesoscale Predictability Experiment (MPEX)." Submitted to NSF, Proposal No. 1230085.

2) Clark Evans and Paul Roebber (Univ. of Wisconsin Milwaukee): "Assessment of the impact of Mesoscale Predictability Experiment (MPEX) observations upon numerical model analyses and forecasts of convective intitiation." Submitted to NSF, Proposal No. 1230322.

3) Ryan Torn (The University at Albany/SUNY): "Sources and growth of initial condition errors in convection-resolving forecasts in MPEX." To be submitted to NSF.

4) Russ Schumacher (Colorado State University): "Examining the influence of enhanced dropsonde observations on analyses and forecasts of long-lived convective systems". To be submitted to NSF.

5) Lance Bosart (The University at Albany/SUNY): "Two-Way Interactions between Mesoscale Convective Systems and their Synoptic-Scale Environments." To be submitted to NSF.

6) Chris Snyder, Craig Schwartz, Tom Galarneau, Jenny Sun (Mesoscale and Microscale Meteorology Division, NCAR):

7) John Brown and David Dowell (Global Systems Division, Earth Systems Research Lab, NOAA): (see letter of support below):

From John Brown:

"The developers (part of the Assimilation and Modeling Branch of the Global Systems Division, Earth System Research Lab of NOAA) of the Rapid Refresh (RAP) hourly assimilation system, soon to be operational within the National Weather Service, and the High-Resolution Rapid Refresh (HRRR) convection permitting forecast model, are very much interested in MPEX, particularly the focus on the potential contribution of additional upper air observations toward improving regional scale NWP of convective storms discussed in Section 2. We see MPEX as an excellent opportunity to obtain a dataset that addresses at least the part of the predictability question that concerns subtle mid-and upper tropospheric potential-vorticity structures that are difficult to observe with the operational data stream."

"We run both the RAP (13km horizontal grid spacing, North American domain) and HRRR (3km over CONUS, initialized from the RAP assimilation cycle, including a diabatic initialization) in real time, including both a more stable configuration and developmental cycles. Assuming the dropwindsonde data is available in near real time, we intend to devote one of our parallel RAP / HRRR cycles to running with this additional data and conducting both subjective and objective evaluation of the HRRR convection-permitting model's forecasts of convection: onset, mode and upscale growth into mesoscale convective systems. This evaluation will no doubt suggest other experiments involving treatment of the drop data and perhaps other model and assimilation configurations that we will carry out retrospectively. We look forward to working together with other MPEX PIs on this activity."