The Mesoscale Predictability Experiment (MPEX)

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**Capsule:**

The field campaign, involving the NSF/NCAR GV aircraft, mobile upsondes, and a high resolution ensemble modeling system, incorporates enhanced mesoscale observations of the upstream and nearby convective environment to improve the predictability of convective events.
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1. Abstract

The Mesoscale Predictability Experiment (MPEX) was conducted from 15 May to 15 June 2013 within the central United States. MPEX was motivated by the basic question of whether experimental, sub-synoptic observations can extend convective-scale predictability and otherwise enhance skill in short-term regional numerical weather prediction.

Observational tools for MPEX included the NSF/NCAR Gulfstream V aircraft (GV), which featured the Airborne Vertical Atmospheric Profiling System mini-dropsonde system and a microwave temperature profiling (MTP) system, as well as several ground-based mobile upsonde systems. Basic operations involved two missions a day: an early morning mission with the GV, well upstream of anticipated convective storms, and an afternoon and early evening mission with the mobile sounding units, to sample the initiation and upscale feedbacks of the convection.

A total of 18 IOPs were completed during the field phase, representing a wide spectrum of synoptic regimes and convective events, including several major severe weather and/or tornado outbreak days. The novel observational strategy employed during MPEX is documented herein, as is the unique role of the ensemble modeling efforts—which
included an ensemble sensitivity analysis—to both guide the observational strategies and help address the potential impacts of such enhanced observations on short-term convective forecasting. Preliminary results of retrospective data assimilation experiments are discussed, as are data analyses showing upscale convective feedbacks.
2. Scientific Overview

2.1 Introduction

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; Dabberdt et al. 2000). Additionally, 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; Done et al. 2004; Kain et al., 2005, 2006, 2008; Weisman et al. 2008; Lean et al. 2008; Rotach et al. 2009; Seity et al. 2011; Clark et al. 2012). However, it is an open question whether current operational analyses are sufficiently accurate to maximize the potential predictability of convective events using such convection-permitting models.

Theoretical studies clearly suggest that the predictability of weather phenomena decreases with decreasing scale, ranging from several days for synoptic scale disturbances, down to mere hours for convective storms (e.g., Lilly 1990). Moreover, most 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 or the indirect use of diabatic heating to represent ongoing convection is no longer discernible after the first six to eight hours of a forecast (e.g., Kain et al. 2010; Sun et al. 2012; Stratman et al.)
However, to the degree that convective storms are forced and constrained by larger-scale phenomena such as fronts, dry lines, jet streaks, etc., or the degree to which convection produces significant modifications to its regional environment, improving the representation of these forcing elements and convective feedbacks has the potential to significantly improve the predictability of the convective weather as well.

With this in mind, the experimental plan for MPEX was guided by the following two scientific hypotheses:

Hypothesis 1: Enhanced synoptic and sub-synoptic scale observations over the Rocky Mountain region (e.g., Colorado, New Mexico, Arizona, Utah, Wyoming) during the early morning will significantly improve the forecast of the timing and location of convective initiation as well as convective evolution during the afternoon and evening over the High Plains.

Hypothesis 2: Enhanced sub-synoptic scale observations in the late afternoon, over regions where the atmosphere is being convectively disturbed, will significantly improve the 0-24 h forecast of convective and synoptic-scale evolution in downstream regions.

The scientific basis for each of these hypotheses is described in more detail in Sec. 2.2 and 2.3 below.
2.2 Regional analysis and numerical weather prediction

Since 2003, experimental daily 24 to 48 h real-time explicit convective forecasts employing horizontal grid spacings between 1 and 4-km over the central U.S. have been evaluated as part of the NOAA Hazardous Weather Testbed (HWT) Spring Forecasting Experiments, wherein forecasters and researchers from a variety of backgrounds have evaluated the application of such high resolution guidance for operational severe storm forecasting (e.g., Weiss et al. 2004, 2007; Kain et al. 2005, 2006, 2008; Clark et al., 2012; Kain et al. 2013). These forecast exercises have demonstrated that increasing horizontal grid resolutions into the convective-allowing regime leads to significant improvements in convective forecast guidance. For instance, such forecasts often realistically represent the structure and evolution of mesoscale convective phenomena, such as supercells, squall lines, bow echoes, and mesoscale convective vortices as well as the convective diurnal cycle, yet significant errors in the timing and location of convective events are also sometimes encountered (e.g., Done et al, 2004; Kain et al, 2008; Hohenegger and Schär, 2007; Weisman et al. 2008; Snively and Gallus, 2014).

Numerous issues could contribute to these forecast errors, including errors in physical parameterization schemes (e.g., Kain et al., 2005; Weisman et al., 2008; Coniglio et al., 2013), coarse horizontal and vertical resolution (e.g. Kain et al., 2008; Schwartz et al., 2009; Vandenbberg et al., 2014), poor representation of atmospheric features crucial to storm initiation and evolution (e.g., Coniglio et al., 2010; Duda and Gallus, 2013), and so on. While studies considering variations in grid resolution and/or model physics
(e.g., PBL and microphysics) do show sensitivity in the details of storm structure and evolution, they have generally not been able to explain the larger, mesoscale forecast errors that are often observed. However, far more forecast sensitivity on the 6 to 48 h timescale is often found by varying initial conditions (e.g., initializing with the NCEP North American Mesoscale (NAM) versus Global Forecast Systems (GFS) analyses), 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; Clark et al., 2010ab).

An example of the range of solutions that often results from using differing analysis schemes is presented in Fig. 1, from 15 May 2013 during the MPEX field campaign. In this example, 12 h forecasts initialized at 12 UTC with an identically configured WRF model using a 3 km horizontal grid (as described in Sec. 3.1) are compared. These forecasts are initialized using GFS, NAM and a representative analysis member of an Ensemble Kalman Filter (EnKF) ensemble system (as also described in Sec. 3.1). A fairly wide spectrum of forecast convective outcomes is noted, ranging from a well-organized isolated bow echo in northeast Texas using the EnKF analysis to more widespread clusters of convection in Texas and Oklahoma using the NAM and GFS analyses. Unfortunately, none of these forecasts closely matches the observed radar composite at 00 UTC, which depicts a primary bow-shaped convective system in south central Oklahoma, with more isolated convective cells extending southward into the Dallas-Ft. Worth, Texas region. Several of these cells in the Dallas-Ft. Worth region were supercellular, producing a series of significant tornadoes that were not well anticipated by operational forecasters based on the early morning guidance.
Such examples suggest that current analysis capabilities at the sub-synoptic and mesoscale may, at times, limit the forecast skill for significant convective events. One of the major goals of MPEX is, thus, to better document the current limitations of the operational analysis systems, and to test whether convective forecasting could be improved through the enhancement of observation density for features of interest using the dropsonde, upsonde and microwave temperature profiler (MTP) data collected during the field campaign. The potential benefits of the enhanced observations for analysis and prediction are being tested using a variety of different methods, as are described in Sec. 3.1 and Sec. 5 below.

2.3 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-\(\alpha\) 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 dis-
sipate 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 within which to sample these features produced by storm-environment interactions.

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. 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).

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 changes extending 10-20 km out from the storm core. These changes likely assist supercell maintenance and may increase storm severity. Similar environmental modifications are noted by Parker (2014) based on near-storm soundings taken during the VORTEX2 field campaign. Thus, even isolated, short-lived thunder-
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storms influence the nearby environment.

While these past studies clearly document the influences of thunderstorms and MCSs on the environment they are embedded within, both nearby the convection and more distant, a careful comparison of the upscale response to convection found in model simulations against environmental observations has not been conducted. 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.

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). For example, Stensrud and Gao (2010) show that a horizontally inhomogeneous background environment derived from an assimilation of surface observations significantly 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, only considering single squall line simulations and only incorporating limited operational data rather than the enhanced field data collected during MPEX. A careful examination of the impact of multiple radiosonde observations at mesoscale space and time scales on the short-term (0 – 24 h) prediction of convection has yet to be performed.

3. Modeling and Deployment Strategies

A mission timeline (Fig. 2) helps to clarify the relative placement and roles of the modeling and observational assets employed during MPEX. As with other recent field efforts (e.g., BAMEX; Davis et al., 2004, VORTEX2; Wurman et al. 2012, DC3; Barth et al. 2014), operations and deployment planning was strongly guided by output from experimental high-resolution models, as described in Sec. 3.1 below. Since a go/no-go decision for the next morning’s flight operations needed to be made at the daily 21 UTC briefing, the primary model forecast input to this planning came from the earlier 12 UTC modeling suites, roughly 24 h ahead of the intended dropsonde and MTP operations and about 36 h ahead of the expected convective event. Initial decisions regarding any possible next day upsonde operations were also discussed at the daily briefing, as operations allowed (e.g., if upsonde operations were not ongoing), with minor modifications considered based on model and observational updates through the evening and following morning.
NSF/NCAR Gulfstream V (GV) research flights generally extended from 09 to 15 UTC, targeting specific regions thought to be especially significant for later-in-the-day convective activity (generally occurring from 18 to 06 UTC). Upsonde teams then positioned themselves in the late-morning through early afternoon period to sample both the pre-through post-convective environments of their specified targeted regions. More specific details concerning these modeling and operational assets and deployment strategies are offered in Secs. 3.1-3 below.

3.1 Realtime Ensemble Modeling and Sensitivity Analysis

Five research model configurations were used in MPEX in addition to the operational models to make weather forecasts and judge forecast uncertainty (Table 1). The primary research guidance was from an experimental 3 km WRF (Weather Research and Forecasting model; Skamarock et al. 2008) initialized from an NCAR generated 50-member ensemble analysis system based on WRF/DART (DART – Data Assimilation Research Testbed; Anderson et al. 2009). DART is an ensemble-based data assimilation system that provides interfaces to a number of models. 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.

For MPEX, each ensemble member forecast included a CONUS (contiguous United States) mesoscale (15-km) and 2/3 CONUS nest (3-km; extending from roughly Utah to
West Virginia), with forecast products based on the explicit nest. Thirty member ensemble forecasts extending through 48 h were produced twice daily (initialized from the 00 and 12 UTC WRF/DART analysis) on the NCAR Yellowstone supercomputer.

The real-time WRF ensemble forecasts generated during this period were also used to objectively determine the locations and variables where errors would have the greatest impact on subsequent forecasts of convection using the ensemble-based sensitivity analysis (ESA) technique (Ansell and Hakim 2007, Torn and Hakim 2008). Here, sensitivity is defined as the change in a forecast metric at some particular lead time (i.e., 36 h precipitation averaged over a particular region) per unit change in an individual model state variable at an earlier lead time (i.e., 24 h wind, temperature or moisture at a location). Locations where the magnitude of the sensitivity is relatively large suggest locations where errors can grow most rapidly and impact the forecast metric; therefore, it provides an assessment for where assimilating additional observations could improve a forecast should an error already exist. Although sensitivity analysis has been used for observation targeting in both midlatitude (i.e., Joly et al. 1999, Szunyogh et al. 1999) and tropical cyclone applications (Aberson 2003, Wu et al. 2004), MPEX represented the first time that sensitivity analysis has been used for mesoscale observation targeting. Moreover, sensitivity analysis provides a quantitative method of testing hypotheses about what features (i.e., troughs, dry line) or fields (i.e., boundary layer moisture, CAPE) contribute to changes in the subsequent forecast.
During MPEX, forecast sensitivities were computed for multiple forecast metrics using the WRF ensemble forecasts, which in turn were used as guidance for planning G-V missions. For each set of forecasts initialized at 1200 UTC, multiple boxes were defined based on locations and time periods where the 3 h precipitation standard deviation and vertical motion was large between 2100 – 0300 UTC during the next day. From the list of potential metric boxes, one or two boxes were subjectively chosen as a basis for a mission based on convective type and coordination with upsonde operations. Maps of sensitivity of the precipitation to individual grid points were overlaid on the particular field valid at 1200 UTC the next day (i.e., centered on the G-V mission time) to scrutinize the relationship between the sensitivity pattern and the features that were believed to be important to the forecast, such as the position of midtropospheric troughs and moisture, surface boundaries, etc. In situations where the regions of large sensitivity lined up with the features that were subjectively believed to be important to the forecast, G-V flight patterns were designed that would sample the feature and the sensitive region.

Additional daily explicit (4-km) WRF deterministic model forecasts were supplied by Colorado State University (CSU) and the National Severe Storms Laboratory (NSSL), based on GFS and NAM initial conditions, respectively, allowing for valuable intercomparisons with the WRF-DART ensemble forecasts. Finally, the dropsonde data were assimilated into real-time models by the Assimilation and Modeling Branch of the Global Systems Division at NOAA’s Earth System Research Laboratory. Parallel, experimental versions of the Rapid Refresh (a 13-km WRF system; Ikeda et al. 2013, Zhu et al. 2013)
and High-Resolution Rapid Refresh (a 3-km WRF system; Ikeda et al. 2013) were run, both with and without dropsonde data assimilation. Forecast output was available in real time during the second half of the field experiment, and forecasts for earlier cases have since been produced retrospectively.

3.2 Morning Dropsonde and MTP Strategies

The goal for the morning dropsonde deployments was to obtain wind, temperature and moisture observations through the depth of the troposphere on a grid that was sufficiently dense to sample sub-synoptic short-wave troughs and ridges, low-level jets, dry intrusions, potential vorticity streamers, and other mesoscale phenomena in the pre-storm environment (typical sample spacing ~75 to 200 km). GPS mini-dropsondes deployed from the GV aircraft (Sidebar 1) were successfully used for this task, representing the first official use of the new mini dropsondes being deployed from an automatic launch system from the GV. An airborne microwave temperature profiling system (MTP; e.g., Haggerty et al. 2014) was also deployed on the GV (Sidebar 2), and offered 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. As such, MTP data significantly enhanced the characterization of atmospheric structure between dropsondes, thereby increasing the effective resolution of the observational data set even further.
The full GV observational domain for MPEX is depicted in Fig. 3. Within this domain, potential drop sites were pre-vetted to avoid no-drop zones based on population, military, or air traffic flow constraints. Also, drop sites were chosen so as to not overlap with existing NWS sites to maximize the value added by the deployment strategy. A flight altitude of at least 12 km (40,000 ft) was used 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.

A sub-domain of roughly 600 by 1000 km was typically chosen for each one-day Intensive Observing Period (IOP) depending on the meteorological scenario. 28-34 sondes were dropped within the specified sub-domain per IOP, with the drop spacing ranging between 75 and 250 km, focused on the targeted sub-synoptic feature of interest. An example flight path is presented in Fig. 4, for 31 May 2013, where dropsondes characterized the environment in the morning upstream from Oklahoma, prior to a significant tornado and flood event in central Oklahoma later that day.

Dropsonde and MTP deployments occurred on days for which widespread (severe) convection (preferably with an identifiable upstream precursor) was forecast, based on operational and experimental convection-allowing forecast guidance, and especially if significant uncertainty was noted in the model or human forecast guidance. In the present context, forecast uncertainty reflected uncertainty in the timing, location or intensity of potential convection. “Uncertainty” was measured via the apparent level of disagreement between the various operational and experimental models and/or human forecast-
ers as well as from the more formal sensitivity analyses produced from the WRF/DART high-resolution ensemble, as described in Section 3.1 above.

3.3 Afternoon Upsonde Strategies

GPS *upsondes* (i.e., balloon-borne radiosondes) were deployed during specific afternoons and evenings to characterize the mesoscale environment over regions of anticipated convection initiation (CI), as well as the mesoscale environment that had been disturbed by subsequent convective storms. Two dual-frequency radiosonde systems operated by Purdue University and NSSL, and an additional single-frequency radiosonde system operated by CSU (see Appendix A for system details) were used. Combined, these systems allowed for up to five sondes to be in the air simultaneously. For one week in late May, a fourth mobile system was contributed by Texas A&M University (TAMU), and thus allowed for simultaneous sampling with six sondes.

Several different deployment strategies were employed by the upsonde teams. For instance, a **PCE** (pre-convective environment) strategy (Fig. 5) could be conducted to sample the full tropospheric structure of the mesoscale environment, prior to and in the region of anticipated CI. Starting with ~60-80 km north-south separation between two of the teams, the basic plan was for both teams to simultaneously release a radiosonde, re-deploy roughly 80 km downstream and then each simultaneously release a second radiosonde; a third team would follow a similar strategy, except with ~20 km redeploy-
ment distance. The three radiosonde teams were positioned relative to the time and location of expected CI, with the first radiosonde observations made upstream of the expected CI location, and the last observations made downstream, when CI occurs. Logistics permitting, locations for the PCE deployments were generally chosen to be downwind of the morning observational domain that was sampled by the GV, and in regions thought to be observationally sensitive, based on the ESA.

Similarly, the goal of the CDE (convectively disturbed environment) strategy was to sample the mesoscale environment that has been disturbed by the subsequent convective storms. Starting with ~2\(xD\) to 3\(xD\) north-south separation, the basic plan (Fig. 6) given offset distance \(D\) was to execute time-coordinated releases of a series of radiosondes at fixed locations, at 0.5 to 1 h intervals. The radiosonde teams were positioned relative to the convective-storm motion (\(C\)), such that the first (last) radiosonde observations would be made in advance of (in the wake of) the moving storm. Distance \(D\) depended on the availability of suitable radiosonde release locations, but nominally was between 5-25 km.

4. MPEX IOP Summary and Case Examples

The weather pattern experienced during MPEX was quite active, offering a wide spectrum of opportunities to sample convective environments, ranging from weakly forced convective events to several strongly forced severe weather outbreaks, including destructive tornadic events impacting Grandbury Texas (May 15), Moore OK (May 20) and
El Reno OK (May 31). In all, 15 morning missions were successfully completed with the GV, with 17 afternoon missions completed with the mobile soundings units (including all but one of the GV days, plus three additional days when the GV was unavailable due to duty cycle limitations). The total of 18 IOPs are listed in Table 2, along with a brief meteorological description and notes on the number of dropsondes and upsondes that were deployed for each case. A few examples of the range of morning dropsonde deployments during MPEX are presented in Fig. 7, representing a weak, upper-level closed low in the Texas Panhandle (May 15), a weak disturbance in southwesterly flow over New Mexico (May 28), a strong jet stream and upper tropospheric front centered over southern Colorado and northern New Mexico (May 30), and an upper-level short wave and associated cold front in northwesterly flow centered over Wyoming (June 8). Afternoon upsonde missions included the sampling of a pair of supercells and their transition to a quasi-linear convective system (QLCS) in the southern Texas Panhandle (23 May), a damaging QLCS and its northern bookend vortex in the Texas Panhandle (29 May), a large tornadic supercell in central Oklahoma (31 May), and a supercell-to-bow echo transition in the Oklahoma Panhandle (3 June) (see Fig. 8).

A more detailed case example from 19 May 2013, which was representative and well sampled with both the GV and upsonde teams, helps illustrate the experimental process followed during MPEX. The synoptic pattern for this day was dominated by a deep and broad 500 hPa trough over the Rocky Mountains, with a strong jet stream and mid-to-upper tropospheric front extending from Nevada through Arizona and New Mexico and northeastward through Texas, Oklahoma, Kansas and Missouri (Fig. 9a). A surface cold
front was situated from northeastern South Dakota southward through Nebraska and western Kansas, with a dry line extending from a weak low pressure center in southwest Kansas southward through the Texas Panhandle and southwest Texas (Fig. 9a). The satellite water vapor image at 12 UTC (Fig. 9b) depicts a fairly moist environment in the mid to upper troposphere from Kansas northward, with the remains of nocturnal MCSs evident in eastern Kansas as well as farther northeast into Illinois and Wisconsin. Ahead of the cold front and dry line, the environment was characterized by high CAPE and strong vertical wind shear, and a significant severe weather outbreak (including tornadoes) was anticipated by Storm Prediction Center (SPC) forecasters across a broad region from north-central Oklahoma northward into central and eastern Kansas and Missouri.

Forecasts from the ensemble initialized at 12 UTC on 18 May suggested two concentrated regions where high impact storms would likely develop on the afternoon of the 19th, with a cluster in central Oklahoma, and strong mesoscale convective systems over central and eastern Kansas (Figs. 10, 11). Many of the forecast storms also displayed high values of updraft helicity (e.g., > 150 m²/s²; Kain et al. 2010) suggesting that the storms would likely be supercellular in nature (Fig. 11a). Given the potential high impact event, we then sought to determine if suitable uncertainty existed for a targeting mission. Automated algorithms identified preliminary forecast features for ESA guidance that helped identify regions of forecast uncertainty. Still, not all forecast regions were associated with robust ESA patterns, such as the precipitation area forecast over central Oklahoma. As such, a manual box was defined over the region of moder-
ate probabilities of convective precipitation in parts of eastern Kansas on the evening of May 19\textsuperscript{th} (Fig. 11b).

Precipitation forecasts over eastern KS were characterized by a clear sensitivity to upstream features in the 24 h forecast, which was centered on the dropsonde mission window (Fig. 12). At this time, the sensitivity magnitude is maximized on the southern edge of the broad western trough over northern New Mexico and Arizona, such that increasing the 500 hPa vorticity, akin to shifting the position of the trough to the south, is associated with increased precipitation in the eastern Kansas box 12 h later. Indeed, this particular region at the base of the trough was also the region that was forecast to propagate eastward over Oklahoma later in the day, contributing to the generation of the local convective environment as well as the triggering of the convection itself. Moreover, the ESA calculation suggested that dropsonde points located along the Colorado-New Mexico border would produce the largest reduction in the variance of the precipitation forecast within the eastern Kansas box (Fig. 12b). Based on available guidance, it was anticipated that dropsonde observations collected from eastern Utah through southwest Colorado and northern New Mexico would better document this jet and upper-level frontal structure (Fig. 9b) and would have the potential to improve later forecasts.

The updated ensemble forecasts from 12 UTC on the 19\textsuperscript{th}, valid 00 UTC 20 May (Figs. 13, 14) continued to forecast an outbreak of severe convection from central Oklahoma, northeastward through central and eastern Kansas, Iowa and eastern Minnesota. The primary convective mode produced in these forecasts was multiple, linear, bow-shaped
convective segments from Kansas northward into Iowa, with a more isolated cluster of
strong cells in central Oklahoma. The analysis system used for the realtime ensemble
forecasts were updated every 6 h, so after four additional rounds of observation inform-
ation this day 1 forecast (Figs. 13 and 14) was considerably more certain of the fore-
cast evolution of storms relative to the earlier day 2 forecast (Figs. 10 and 11). Never-
thless, ESA applied to the morning analysis still indicated sensitive observations within
the region earlier targeted for sampling (not shown). The reflectivity frequency plots
constructed from the ensemble suggests a fairly consistent forecast for heavy precipita-
tion from Kansas north-northeastward, but perhaps a bit less certainty for the cluster of
storms being forecast in central Oklahoma. Additionally, the frequency plot for updraft
helicity again indicates a high likelihood for supercell storms throughout the region of
interest. The observed radar at 00 UTC (Fig. 13a) clearly shows a strong cell in central
Oklahoma, which had been significantly tornadic, along with scattered storms across
western Missouri. A primary bow-shaped segment is also present in eastern Kansas,
which mostly led to reports of severe winds. Ensemble forecasts largely captured the
convective mode and features of the observed event, but with notable differences such
as the location of the bowing segment in Kansas. Ongoing retrospective studies find the
assimilation of dropsonde observations primarily impacts the eastward progression of
the bowing segment, improving the timing and location of convection for this event.

Seeking a more isolated convective feature to study, the upsonde teams elected to tar-
get a region in north-central Oklahoma for its missions on the 19th of May. A linear ob-
serving array extending from Blackwell, OK southward to Perry, OK and then Guthrie,
OK was used to sample the preconvective environment (and one that later supported a tornadic supercell). Each team collected 19 UTC soundings at their respective locations. Deep convection initiated south and west of this array during the next hour, and a rapidly intensifying cell moving towards the array was chosen for further sampling. Teams re-deployed east and south to employ a CDE strategy, with NSSL near Stillwater, OK, CSU near Perkins, OK (both north of cell) and the Purdue team south of the cell near Warwick, OK and later Rossville, OK. Several soundings were collected by the teams as the now tornadic supercell passed through this array. The teams then re-deployed south and east to sample other cells that were developing further southwest. Of note was the tornadic supercell that was sampled at approximately 0045 UTC, within a triangular observing array, with NSSL west of and in the wake of the supercell, CSU north of the supercell, and the Purdue team south of and in the inflow of the supercell (Fig. 15).

Ongoing analyses of the soundings (e.g., Fig. 16) and complementary model simulations are showing that the thermodynamic structure of the near-storm atmosphere above the convective boundary layer is relatively un-modified by more isolated deep convection such as supercells. Indeed, for supercells, the most significant upscale feedback identified so far appears to be associated with the storm-generated cold pool.

5. Research Plans and Opportunities

Given the active weather regime and large number of successful deployments, the scientific opportunities afforded by MPEX are plentiful, and could contribute significantly to our understanding of the predictability of mesoscale convective weather. To begin with,
the enhanced temperature, moisture and wind observations throughout the troposphere will allow us to characterize the upstream and near-convective environments with far more certainty than has generally been available, either operationally or as part of past field campaigns. This will allow for better validation of the existing operational and research analysis systems over the sparsely observed Intermountain West upstream of Central Plains convective events, and will also help to identify any systematic and/or significant analysis errors during this time period that may have subsequently impacted the convective forecasts. Notably, many strong jet-stream-associated upper-level fronts were sampled during the field campaign, offering a unique opportunity to document the mesoscale variations in these features over the complicated terrain of the intermountain regions. More generally, the MPEX observations can be used to better establish the representativeness of the sparse operational radiosonde network over this region.

One of the major questions is whether the relevant analysis errors come from translating mid-tropospheric features upstream of convection or more local inhomogeneities in moisture, the locations and structure of surface boundaries, etc. Initial results from the sensitivity analyses suggest that both upstream and local errors are important.

One of the primary goals of MPEX is to use retrospective case studies to assess the impacts of the targeted observations on the subsequent model forecasts. For retrospective events, the assimilation frequency is being increased to hourly cycles to better accommodate the long window of time for GV dropsonde missions to collect observations.
Preliminary results suggest a range of responses to the dropsondes from case to case, but generally confirm that the enhanced data can have a positive impact on the subsequent forecasts.

The retrospective experiments with and without dropsonde data also provide an opportunity to assess whether ESA can identify the critical regions where dropsonde data could benefit the forecast. This will be accomplished by repeating the dropsonde experiments described above, but only the subset of dropsondes that overlap with the locations identified by sensitivity analysis (using the algorithm outlined in Torn (2014)) are assimilated. The forecasts generated from these analyses will be compared to the control and an experiment that contains all of the dropsonde data. If the location(s) identified by sensitivity analysis represent the critical initial condition error, then the impact from assimilating a subset of dropsondes should be similar to assimilating all dropsondes.

Forecast sensitivity analysis also affords the opportunity to better understand the processes that impact the predictability of convection events. As an example, sensitivity analysis identified that forecast metrics that measure convection on the 19th May (i.e., area-average precipitation or vertical kinetic energy) were sensitive to the southern extent of the upper trough over Colorado and to the lower-tropospheric meridional moisture transport over north-central Texas at 1200 UTC. Future work will evaluate the relative importance of each of these sensitivities, apply processed-based studies to understand why sensitivity analysis identifies these features, and compare the results to other
strongly-forced events during MPEX, such as on May 30th. Ultimately, these studies could help us identify which weather regimes could benefit the most from additional data, as might be afforded by targeted dropsonde or upsonde operations.

The afternoon upsondes will be especially useful for producing composite inflow soundings for the many severe storms that were sampled, and will also be used to produce composites of triangle calculations over different stages of storm evolution, which will help assess the impacts of the convection on the regional environment. More generally, the upsonde data will be used to verify the earlier model forecasts, especially offering valuable insights into the processes of convective initiation as represented by the high-resolution forecasts. Furthermore, the upsonde and available radar reflectivity and velocity data will be assimilated to create enhanced storm-scale analyses for input to subsequent convective-scale forecasts.

Given the extensive set of mesoscale observations obtained during MPEX, the ultimate goal of the related research is to better establish how mesoscale analysis errors impact subsequent convective scale forecasts over a 0-24 h timescale, and perhaps beyond. An important component of this is to clarify where the weaknesses reside in our current observational system, and, in particular, which variables generate the largest sensitivities in the subsequent convective forecasts. However, not only will MPEX afford researchers the opportunity to help identify any systematic and/or specifically significant analysis errors, but it will also help expedite the identification of systematic errors or
shortcomings in the cycled data analysis system and/or numerical model system and their components (e.g., sub-grid parameterizations).

Finally, MPEX will also serve as an opportunity to evaluate the practical and intrinsic short-range predictability of more specific attributes of convection. For instance, research is ongoing to quantify the practical predictability of convective initiation, how it is influenced by the assimilation of MPEX dropsonde observations, to examine how both observational and PBL parameterization uncertainty limits its intrinsic predictability, and to identify systematic model biases influencing the skillful prediction of convective initiation.
Acknowledgements

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Sidebar 1: The NCAR GV and mini-Dropsonde System

The NSF/NCAR GV Airborne Vertical Atmospheric Profiling System (Hock and Franklin 1999; Fig. SB1) is an atmospheric instrument that measures vertical profiles of ambient temperature, pressure, humidity, wind speed and wind direction. Measurements are taken by a parachuted dropsonde that is launched from the aircraft and descend to the surface. In-situ data collected from the sonde’s sensors are transmitted back in real time to an onboard aircraft data system via radio link. Up to 8 dropsondes can be tracked in the air simultaneously.

The dropsonde is composed of a small electronic circuit board, sensors and a battery housed in a cardboard tube with a parachute. The total weight of the sonde is less than 6 ounces with dimensions of a 1.75” diameter tube 12 inches long. The inner electronic components of the dropsonde consist of precision temperature, pressure and humidity sensors, telemetry transmitter, GPS receiver for winds and microprocessors. As the sonde descends it continuously measures the atmosphere from the release altitude to the earth’s surface. Measurements are made every half second for the thermodynamic data and every 0.25 seconds for winds, which provides a precise detailed profile of the atmosphere. The parachute deploys from the top of the sonde within seconds of being released from the aircraft. The parachute is specially designed for high reliability and a very stable descent. The fall velocity of the dropsonde varies with air density, ranging from ~22 m/s at 200 hPa to ~12 m/s at 875 hPa during the MPEX missions. As the sonde descends the GPS receiver tracks the position and velocity of the sondes, this change in motion corresponds to the atmospheric winds. Once the sounding is com-
plete, the data is automatically sent to the ground via the GV satellite system for quality
control processing, creating skew-T plots and WMO Temp-drop message. MPEX was
the first deployment of the NCAR mini-dropsonde from the GV using a newly developed
automated dropsonde launch system.

The pressure, temperature and humidity sensor used in the sonde is a Vaisala sensor
module, which is almost identical to that used in the RS-92 radiosonde. These sensors
where chosen for their performance characteristics of accuracy, range, response time
and minimal impact by solar radiation. Each sensor module is individually calibrated for
precise accuracy.
Sidebar 2: The Microwave Temperature Profiler

The Microwave Temperature Profiler (MTP; Haggerty et al. 2014) is a scanning radiometer that provides measurements related to atmospheric temperature structure above and below the aircraft. Basic components of the MTP are a receiver that measures emission centered on three lines within the oxygen absorption complex and a scanning mirror which views emission at 10 elevation angles between nadir and zenith. Profiles are produced every 17 s, or about every 4 km along the flight path. A statistical retrieval algorithm using historical radiosonde profiles is applied to convert the observed brightness temperature into temperature as a function of altitude.

An example from 19 May 2013 is shown in Fig. SB2. The segment of the GV mission shown at lower left transected the upper-tropospheric front over northern New Mexico. The front is seen as a fold in the 2 PVU surface of potential vorticity as depicted by the National Centers for Environmental Prediction Global Forecast System (GFS) analysis for 12 UTC 19 May (purple) in the top panel. Temperature anomalies derived from the MTP are shaded in blue (negative) to red (positive), where the anomaly is defined relative to the mission-average temperature at each altitude. The reversal of the meridional temperature gradient from troposphere to stratosphere is clearly seen, as is the weakening of the temperature gradient where the tropopause becomes vertical in the jet core near 36N. A deep temperature sounding through the upper-level frontal zone (light blue vertical line marked 'Skew-T') is constructed by superposing a weighted average of dropsonde temperatures and the mean of MTP profiles over a 5-minute period (bottom
panel, temperature in red, dewpoint in green). The composite sounding reveals three isothermal layers, one near 500 hPa (the upper-level front), another near 200 hPa (the nominal tropopause) and a third well into the stratosphere above 100 hPa.
Appendix A: Mobile Upsonde Systems

The Purdue and NSSL systems are comprised of the iMet-3050 and iMet-3150 403 MHz GPS radiosonde receiver and antenna (manufactured by International Met Systems). Laptop computers running the iMETOS were used to process the radiosonde data, which was collected using iMet-1-AB 403 MHz GPS radiosondes with a pressure sensor; pre-flight calibration is not needed with the iMet-1-ABs. The sondes were suspended from 200-gm latex balloons, with a de-reeler and 30-m string.

The CSU system is a Digicora MW21 using Vaisala RS92 sondes with a GC25 (Ground Check system). It uses a GPS antenna for wind finding and a UHF antenna operating around 400 Hz for transmitting the signal from the sonde to the ground system. Similarly, a laptop computer running the Digicora software was used to process the radiosonde data. As with the NSSL and Purdue systems, the sondes were suspended from 200-gm latex balloons, with a de-reeler and 30-m string.
References


Table 1. Summary of high resolution modeling tools employed during MPEX.

<table>
<thead>
<tr>
<th>Name</th>
<th>Run time</th>
<th>Update time</th>
<th>Time available to community</th>
<th>Initialization approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 km NCAR WRF-ARW Ensemble forecasts</td>
<td>2 48-hr sims run daily</td>
<td>00Z 12Z</td>
<td>06Z=0000 MDT 18Z=1200 MDT</td>
<td>Cycling WRF-DART analyses</td>
</tr>
<tr>
<td>3 km WRF-ARW Ensemble Sensitivity Analyses</td>
<td>based on 12Z 3-km WRF ARW</td>
<td>12Z</td>
<td>19Z=1300 MDT</td>
<td>Not applicable</td>
</tr>
<tr>
<td>4 km WRF NSSL Weather forecasts</td>
<td>2 36-hr sims run daily</td>
<td>00Z 12Z</td>
<td>05Z=2300 MDT 17Z=1100 MDT</td>
<td>NAM analyses</td>
</tr>
<tr>
<td>3 km HRRR Forecasts</td>
<td>15-hr forecasts</td>
<td>Hourly</td>
<td>analysis time plus 2-hrs</td>
<td>RAP analyses</td>
</tr>
<tr>
<td>CSU 4-km WRF forecasts</td>
<td>39-hr forecasts</td>
<td>12Z</td>
<td>21Z=1500 MDT</td>
<td>GFS analyses</td>
</tr>
</tbody>
</table>
Table 2: Summary of MPEX Cases

<table>
<thead>
<tr>
<th>IOP</th>
<th>Case Description</th>
<th>Instruments</th>
</tr>
</thead>
</table>
| 1: 15 May | Upper level vortex in west Texas. Widespread convection and severe weather in Texas and Oklahoma (unexpected tornadoes near Dallas). | GV drops: 27  
Upsondes: 5 |
| 2: 16 May | Upper tropospheric vortex over Colorado. Convection in Kansas and Nebraska.                                                                                                                                 | GV drops: 30  
Upsondes: 6 |
Upsondes: 16 |
| 4: 19 May | An upper-level jet-front system over Colorado and New Mexico. Tornado outbreak in eastern Oklahoma and Kansas.                                                                                                  | GV drops: 29  
Upsondes: 17 |
| 5: 20 May | Strong upper-level trough and jet over New Mexico and Oklahoma. Tornado outbreak targeted in central Oklahoma (Moore, OK tornado).                                                                                 | Upsondes: 18 |
| 6: 21 May | An upper-level trough in New Mexico and west Texas. Widespread convection in east-central Texas.                                                                                                               | GV drops: 27 |
| 7: 23 May | Surface front in northwest Texas along with weak upper tropospheric PV features in New Mexico and Arizona. Severe convection in west-central Texas.                                                             | GV drops: 29  
Upsondes: 23 |
| 8: 27 May | An upper tropospheric feature over the intermountain region embedded within sub-tropical southwesterly flow contributes to locally intense convection in western and south-central Nebraska and north-central Kansas. | GV drops: 29  
Upsondes: 22 |
| 9: 28 May | Weak upper-level features in southwesterly flow over New Mexico. Strong convection in southwest Kansas and the Oklahoma and Texas Panhandles.                                                                  | GV drops: 21  
Upsondes: 18 |
| 10: 29 May | Deep trough over the intermountain region with strong southwesterly flow over the high plains. Widespread convection from Texas through South Dakota. Bow echo in western OK and Texas Panhandle.          | Upsondes: 20 |
| 11: 30 May | Strong trough and associated jet over Wyoming, Colorado and New Mexico. Widespread severe convection in eastern Kansas, east-central Oklahoma, extending northeastward into Illinois. | GV drops: 26  
Upsondes: 26 |
| 12: 31 May | Strong jet over Colorado, New Mexico and west Texas. Tornadic storms in central and eastern Oklahoma, extending northeastward into Missouri and Illinois (El Reno, OK tornado). | GV drops: 28  
Upsondes: 17 |
| 13: 03 June | An upper-level trough and associated cold front in Wyoming and Colorado. Scattered convection from western Nebraska southward to the Oklahoma Panhandle.                                                            | GV drops: 32  
Upsondes: 17 |
| 14: 04 June | Dry line targeted in Texas Panhandle in the wake of an earlier MCS. Only weak convection ensued.                                                                                                               | Upsondes: 15 |
| 15: 08 June | A weak trough embedded within strong northwesterly flow over Wyoming and Colorado. Widespread convection from the Oklahoma Panhandle northeastward into Iowa.                                                  | GV drops: 31  
Upsondes: 22 |
| 16: 11 June | An upper-level trough in northern Utah embedded in southwesterly flow. Convection from Montana southeastward to northern Nebraska.                                                                                 | GV drops: 33  
Upsondes: 21 |
| 17: 12 June | Upper-level trough extending from North Dakota southward through Nebraska. Severe convection from Iowa eastward (a strong Derecho was anticipated from Chicago eastward). A weak upper-level feature in northern Utah contributes to convection in northeast Wyoming. | GV drops: 33  
Upsondes: 19 |
| 18: 14 June | A weak trough and associated surface front embedded in southwesterly flow over Colorado and Wyoming. Moderate convection from southeast Colorado northeastward to south-central Nebraska.马丁    | GV drops: 33  
Upsondes: 8 |
Figure Captions:

**Figure 1.** a) Observed composite reflectivity for 00 UTC, 16 May 2013, as compared to 12 h reflectivity forecasts using the WRF-ARW model with a 3 km grid spacing, initialized at 12 UTC on 15 May using b) a representative analysis from the DART ensemble, as described in the text, c) the analysis from the operational NAM model, and d) the analysis from the operational GFS model.

**Figure 2.** Mission Timeline

**Figure 3.** Full domain of interest for MPEX morning dropsonde operations, along with a pre-vetted set of dropsonde sites (numbered stars). Operational NWS sounding sites are indicated by the red dots.

**Figure 4.** Example upstream GV deployment for the early morning of 31 May 2013 (~9 to 15 UTC), showing airflight winds at ~ 40000 ft MSL. The visible satellite background is for 00 UTC, 01 June, depicting the resulting severe convective outbreak extending from central Oklahoma northeastward through Missouri. The “red” versus “yellow” GV flight track signifies the last hour of the flight.

**Figure 5.** Example upsonde locations (circles) for the PCE (pre-convective environment) sampling strategy.
**Figure 6.** Example upsonde locations (circles) for the CDE (convectively disturbed environment) sampling strategy. The open circles represent additional/optional soundings that can be made if time allows.

**Figure 7.** Example morning dropsonde deployments during MPEX, depicting dropsonde winds at 500 hPa obtained during the 5-6 h flight (not time-lag adjusted), on a background water vapor image from 12 UTC: for a) 15 May, b) 28 May, c) 30 May, and d) 8 June 2013.

**Figure 8.** Examples of upsonde deployments during MPEX on: a) 23 May, b) 29 May, c) 31 May, and d) 3 June 2013. Sonde release locations indicated by circles are overlaid by composite reflectivity factor (NSSL NMQ product). Inverted triangles show tornado reports.

**Figure 9.** a) 500 hPa analysis and significant surface features and b) satellite water vapor, including dropsonde winds at 500 hPa from the early morning GV mission, for 19 May 2013 at 12 UTC. The yellow dashed line in a) indicates the location of the surface dry line. Other frontal symbols are standard.

**Figure 10.** a) Composite radar reflectivity (maximum in the column) valid 00 UTC on 20 May 2013, as compared to b), c), d), e), f) five representative members of the 36 h EnKF forecasts, initialized at 12 UTC 18 May and valid at 00 UTC 20 May.
**Figure 11.** a) Cumulative tracks of the ensemble maximum updraft helicity over period 18 UTC 19 May through 06 UTC 20 May and b) ensemble probabilities of accumulated rainfall greater than 10 mm h\(^{-1}\) over period 00-03 UTC 20 May, based on EnKF initialized forecasts from 12 UTC 18 May 2013. The box labeled ‘sensitive’ in (b) indicates the region used for the ensemble sensitivity analyses, as described in the text.

**Figure 12.** a) Sensitivity of the 36-39 h forecast of precipitation averaged over the box in Fig. 11b to the 24 h 500 hPa vorticity forecast (shading, units: mm per standard deviation) for the forecast initialized 1200 UTC 18 May 2013. The contours denote the ensemble mean 500 hPa vorticity (units: 10\(^{-5}\) s\(^{-1}\)). b) Hypothetical reduction in the variance of the 36-39 h precipitation averaged over the box in Fig. 11b due to assimilating a dropsonde profile at that point on 1200 UTC 19 May 2013.

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**Figure 14.** Same as Fig. 11, except based on EnKF initialized forecasts from 12 UTC 19 May 2013, and overlain in a) are preliminary storm reports as compiled by the NOAA Storm Prediction Center (SPC) during the same period as the forecast.

**Figure 15.** As in Fig. 8, except for the upsonde deployment on 19 May 2013.
**Figure 16.** Sample soundings from the upsonde deployment portrayed in Fig. 15, from the a) CSU, b) NSSL and c) Purdue mobile sounding units. Dashed black lines indicate the parcel path for a 500-m mean-layer lifted parcel. Calculations of thermodynamic quantities should be viewed with caution because not all soundings reached the level of neutral buoyancy.

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Surround Strategy (Upstream and Downstream Effects)

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