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A MESOSCALE RE-ANALYSIS OF ANTICIPATED SEVERE WEATHER THREATS IN THE OZARKS DURING THE WEEK OF MAY 4-10TH 2003

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1. INTRODUCTION

The availability of real-time mesoscale data, including surface observations, wind profilers and upper-air soundings, coupled with mesoscale numerical model output has enabled operational meteorologists to test hypotheses presented in recent studies regarding forecasts of severe weather threats. These studies have suggested that successful analysis of the near-storm environment, specifically with respect to lower tropospheric thermodynamics and kinematic profiles, can provide significant skill in discriminating among severe weather threats. The week of May 4-10th 2003 brought an extraordinary frequency and intensity of severe weather to the Missouri Ozarks and Southeast Kansas, including very large hail, damaging winds, and strong tornadoes. While expected threats included strong to violent tornadoes on three separate days during the period, such an event occurred only on May 4 2003. This paper will use several techniques developed by previous authors to re-evaluate anticipated severe weather threats during the May 2003 outbreak week over the Ozarks region.

2. TORNADO INGREDIENTS

Paul Markowski and collaborator Erik Rasmussen have hypothesized that there are three primary ingredients necessary for tornado formation: a persistent, rotating updraft; enhanced storm-relative helicity; and the development of a relatively warm and moist rear-flank downdraft (RFD).

It is the development of an RFD with the special characteristics of being relatively warm and moist that is the most recent finding from VORTEX, and will receive the most discussion here.

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2.1 Development of a Persistent, Rotating Updraft

It has generally been accepted for a number of years that the generation of a rotating updraft is the result of vertically tilting and stretching pre-existing horizontal vorticity tubes created by vertical wind shear.

If sufficient buoyancy is present in the boundary layer to support deep convection, the development and persistence of a rotating updraft can be tied to several features. One such feature is the presence of large low-level ambient relative humidity to help prevent the rear flank gust front from advancing too far downstream from the updraft. The proximity of the RFD to the updraft prevents buoyant air in the inflow region from being severed. In addition to its role in the formation of vertical vorticity tubes, deep layer shear acts to mitigate the effects of updraft suppression from precipitation loading. Strong storm-relative winds act to advect the precipitation core out and away from the updraft.

2.2 Enhanced Boundary Layer Storm-Relative Helicity

Only in rare cases, such as May 4 2003, is the meso-alpha scale storm-relative helicity (SRH) so large that locally enhanced SRH is not needed to generate significant tornadoes. Large outbreaks, where many supercells produce significant tornadoes, typically have background SRH at or above 300 m^2s^{-2} over the entire warm sector. It is not clear how much SRH is required for a supercell to become tornadic, in most cases however, tornadic supercells occur where SRH tends to be locally enhanced.

SRH is highly variable both spatially and temporally (Markowski et al., 1998a). Local enhancement of SRH can result from mesoscale boundaries such as warm fronts, convective outflow boundaries, anvil shadows, and the forward flank downdraft (FFD); acceleration of inflow parcels; and variations of vertical shear parameters due to small wind perturbations (wiggles in the hodograph) (Markowski et al., 1998b). Of these, only mesoscale boundaries occur on the operationally observable scale. In VORTEX, two thirds of significant tornadoes occurred within 20 km of *conventionally detected* boundaries using platforms such as surface observations, satellite imagery, and WSR-88D imagery

(Markowski et al., 1998c). This suggests that the operational forecaster can *infer* the existence of enhanced SRH near conventionally detected mesoscale boundaries.

2.3 Development of a Relatively Warm and Moist RFD

Operationally, radar identified hook echoes and velocity structures on WSR-88D and Dual Doppler analyses have provided little observational assistance in discriminating tornadic from non-tornadic supercells. In fact, VORTEX mobile mesonet observations indicate that most mesocyclones actually exist all the way to the ground regardless of whether or not a tornado forms.

On a more encouraging note, recent research and simulations have shown that tornadoes are largely comprised of air parcels that have passed through the RFD. Results from VORTEX did show that most significant tornadoes had relatively warm and moist RFDs, while non-tornadic storms had RFDs that were relatively cold (low θ_v) as measured by the mobile mesonet. This relationship was shown to only have a .2% chance of occurring randomly. Therefore, it can be reasonably concluded that tornadogenesis and longevity requires an RFD that is relatively buoyant.

It is important to note that no differences were found between tornadic and weakly tornadic (F0-F1 lasting less than 5 minutes) supercells even with a dense mobile mesonet. It appears that even though these weak tornadoes account for 68% of all reported tornadoes (Grazulis, 1993), their detection is not possible using current technology. Fortunately, only 1% of all tornado deaths are caused by weak tornadoes (F0-F1).

While mesonets dense enough to measure θ_v in RFDs do no exist operationally, RFD buoyancy might be at least partially *inferred* based on conventional observations of surface-based dewpoint depressions. Observed dewpoint depressions in the storm inflow region during VORTEX showed a statistically significant relationship to mobile mesonet measured θ_v in RFDs. As dewpoint depressions in the inflow increased, RFD θ_v tended to decrease, and this seemed to be associated with a decreased likelihood for tornado genesis. Of course, in areas where mean boundary layer convective inhibition (MLCIN) is large and dewpoint depressions are low (on the cold side of a boundary) sustained, surface-based upright convection and in turn tornadoes are very unlikely. It appears then that the dewpoint depression in the inflow seems to hold some promise for determining the buoyancy of the RFD *in a probabilistic sense*.

It is important to stress that the simultaneous occurrence of all 3 ingredients; a persistent, rotating updraft; enhanced storm-relative helicity; and a relatively warm and moist RFD is a very rare event. Erik Rasmussen has referred to tornadoes in many cases as "mesoscale accidents", and Paul Markowski has stated that it is not possible to forecast significant tornadoes deterministically. (Verbal Communication). Rotating updrafts can be observed, but enhanced SRH and buoyancy of the RFD can only be partially inferred through observations of mesoscale boundaries and dewpoint depressions.

3. AWIPS APPLICATIONS

The Advanced Weather Interactive Processing System (AWIPS) provides operational NWS forecasters with an integrated display system to concurrently analyze meteorological data including numerical model output, WSR-88D data, satellite imagery, and observations of the near-storm environment. Using these tools, the forecaster can examine the likelihood of occurrence of the 3 tornado ingredients, then in turn establish a qualitative probability of significant tornadoes.

3.1 Forecast and Detection of a Persistent, Rotating Updraft

Convective available potential energy (CAPE) averaged over the lowest 100mb (mean layer) is commonly used operationally as a measure of boundary layer instability. MLCAPE, along with the strength of the convective cloud layer wind shear, are tools a forecaster can use to estimate the potential intensity of convective updrafts. Numerical model forecasts of MLCAPE are available on AWIPS every 3 hours for the Eta Model out to 60 hours, and every hour for the RUC2 Model out to 12 hours. MLCAPE can also be calculated from observed and modified rawinsonde soundings.

Observations of CAPE on a regional scale based on GOES satellite soundings in cloud-free areas are available. On the state scale, the Local Analysis and Prediction System (LAPS) from the Forecast Systems Laboratory gives hourly graphics of CAPE and CIN. The LAPS products are based on satellite data, ground-based observations, profilers, WSR-88D data, and numerical model initialized fields.

Deep layer vertical wind shear > 35 knots within the convective cloud depth is often used to discriminate supercells from other convective modes. It has been noted in several recent studies that the discrete supercell environment is maximized when the deep layer shear vector is at an angle around 45 degrees with respect to the forcing mechanism. Deep layer shear calculations are readily available to NWS forecasters from the Eta and RUC2 models, as well as through soundings, profilers and 88D VAD wind profiles.

Forecasts of storm-relative helicity are commonly used by operational forecasters to determine the potential for persistent low-level rotation in convective updrafts. The Eta Model yields graphics on AWIPS of 0-3 km storm-relative helicity every 3 hours out to 60 hours.. The helicity is calculated based on the Bunkers method (Bunkers et al. 2000). It is important to emphasize that this should be viewed as a background value. As stated before, it is rare that SRH will be sufficient (>300 m^2s^{-2}) over a wide area to generate significant tornadoes. Usually some type of local enhancement of SRH is needed.

Observed background SRH is available hourly on AWIPS via LAPS, however LAPS predicted storm motion is typically 20 degrees or more to the left of storm motion calculated by the Bunkers method. This commonly leads to an underestimation of LAPS SRH as compared to SRH produced by the ETA.

3.2 Inferring Enhanced SRH

As stated in section 2.2, enhanced SRH can be *inferred* from observations of mesoscale boundaries. Outflow boundaries can often be detected as thin lines on the WSR-88D 0.5 degree reflectivity product; cumulus lines on visible satellite imagery; and surface temperature, dewpoint, and wind discontinuities on LAPS graphics. Spin-down time for enhanced SRH on an outflow-induced baroclinic boundary will vary according to stability, but for typical boundary layer atmospheric viscosities, enhanced SRH can exist for several hours after the thermal gradient has dissipated.

3.3 Inferring the Presence of a Relatively Warm and Moist RFD

VORTEX results have shown that the relative buoyancy of the RFD is an important ingredient for the genesis of significant tornadoes. Data from the VORTEX mobile mesonet was used to establish a statistically significant relationship between RFD θ_v and conventionally measured surface dewpoint depressions. It follows that conventional observations of dewpoint depression might allow the operational forecaster to infer RFD buoyancy and that forecasts of RFD buoyancy might be inferred through numerical model predictions of dewpoint depression. AWIPS allows one to display forecasts of surface dewpoint depression every 3 hours.

Hourly observations of dewpoint depression in AWIPS are available through the MAPS Surface Analysis System (MSAS). The MSAS analysis combines the previous analysis as a first guess with current surface observations including ASOS, any mesonets (through LDAD, a local ingest into AWIPS), and profilers. In data sparse areas, the Eta Model forecast dewpoint depression is used as a first guess.

Unfortunately, the inference of a low LCL height as related by surface dewpoint depressions is not necessarily indicative of low LFC heights (Davies 2004). In addition to noting observed and forecast mean boundary layer convective inhibition (MLCIN), recent studies (Davies 2002) have shown that 0-3km (low level) CAPE > 150 J/kg can be integrated with the above inferences to determine the potential buoyancy of RFD parcels.

4. CASE STUDIES

4.1 May 4, 2003

May 4th was largely predicted to be a major tornado outbreak several days in advance, and the re-analysis of this case certainly justifies that belief in every capacity. The synoptic setup was characterized by an unseasonably strong Plains cyclone situated underneath a deep negative tilt trough and an unusually strong upper jet streak. The airmass over the Missouri Ozarks during the morning on May 4th was very moist and well within the cold sector, with elevated precipitation, drizzle and fog occurring. A strong warm front mixed slowly northeastward during the day, allowing a very warm and humid maritime tropical airmass with strong surface heating to spread northeast while a non-capping elevated mixed layer advected east from the High Plains. Explosive thunderstorm development occurred during the afternoon hours along a pre-frontal surface trough that developed just ahead of the dryline. The background storm relative helicity on May 4th is shown to be more than sufficient on the meso-beta scale for significant tornado potential, even though several boundaries were present as well. Instability and shear parameters are also shown to be more than ample for discrete supercells.

Table 1 is a subjective analysis of the KSGF 18Z sounding, with surface thermodynamics and kinematics modified for the warm sector airmass that was developing over western Missouri and southeast Kansas. It is important to note that our objective to keep the re-analysis as a forecast, so only data available prior to convection are being used. Note that the effective cloud layer shear is used instead of the more typical 0-6km shear to assess the overall shear within the depth of the convective cloud layer (Thompson 2004b).

All three ingredients for significant tornadoes were clearly present over the Missouri Ozarks during the afternoon and early evening of May 4th, with persistent, rotating updrafts aided by strong boundary layer based instability and prolific deep layer shear profiles. Low dewpoint depressions, low LFC heights and a pronounced degree of low level CAPE all aided in keeping the RFD positively buoyant, while background low level shear profiles were more than sufficient for strong to violent tornadoes. Several significant tornadoes occurred across the NWS Springfield forecast area, producing a historic swath of devastation and monetary losses.

Table 1 - KSGF Modified Sounding 05/04/2003 18Z

100mb MLCAPE	3200 J/kg
100mb MLCIN	< 10 J/kg
BL-3km CAPE	210 J/kg
Dewpoint Depressions	4-8F
LCL Height	2400 ft.
LFC Height	2400 ft.
0-1km SRH	340 m^2s^{-2}
0-3km SRH	450 m^2s^{-2}
Effective Shear	255 degrees @ 108 kts
Result: Long-tracked F3-F4 tornadoes, very large hail up to baseball size and damaging wind gusts > 80 knots.	

4.2 May 6, 2003

The overall synoptic pattern had changed little by May 6th and with another unseasonably strong upper level trough and surface front approaching, a second significant severe weather outbreak, including strong tornadoes, was again expected over areas similar to May 4th.

Morning satellite observations showed a lack of cloud cover in the cold sector and a weak lower tropospheric inversion, allowing the synoptic scale warm front to advance rapidly northward across the Ozarks as the surface cyclone deepened over eastern Kansas. Discrete supercell thunderstorms were again expected to develop both along a pre-frontal trough as well as along the northwest-southeast oriented warm front.

Re-analysis of this event shows that one key ingredient was missing for significant tornadogenesis, namely the ability for a warm/moist RFD to develop. Almost full insolation in the warm sector allowed temperatures to warm well into the 80s, resulting in dewpoint depressions on the order of 16 to 20F. Table 2 depicts the results of a subjective analysis performed on the 18Z KSGF thermodynamic sounding and hodograph, as modified for surface conditions realized in pre-convective inflow region.

Table 2 - KSGF Modified Sounding 05/06/2003 18Z

100mb MLCAPE	3400 J/kg
100mb MLCIN	30 J/kg
BL-3km CAPE	70 J/kg
Dewpoint Depressions	16-20 F
LCL Height	4700 ft.
LFC Height	5000 ft.
0-1km SRH	70 m^2s^{-2}
0-3km SRH	220 m^2s^{-2}
Effective Shear	260 degrees @ 77 kts
Result Several brief F0-F1 tornadoes causing only minor damage along intersection of gust fronts. Very large hail and damaging wind gusts accompanied the initial supercells over western Missouri and southeast Kansas.	

Discrete supercell thunderstorms developed rapidly along the pre-frontal trough during the afternoon on May 6th, producing very large hail and damaging winds. However, these storms quickly transitioned into multi-cellular convection. It is hypothesized that the dry low level ambient air allowed for cold pool dominance, preventing buoyant RFDs from forming. As these storms quickly advected away from their source region (the pre-frontal trough), any boundary enhanced low level helicity was also removed. It should be noted that several brief, weak tornadoes did develop where deep convection intersected gust fronts from other storms.

A large discrete supercell thunderstorm also developed just north of the retreating warm front over central Missouri, and appeared to have the best potential for significant tornadogenesis. However, surface observations showed that this storm was embedded within the cold air north of the warm front and was elevated above the boundary layer. The RFD associated with this cell was clearly not positively buoyant and strong low level helicity was not being ingested into the elevated updraft. In the case of the latter supercell, the pre-existing warm front was aligned nearly parallel to the deep layer shear vector. This storm quickly evolved into strong bow segment that produced significant wind damage in the NWS St Louis forecast area.

4.3 May 10, 2003

The morning of May 10th again delivered a forecast of explosive supercell development and strong to violent tornadoes over the Missouri Ozarks, capping an incredible week of widespread significant severe weather. During the morning, a northwest-southeast boundary extended from a triple point near Kansas City to just south of St Louis, Missouri. This synoptic scale warm front has been reinforced by a nocturnal severe MCS that had moved across northern Missouri during the early morning hours.

Meanwhile, a strong elevated mixed layer had infiltrated the warm sector airmass present over much of the Missouri Ozarks, and continued to strengthen during the day, with 820mb temperatures of 16-17C noted on the 18Z KSGF sounding, resulting in 120 J/kg of mean boundary layer CIN. The airmass below the capping inversion was moist with steep lapse rates, allowing for widespread strato-cumulus to develop over the warm sector, allowing only weak insolation to occur. Mixing underneath the 820mb inversion also allowed low level flow to veer significant during the day into the south-southwest. The airmass expected to be over the Missouri Ozarks that afternoon, had shifted into northeast Missouri and western Illinois, where strongly backed flow and strong surface heating were occurring in advance of the synoptic scale warm front. The initially stable boundary layer in the wake of the MCS, and much cooler mid level temperatures, actually aided in airmass destabilization in that region as strong surface heating occurred in the absence of cloud cover.

Partial clearing occurred over far southwest Missouri during the early afternoon, aiding in the development of scattered thunderstorms along an advancing cold front. Meanwhile, rapid and explosive initiation was occurring north of the NWS Springfield forecast area along the triple point where strong insolation was occurring. A few reports of minor wind damage were received with the initial storms over southwest Missouri, however large hail up to golf ball size was the primary severe weather threat as these storms moved east.

Re-analysis of this event clearly shows that significant severe convection was unlikely within the NWS Springfield forecast area, especially with respect to tornadic potential. Although CAPE and deep layer shear profiles over the Missouri Ozarks (Table 3) were supportive of supercells, the boundary layer airmass in the warm sector was not positively buoyant and therefore was not ingested into the storm updrafts. As a result, thunderstorms quickly became elevated as they advected away from their source region (cold front), resulting in scattered elevated supercells which produced only large hail.

In this case, low dewpoint depressions and low LCL heights (which were 2400 feet) were misleading without other information, as they merely identified the layer at which at which strato-cumulus readily developed. Satellite imagery and surface observations show that the supercells which moved across southern Missouri were based at around 9000 feet and much more benign appearance than the significant tornado producers over northeast Missouri and western Illinois.

Table 3 - KSGF Modified Sounding 05/10/2003 18Z

100mb MLCAPE	1900 J/kg
100mb MLCIN	120 J/kg
BL-3km CAPE	0 J/kg
Dewpoint Depressions	4-5F
LCL Height	2400 ft.
LFC Height	9000 ft.
0-1km SRH	130 m^2s^{-2}
0-3km SRH	140 m^2s^{-2}
Effective Shear (3-10km)	264 degrees @ 54 kts
Result: Some minor wind damage early, but mainly large hail up to 1.75" with elevated supercells	

5. SUMMARY

Results from VORTEX, together with previous research, have led Paul Markowski and collaborators to hypothesize that 3 key ingredients are necessary for genesis of significant tornadoes (F0-F1 lasting more than 5 minutes and all F2 or greater): a persistent, rotating updraft; enhanced storm-relative helicity; and the development of a relatively warm and moist rear flank downdraft. The WSR-88D is an effective tool for detection of persistent, rotating updrafts, however both enhanced storm-relative helicity and relative buoyancy of the RFD are not observable using current observational systems. Fortunately for operational forecasters, AWIPS makes it possible to infer these quantities through observations of related features. Existence of enhanced storm-relative helicity can be inferred near mesoscale boundaries, and existence of a relatively buoyant RFD can be inferred through observations of low dewpoint depressions, low LFC height and low level CAPE.

While tornado forecasting is still far from deterministic, re-analysis of the May 6, 2003 and May 10, 2003 cases indicates strong signals were present that would have allowed forecasters to make adjustments to pre-storm outlooks, forecasts, possibly warning decisions regarding the potential for significant tornadoes.

6. FUTURE WORK/RECOMMENDATIONS

The AWIPS Warning Event Simulator (WES) is the architecture through which NWS forecasters can re-analyze past events using data archived by AWIPS. The authors of this paper are very much interested in adding several newly constructed parameters developed by the Storm Prediction Center to AWIPS and the WES. The integration of objectively analyzed composite parameters such as effective bulk shear (Thompson, et. al 2004c), the Supercell Composite Index (SCI) and the Significant Tornado Parameter (STP) may allow operational meteorologists even greater confidence in discriminating those event where significant tornadogenesis is more likely to occur (Thompson, et. al 2004a).

It can be reasonably concluded that accurate assessment of near-storm environment is heavily weighted by the availability of near real-time observations on the meso-beta scale. The sparse data network over the NWS Springfield, MO forecast areas continues to be a significant hindrance to our research and ultimately, real-time operational use of our findings. Presently, only five automated ASOS/AWOS stations and one part time military site cover the Missouri Ozarks and extreme southeast Kansas, resulting in many large data void regions in an area of varying terrain and resulting boundary layer thermodynamics. In order to address this deficit and the associated challenges with mesoscale forecasting, a data acquisition project initiated by the author has been underway since early July. With the assistance of Missouri Department of Transportation, local emergency management and local citizens, over a dozen real-time surface observation systems have been added across the area with more on the way. It is encouraged that NWSFOs use available means to improve the spatial and temporal resolution of their observation networks to greatly enhance the real-time analysis and numerical modeling of severe local storms, potentially resulting in much improved warning decisions.

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