Dryline Convective Case Study: May 5th 2003 Severe Storm Outbreak

Abstract

During the spring, thunderstorms develop ahead of a boundary called the dryline. This was the case with the May 4rd, 2003 Outbreak. A vorticity maximum sparked the tornadoes in eastern Kansas ahead of the dryline. One in particular moved over Kansas City, Missouri that was assisted by warm frontal shear

Introduction

Across the continental United States, the dryline is a major initiator of convection. These entities separate moist air flowing from the Gulf of Mexico and desiccated air descending from the high country. The moisture convergence associated with these boundaries can trigger thunderstorms. The setup for the dryline also lends itself to convective instability with lapse rates approaching dry adiabatic (approx. 9.8C/km). The rapid changing of wind vectors with height, called shear, was prolific. These and other necessary conditions came together to spark 85 reports of tornadoes, 109 reports of wind damage, and 295 large hail reports. Damage estimates ranged anywhere from 1.55 to 2.25 billion dollars, making it one of the most costly tornado outbreaks in U.S. history. Some of the most intense convection fired directly along the dryline in Eastern Kansas and Western Missouri. One such cell tore a path across the Kansas City metropolitan area while other cells tracked in rural regions of Kansas and Missouri. This event was well forecasted as meteorologists were able to warn the public about the possibly dangerous scenario that did end up coming to fruition. An outbreak of this magnitude must be studied. The storm's initiation appeared to coincide with the movement of a dry air plume in the vicinity of the dryline. This case study will examine the synoptic and mesoscale elements that were present at the time of the storm. The focus will be to determine the role of this dry air aloft and the warm front and how they could have contributed to this prolific severe thunderstorm outbreak.

Data

Satellite, radar, model initial analysis, soundings, and metar are all utilized throughout the course of this case study. All satellite and radar is viewed through the General Meteorology Package (GEMPAK) or a derived graphical interface called Global Atmospheric Research Programme (GARP). Satellite data was obtained via Department of Commerce's National Oceanic and Atmospheric Administration's (NOAA) Geostationary Operational Environmental Satellite (GOES). Visible imagery was viewed at 0.65 microns and the water vapor imagery is viewed at 10.7 microns. All radar reflectivity came from the National Weather Service's (NWS) Weather Surveillance Radar-1988 Doppler. The eta model gridded data for the initialized time 12z on the 4rd and 00z on the 5th was employed for the vorticity analysis, streamlines, cross sections, as well as mixing ratio. NOAA through the Storm's Prediction Center provided storm data and cost estimates. The Meteorological Aerodrome Reports were accessed through GARP.

Synoptic Overview: 12z

The synoptic backdrop for this meso-beta/alpha scale event begins to take shape in the 12z analysis on the morning of May 4th, 2003. A high amplitude regime at 300mb is in place over the continental U.S. A strong negatively tilted trough is located over the Pacific Northwest, from north of Vancouver Island to northern Nevada. This trough was associated with a 60 m/s jet streak on the west side. By 12z, the left entrance region of the jet, an area of

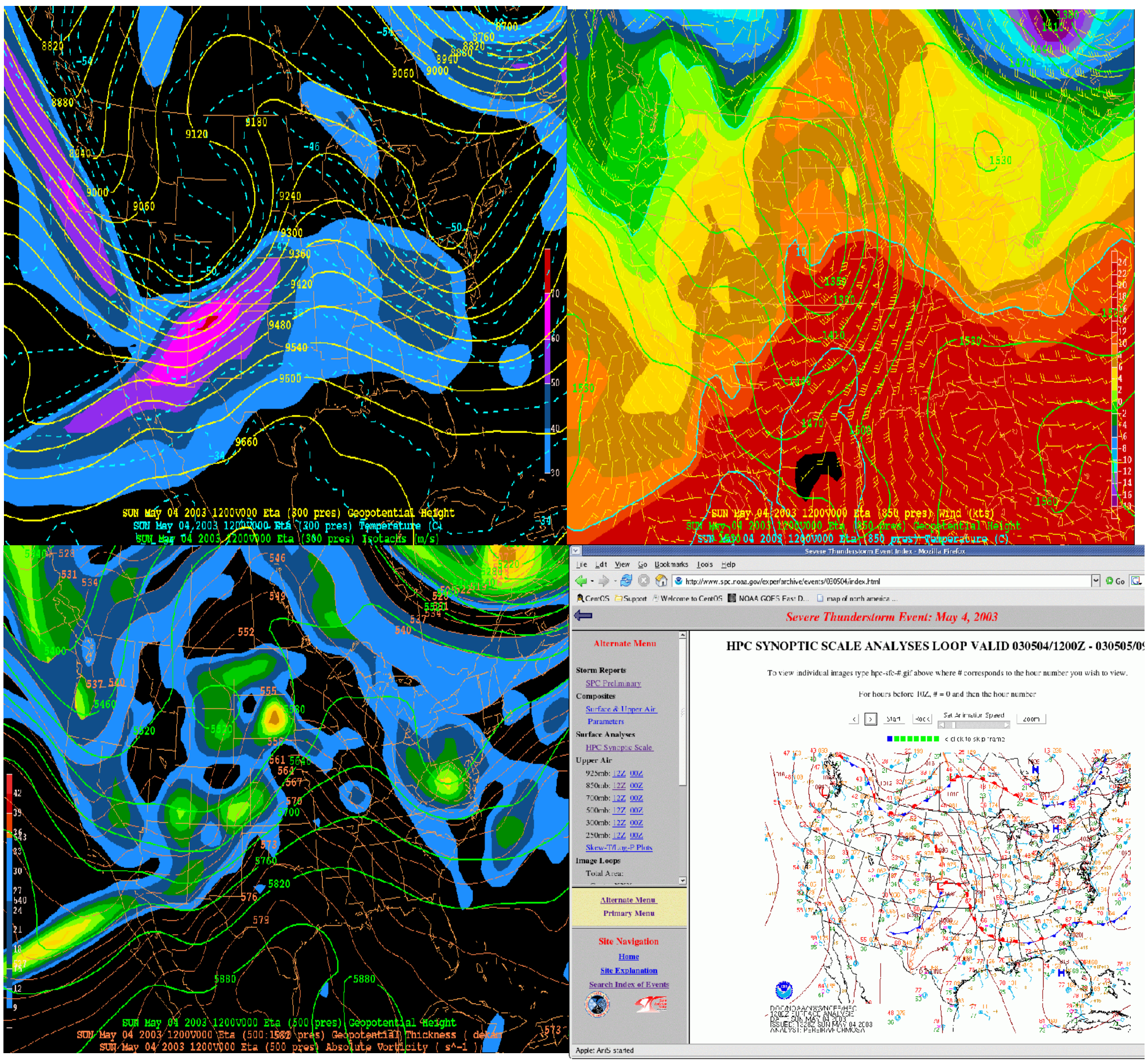


Figure 1. 4 Panel Plot of 300mb heights and winds; 500mb vorticity, heights, 1000-500mb thickness; 850 temperatures, heights, and winds; surface obs w/front

amplitude regime at 300mb is in place over the continental U.S. A strong negatively tilted trough is located over the Pacific Northwest, from north of Vancouver Island to northern Nevada. This trough was associated with a 60 m/s jet streak on the west side. By 12z, the left entrance region of the jet, an area of ageostrophic divergence and vertical motion, has moved south of the bottom of the trough. As a consequence, the trough will not deepen and not become a major factor in this system. A broader and older open low pressure was dominating the rest of the western half of the country. A slightly stronger jet bounds the southern extent of the trough which stretches from off the Baja coast to central Kansas. Maximum winds of 70 m/s from the southwest are present in the core of this storm. Ageostrophic motions are enhanced over the 4-corner region as the along flow accelerations increase with the packing of isotachs. The north side of this jet is also coincident with a reduction in middle and upper tropospheric moisture and an increase in potential vorticity(PV). The potential vorticity is a reflection of the vorticity created on the north side of the jet, where cyclonic shear prevails. This is reflected in water vapor imagery as brightnesses decrease to 128. As PV surfaces are deformed closer to the surface, stratospheric air is pulled down to lower pressure levels. Stratospheric air is very dry and therefore can be seen in water vapor sensitive as smaller brightnesses.

The 6.7 micron water vapor channel imagery can now be used to trace in real time the strength and placement of the PV anomaly. The warm air advection in the core lends itself to rising motion. This jet streak and the circulations will be an important feature as the day continues. In conjunction with the negatively tilted trough is a negatively tilted ridge arcing from Saskatchewan to the central Mississippi River valley.

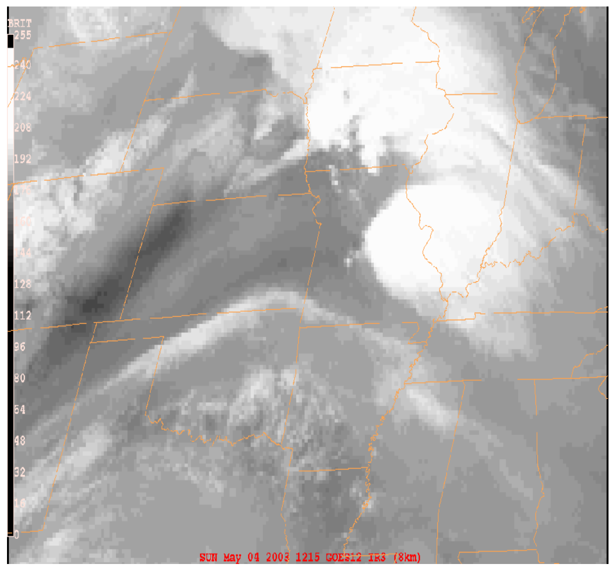


Figure 2. Water Vapor imagery for 1215z on May 4th 2003 over Kansas

500mb contains many similarities as 300mb at the continental scale with the broad trough across the intermountain west and ridging over the central states. Southwesterly flow maxing at 30m/s prevails in most of Nebraska, Kansas, and Oklahoma at 12z. There is also a distinct temperature gradient from the Kansas/Missouri border to Kansas/Colorado/Nebraska triple point. Temperatures fall from -12C to -18C down the gradient. The southwesterly flow is providing for warm air advection in central Kansas. This not conducive to the development of thunderstorms because this will lessen the mid level lapse rate and thus decrease the stability.

The absolute vorticity depicts several regions of a higher vorticity contained within the height depression at 500mb: one in eastern South Dakota, another in southeastern Utah, and a third centered to the east of Pueblo, Colorado. The last vorticity maximum mentioned at the 500mb is the representation of the 300mb anomaly seen in the previous paragraph. The development of the vorticity maximum will be crucial to the development of the thunderstorms along the dryline. When the thickness lines are superimposed on the thickness, it is clear that the thermal wind vector is parallel to the vorticity gradient vector. Such a setup is one of the main forcings of upward vertical motion in the lower troposphere. With the rising motion the pressure should drop through the column ahead of the vorticity maximum. Since vorticity is directly related to the Laplacian of the pressure, the vorticity at this level should increase. Without this orientation of thermal wind and vorticity gradient, the vorticity feature will be forever linked to the jet streak and can never be distinct feature. There is only one serious jet streak at this level that plays a role in the severe weather outbreak. At 12z is largely over northern Mexico with a maximum speed of 45 m/s just south of the Arizona border.

At 850mb on May 4th 12z, features and perturbations represent the surface more than their upper level counterparts. A closed contoured height minimum of 1350m (standard height of 850mb level) existed over 12z western South Dakota and Nebraska with a trailing weak trough into the *Occidental Collidera*. There are two distinct circulations center: one over northeastern Colorado and the other over southern Montana regions of The low pressure minimum lies within a larger scale Rossby wave with a wavelength from the Pacific Coast to the Mississippi river. Westerly ageostrophic flow down the height gradient predominates west of the trough with southwesterly to southerly flow ahead of the trough. A distinct thermal ridge has appeared over the southern plains with the 15 degree isotherm to Kansas/Nebraska border. Outside of this thermal wave, there is very little in the way of thermal contrast across the U.S. The aforementioned southerly winds are transporting southerly warm air northward. In addition to the warm air, it also becomes laden with moisture. Specific humidity values soar to 12 g/kg in a thin axis in the center of the thermal ridge from the Kansas/Nebraska border to off the coast of Mexico in the gulf. Even high dewpoint reside in Central Texas. Streamline analysis for 12z shows an effective flow along that same axis. This warm and moist air advection regime is conducive to vertical motion as parcels slide along isentropes. The high moisture content allows for quick saturation and thus cloud cover and precipitation develops in this regime. The height trough in Western Kansas is coincident with the back edge of the moisture (4 g/kg isodrosotherm). Also of note, a notch in the moisture field is becoming evident over southwestern Kansas.

At the surface, the pattern is quite

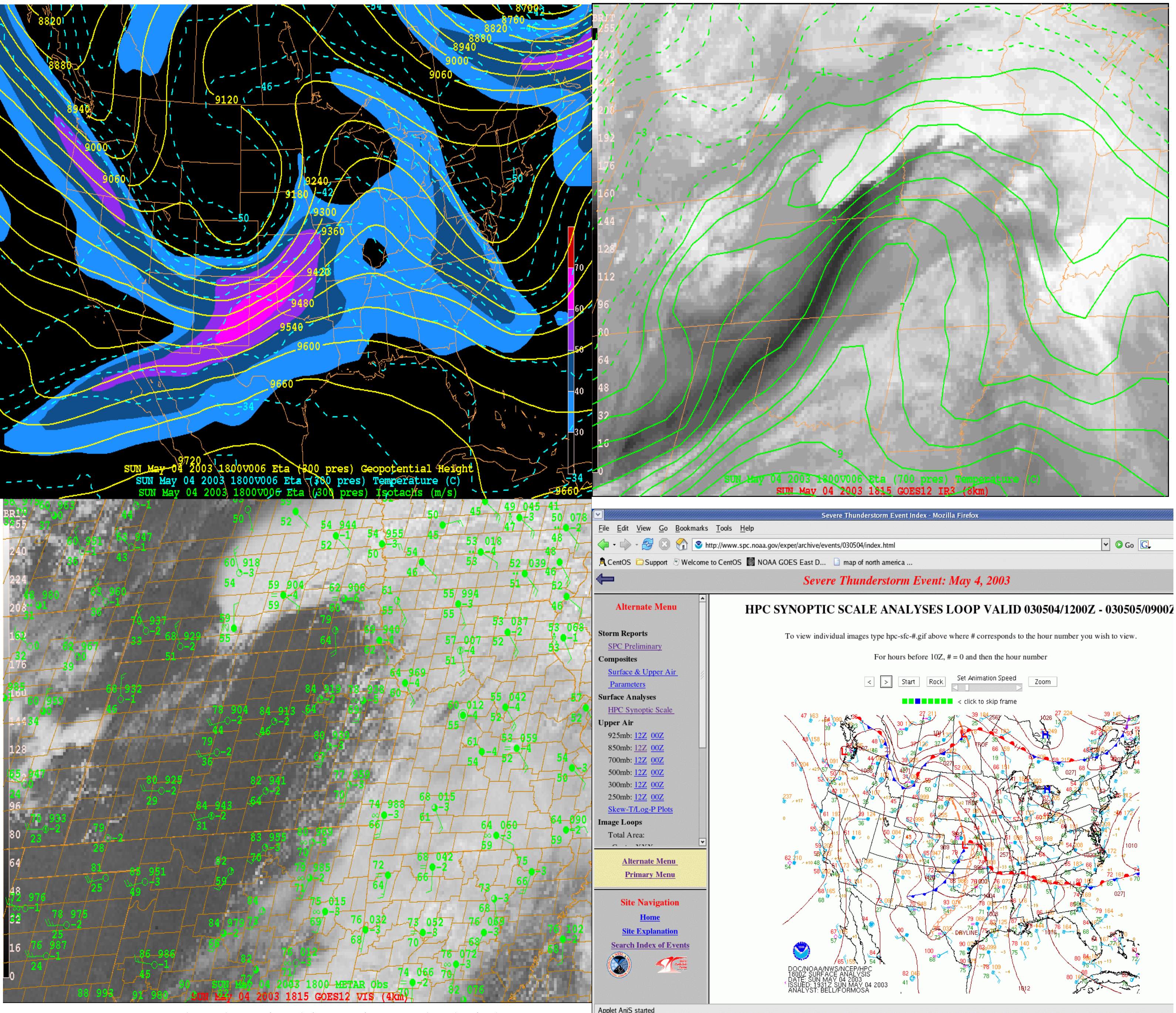


Figure 3. 4 Panel Plot for valid 1800z

similar to the 850mb level. The low centers pressures have migrated a little further east of their positions at 850mb. The trough has moved to west by about 50-100 km and it is directly aligned with surface dryline. HPC synoptic surface map displayed a cold front instead of dryline along the moisture discontinuity. This is certainly accurate based on thermal contrast at the time. The cold front slopes back toward Colorado with height while the moisture interface slopes eastward with height. The dry air behind the "cold front" could not cool because the moisture in the moist sector prevents the surface from radiating while the dry sector can radiate freely. A radiational boundary of this nature would explain the visible thermal contrast Temperatures at 12z were still holding around 20C in much Kansas, Oklahoma, and Nebraska. The previous night's temperatures had been elevated due in fact to the warm air advection aloft had sparked clouds and precipitation. This in turn prevents the solar radiation from escaping in the upper atmosphere. The clouds that are locking in the previous day's radiation could prevent the current day's solar insolation from warming it to maximum instability. This is an operational forecasting nightmare and can put the breaks on any Day 2 moderate or high risk region. Until the spatial distribution of cloud cover is known, forecasting convective weather can be a shot in the dark

18z

The core of the strong winds at 300mb has moved to the panhandle regions of Texas and Oklahoma and decrease in speed by 5 m/s. The negatively tilted trough has spun counterclockwise around the center of rotation, moving the trough to the north. Any advection patterns associated with the jet have melted back into the barotropic background state of 300mb. The flow over Kansas is still largely from southwest

The vorticity maximum at 500mb has strengthened significantly in the model data as predicted by the positive vorticity advection by the thermal wind. The water vapor imagery confirms this strengthening as brightnesses within the anomaly continue to fall. In the water vapor, the vorticity anomaly is slightly further to the east of the model data. While the difference is small, it is crucial to development of the storms. The combination of 700mb temperatures and water vapor at 1800z shows PVA by the thermal wind. Not surprisingly, the convection erupts shortly thereafter. The PVA is strongest in northern Kansas and Nebraska weaker to the south in southern Kansas, which indicates that the storm should pop first the north and begin to unzip down a boundary.

Because the vorticity and pressure are directly related by a laplacian, and 500mb is largely barotropic, an increase in vorticity could lead to lowering temperatures at 500mb.

Temperatures in fact did fall across Kansas fell by 2 degrees over the course of 6 hours (12z-18z). This cooling is not due to advective processes because of the warm air advection observed at 12z. As was previously stated, this will steepen the lapse rate and add to the instability.

By 18z, the dryline and the cold front have separated with the dryline between Junction City and Salinas, Kansas and the cold front near Hayes, Kansas. The warm front did not make much progress as it became reinforced by the radiational heating boundary between the thick overcast and broken cloud cover. Clouds had begun to erode 15z and clear skies prevailed south and west of a line from Topeka to Joplin at 18z. Temperatures in the moist sector have crawled to the lower 80's. Moisture transport along the streamlines and evapotranspiration from crops had raised the dewpoint to the upper 60's and lower 70's in eastern Kansas.

Mesoscale Analysis

Individual severe thunderstorms, including supercells, have very small horizontal scale (10-20km) compared to the mid-latitude cyclones (2000km). Also these convective entities have large vertical scales (10km). This implies that vertical stability dominates the dynamics rather than coriolis-enforced accelerations. Also the other key to convection is the amount of shear in the atmosphere. Shear controls if and how the updraft the downdraft organizes and develops. It is this balance between these two qualities that determine the nature of convection. The sounding and the hodographs are the embodiment of these qualities.

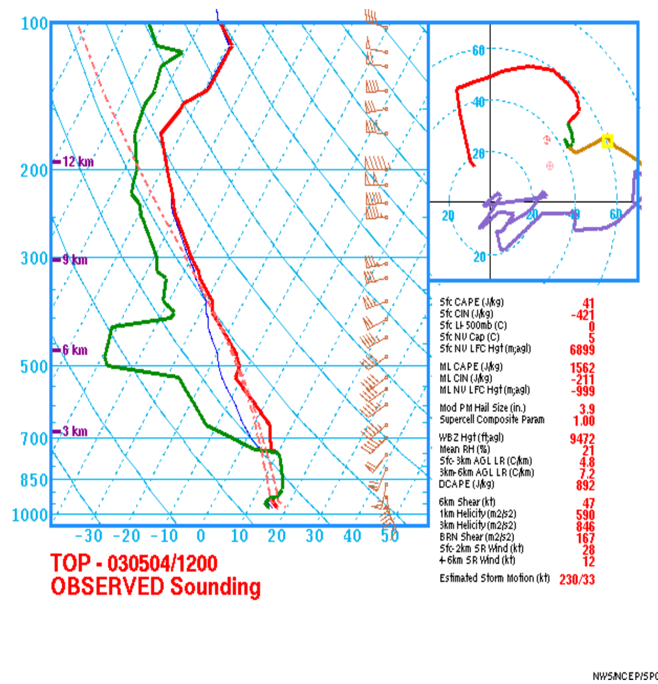


Figure 4. Sounding and Hodograph for Topeka, Kansas valid for 12z on May 4th, 2003

At 12z, the Topeka sounding gives a pre-storm environment and an idea of how the environment must modify in order to convect and sustain supercells. Topeka is close to the warm front at 12z so it is to be expected that gulf moisture and warmth is overriding cooler drier air. The sounding confirms this with the presence of a very strong inversion 70mb above the surface. The environment is saturated from the inversion to approximately 735mb. Prior to 12z, a large amount of elevated convection is on going which pumping moisture into the lowest 2 km. Rich theta-e advection which is probably sparking the convection is also adding moisture to column. Veering winds with height as seen on the sounding is a key indication of warm air advection because of the thermal wind balance

The sounding also shows a wind maximum of 60kts around 850mb. This signals the possibility of a low level jet which is by far the most effect method in moisture transport. Ageostrophic flow up the slope from the Mississippi River valley toward the continental divide is ongoing most of the day. Mixing is also occurring simultaneously as the sun heats the air near surface during the day. At night, as the air near the surface cools faster than the air above it, an inversion forms. The inversion separates the ageostrophic flow from the friction and makes it inertial. Any inertial momentum is turned by the inertial oscillation. By 12z, the inertial oscillation has swung to a south-southwesterly direction and this is approximately the direction of the strongest wind speed. The Richardson number dominates the speed of a low level jet because it defines a ratio that determines convective overturning capability of a fluid: namely the static stability over the shear squared. Empirical data shows that if the Richardson number is greater than .25, then the fluid will not overturn. The static stability is much higher in the presence of a warm front. This leads to greater shear which implies a higher speed at the top of the nocturnal boundary layer. These three mechanisms led to the saturated layer from 900mb to 735mb.

Above this moist layer, is a very dry layer with much steeper lapse rates. Wind vectors from the west and the trajectories off of the New Mexico high country. These two facts define the elevated mixed layer. The interface between this moist and dry region of the column is vertical manifestation of the dryline. The dryline overriding the top of the warm front boundary is trapping the moisture between two theta-e discontinuities. Even at 12z the loaded gun sounding is set, although not for surface based convection. Surface based CAPE and CIN values reflect this with a meager 41 J/kg and a overwhelming -421 J/kg respectively. The mid level CAPE and CIN values are quite impressive, 1562 J/kg and -211 J/kg respectively. Another challenge with a sounding like this is to keep the elevated convective potential from firing before the surface based instabilities form. With CIN over -40 J/kg a large amount of forcing would be required initiate convection. Ahead of the main impulse at 500mb, there are no other synoptic scale features to overcome a cap of this nature.

The hodograph tells the story of the shear. The wind shear again determines the mode of the convection: multicelled and supercelled. Directional and speed shear are both shown on the Hodograph. The ideal hodograph for supercellular tornadoes has a right turning semi-circular shape until 600mb that takes on more straightline shape with the higher altitude. The semi-circular portion of the signature represents the clockwise turning of the wind vectors with height called veering. The updraft of a thunderstorm bends a portion of the horizontal vorticity vector into a vertical vector. This creates a cyclonic circulation that manifests itself as the mesocyclone. The rotation of the storm then makes the thunderstorm inertially stable with respect to rotation. Such stability acts wall off the inflow from lower theta-e air often present at mid levels. This maintains high moisture content within the cloud and eliminates downward motion initiated by saturation of the dry air at mid levels. The 12z Topeka hodograph is an excellent example of a good low level shear profile for supercells. The lowest kilometer shear is incredible. Winds veer from SSE to SW in the lowest kilometer. Helicity values exceed 500 m^2/s^2 in this hodograph. Standard helicity values consistent with tornadic thunderstorms are 100m^2/s^2. The directional shear above that is minimal as winds become unidirectional. The changing of speed with height is the other component of shear. This tilts the storm updraft preventing the storm from precipitating within the updraft thus choking the storm. 47 kt speed shear between the surface and 6 km is more than adequate to maintain the storm circulation.

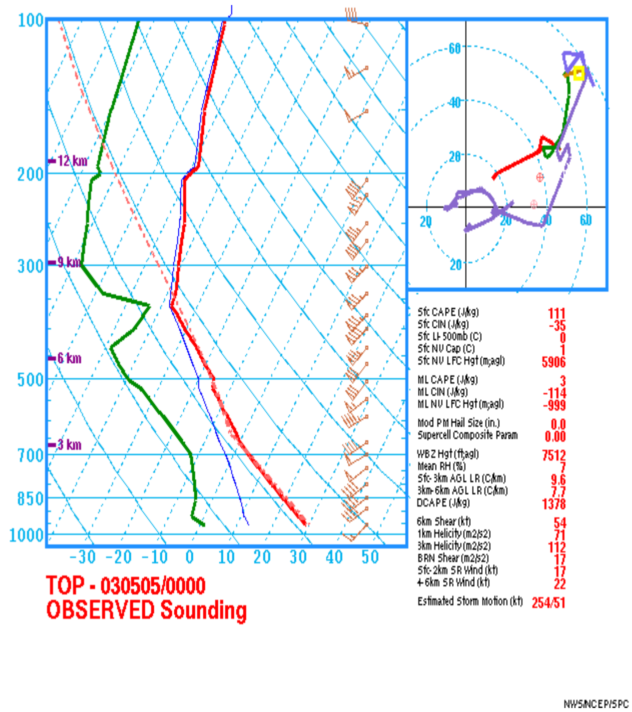
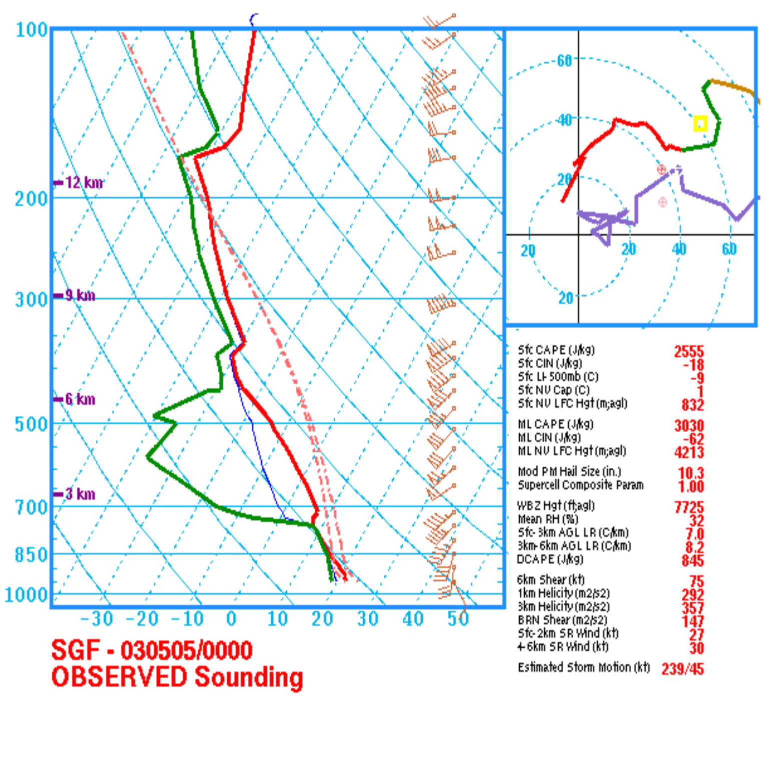


Figure 5. Sounding and Hodograph from Topeka, Kansas valid at 00z on May 5th, 2003

18z sounding and hodograph data from May 4th, 2003 were not made available to us therefore concluding the nature of the atmosphere at the time of initiation require some speculation. The increase in surface temperatures and dewpoint clearly destabilized the atmosphere by 18z. If the 12z sounding is adjusted to the temperature and dewpoint observed at Topeka at 18z, the sounding clearly becomes much conducive at the low levels to convection. It is also clear that the saturated layer at 12z has thoroughly dissipated because of the lack of cloud cover. Mixing process due to the fast winds aloft probably dried out the atmosphere about the boundary layer. It is possible to get an idea of the thermodynamic profile above the surface by considering a sounding that lies slightly to west of the dryline. Such an opportunity is afforded as 00z sounding from Topeka is taken with an hour of the dryline passage. A well mixed layer can be seen extending up to the 500mb level. The steep lapse rates continue all the way to 400mb. Such an airmass advected over the top of a moist one is very unstable indeed. The moisture in the boundary layer must be rather significant because as soon as the clouds, cumulus form within a couple hours of the clearing out. Dry air also accompanies the steep lapse rates throughout the depth of the atmosphere. This dry airmass will be fed into the precipitation



shafts of the storms that do form. As the precipitation is fed dry air it will cool

and descend, enhancing the forward and rear flanking downdraft. The Springfield, Missouri 00z sounding contains the combination of these two airmass, but this sounding is not a fair evaluator the thermodynamic profile of the atmosphere over eastern Kansas because of its proximity to the warm front and its long distance from the surface dryline.

The hodograph is much less impressive at 00z than it is at 18z at Topeka. The curvature and veering with height is loss and replaced with a more chaotic hodograph. It begins first as a straight line hodograph that slowly backs in the counterclockwise direction. This would produce negative helicity and would inhibit supercell growth. The mixed layer implies a low static stability and low Richardson numbers. This means that vertical speed shear decreases which also is not helpful in the formation of supercells. Just as the sounding data, Springfield hodograph has the same beautiful signatures witnessed from the Topeka 12z, but the distance away from action is a detriment to using it as a valid claim for moist-sector shear. The Springfield Hodograph will act as a sample of the shear on the cool side of the warm front

The Storms

The initial line of storms erupted at 1828z in northern Kansas. They are slightly ahead from the initial dryline itself which means that it most likely developed in the PVA ascent region. The thunderstorms develop very rapidly and within an hour of storm development, some of them become supercellular. They have formed along a curved meridional line but the individual storms seem to form at an oblique angle to the meridional line. Other the storms try to form ahead of this axis with little success outside of the PVA dependent synoptic ascent region to the north.

By 1950z, there are 4 main cells that have just begun to cross the Missouri River in Missouri. The warm front is still being held up by the cool easterly flow from the Canadian High pressure and the lack of strong insolation from daytime heating. The warm front is lying directly over Kansas City metropolitan area. The intense shear profiles from Springfield at 00z and Topeka at 12z are associated with warm front are the same that are present over Kansas City. As the middle storm tracks across this boundary, the storm will use the helicity provided by the front to enhance the circulation with this storm. Once it hits the boundary, it becomes a right mover. This is a big indication of intensification as the updraft is able to gather more rotation from the ambient atmosphere. Vertically Integrated Liquid explodes during the same frame, from 50 kg/m^2 to 70 kg/m^2 over a 20 minute interval. The hook echo region becomes very pronounced at 2124z. The storm is becoming a mature supercell with distinct precipitation free updraft and inflow area. While the storm surely has complex inflow system which involves pulling from a source of high instability air, the shear is probably driving the thunderstorms. The thermodynamics are no longer as impressive over that region. The convective Richardson number which was a higher probably favored CAPE number in the moist sector shifted over to a lower a more sheared environment number. By the time the storm has exited the greater Kansas City metro area, it has left a path of F4 destruction, interstates backed up for miles, and a few fatalities.

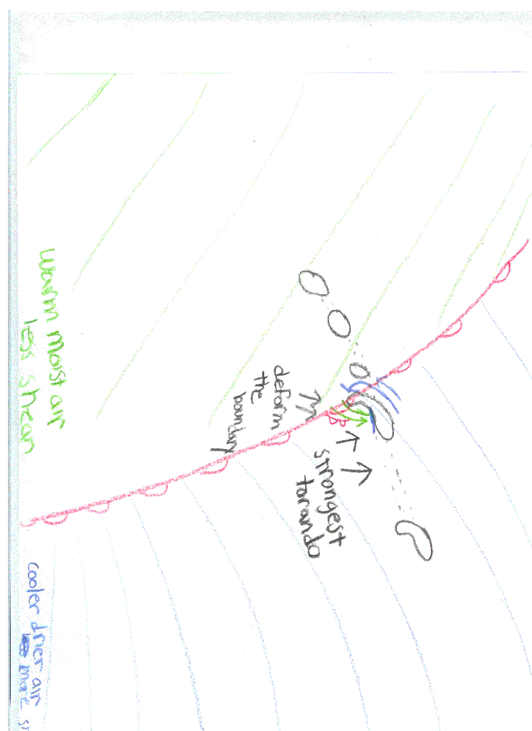


Figure 6. A Conceptual Model of the Kansas City, MO Tornado

More storms form as the dryline continues marching eastward. The more southern storms have now begun to fill in by 2030z. Again the storms are forming ahead of the actual boundary. Although the forcing is weaker the south, the instability is a little bit greater. They did not form immediately with first band the daytime heating had to do more work to overcome the cap. The southern portion of the vorticity maximum increases with time and therefore PVA should increase as the other factors stay constant.

Conclusions and Remarks

It is clear that the vorticity maximum from Colorado plains forced the initial severe weather in Kansas. This cyclone went on the produce a lot more severe weather than what is displayed. While the majority of the storm developed ahead of the dryline, the thermodynamic setup involved in forming the dryline was crucial in providing the instability needed for the storms to develop. Strong shear supported supercellular organization of the storms that did develop. The Kansas City storm that produced the tornado formed in moist sector and crossed the warm frontal boundary into a very high shear environment. The storm fed off of the shear and subsequently produced several tornadoes.

This phenomenon of storms crossing synoptic thermal boundaries should be investigated further. The other side of the warm front was rather cool and should have cut the storm off, but it continued for another 2 hours and 70 miles. Temperatures were only in the middle to upper 60’s with dewpoints in the lower 50’s. These are not ideal conditions. One question to ask is if the storm remains supercellular but becomes more elevated as surface inflow becomes a problem? If this not the case, then a model should be proposed to explain what the inflow field is in order maintain a surface based supercell. Does the supercell have a dynamic flywheel that can maintain the storm as it moves into more stable regions? One last question is whether not these events are common and what is frequency and outcome of other similar events?

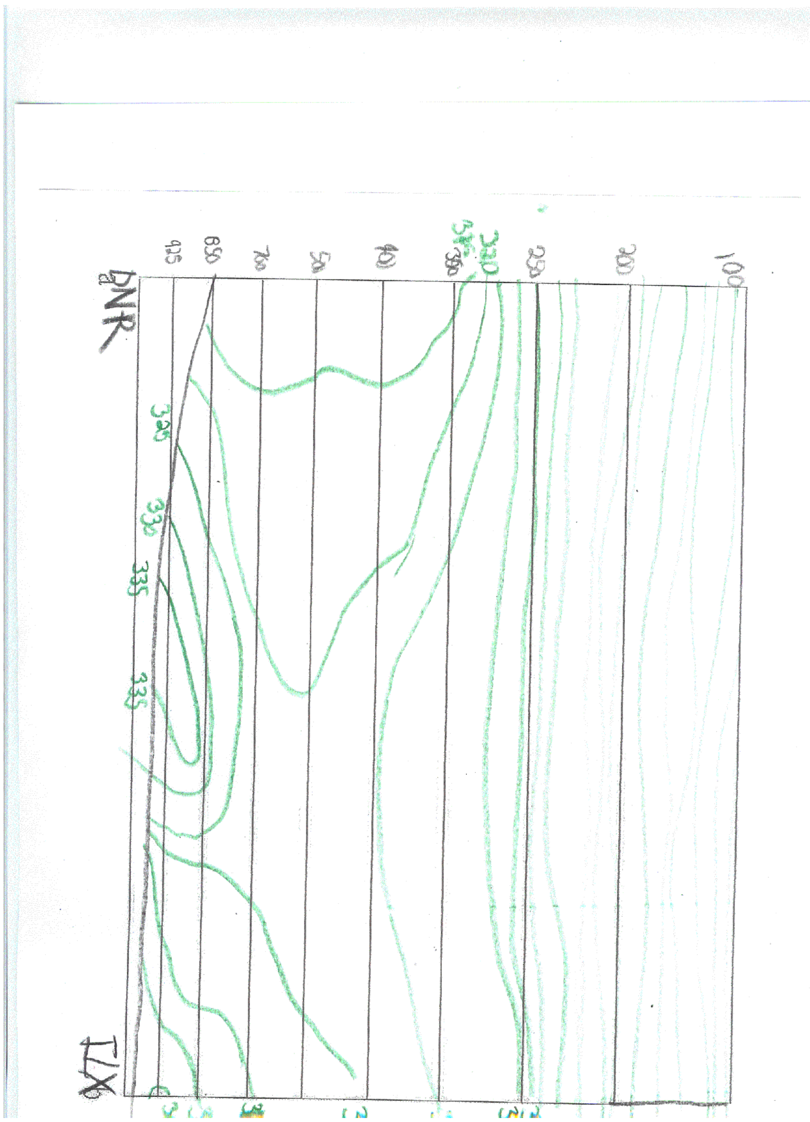


Figure 7. A Cross section of Theta E from 12z May 4th 2003 (DNR to ILX)

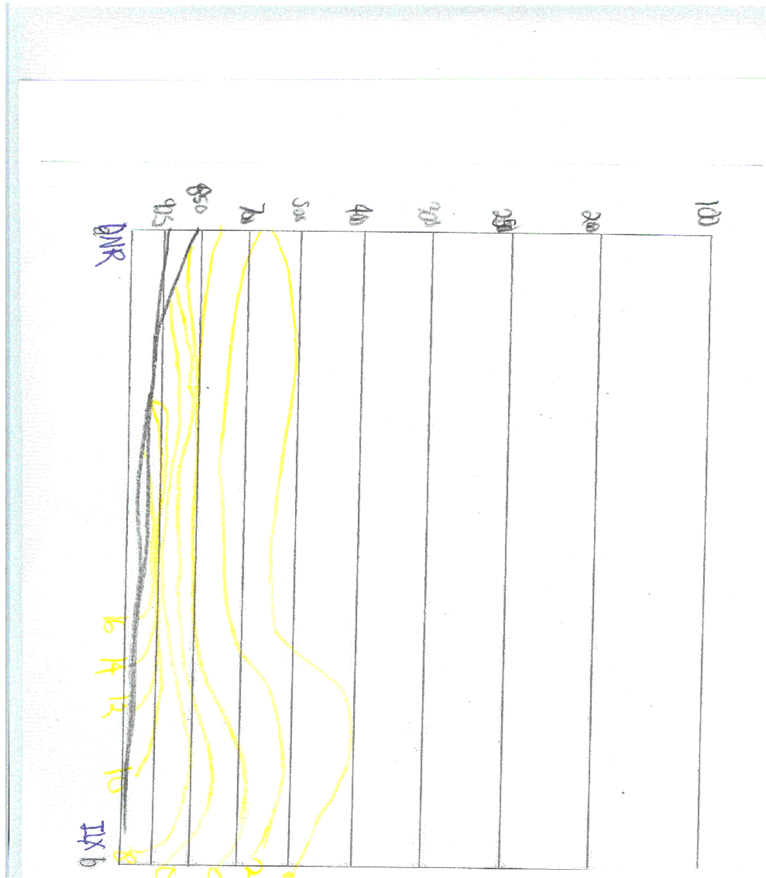


Figure 8. Mixing ratio over the same interval on the same day