DOES PRECIPITATION FALL PREFERENTIALLY OVER DRY (OR WET) SOILS?

An Undergraduate Research Scholars Thesis

by

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ABSTRACT

Does rain fall preferentially over dry (or wet) soils? (May 2014)

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Previous work suggests precipitation is more likely to fall over dry soils than wet soils. The limited knowledge of the association between surface moisture content and convective activity raises many questions about whether a positive (or negative) feedback exists. A positive feedback implies higher soil moisture values correspond with enhanced precipitation. While soil moisture does not directly influence precipitation, it does moderate latent and sensible heat fluxes, which may lead to influencing convective initiation. In this study we analyze synoptically benign (SB) environments that do not feature a low-level jet (noLLJ). Because these atmospheric conditions are expected to be much less conducive to convection and precipitation, we can better understand the possible impacts of soil moisture. This case study approach will focus on convective events that are characterized as localized convective precipitation as opposed to stratiform precipitation caused by large-scale frontal systems. Convective initiation was found to occur over relatively dry soils largely influenced by sensible and latent heating and consequently increasing atmospheric instability leading to convection.

ACKNOWLEDGEMENTS

I would like to thank my research advisor Dr. Steven Quiring for his continuous support throughout this project and for the past 2 years. I would not be the researcher I am today without his continued support and encouragement.

I would also like to acknowledge and thank current Ph.D. student, Trent Ford, for all his assistance during this project.

CHAPTER I

INTRODUCTION

Importance of soil moisture

Soil moisture plays a large role in the climate system. It controls the partitioning of moisture and energy fluxes and influences the relationship between the land surface and atmosphere (Entin *et al*., 2000; Legates *et al*., 2010). Studies have evaluated soil moisture characteristics using land surface models and climate models to investigate soil moisture feedbacks and land-atmosphere interactions (Giorgi *et al*., 1996; Mostovoy and Anantharaj, 2008). Unfortunately, these models have limitations, including errors in the forcing of data (Koster *et al*., 2004). Observed soil moisture data can improve regional and global climate models by adding robustness and validating soil moisture characteristics (Pal 1997; Delworth and Manabe 1988; Li e *et al*., 2005; Wu and Kinter, 2009). Data sets of observed soil moisture measurements, therefore, are beneficial for investigating soil moisture variability over various length scales.

Soil moisture is persistent (i.e. soil moisture memory) (Delworth and Manabe 1988, 1993; Robock *et al*., 2000; Mostovoy and Anantharaj, 2008). The degree of persistence varies by region, but has been shown to range from 1-3 months in the central United States. Soil moisture persistence affects long-term atmospheric conditions over land and influences the climate on monthly to seasonal timescales (Liu, 2003; Karl, 1986; Wang and Kumar, 1998). Anomalously low soil moisture may lead to a reduction in localized precipitation due to lack of moisture available to evaporate in comparison with anomalously high or normal soil moisture (Dirmeyer *et al*., 2000). It is still, however, unclear under what conditions land-atmosphere interactions create a negative or positive feedback between soil moisture and precipitation. It is crucial to study these interactions to gain a better understanding of the role of land surface conditions on the hydrologic cycle.

Multiple studies have explored the feedbacks between soil moisture and convective initiation (e.g., Carleton *et al*., 2008; Alfieri *et al*., 2008; Allard and Carleton, 2010; Brimelow *et al*., 2011). In fact, many authors have found opposing results on the existence of a positive feedback (Findell and Eltahur, 1997), negative feedback (e.g. Cook *et al.,* 2006), or have found no evidence of any feedback (Salvucci *et al*., 2002) between soil moisture conditions and subsequent precipitation. Ek and Holtslag (2004) examined the influence of surface heat fluxes on the planetary boundary layer (PBL) convective cloud development: higher soil moisture values corresponded with higher transpiration rates, that is, a stronger transfer of energy from the surface can enhance rainfall (e.g., Koster and Suarez, 2004). Taylor and Ellis (2006) analyzed horizontal variations of soil moisture using microwave data and the effects of this variability on atmospheric processes. They found strong gradients of sensible heat flux, caused by soil moisture gradients, were more likely to cause mesoscale convection over dry soils than wet soils. Suppression of the cold pool during convection activity occurred more over wet soils where surface fluxes caused a more shallow and moist boundary layers compared to dry soils (Taylor and Ellis, 2006).

Frye and Mote (2010) compared multiple convective parameters (e.g., convective available potential energy, convective inhibition, lifted index) with varying soil moisture measurements and found a synergistic relationship between soil moisture and 850 hPa level low-level jet (LLJ). Daily events were classified into four distinct synoptic-type categories. They found a strong dependence between synoptic-scale patterns, convective parameters and soil moisture. They concluded that the presence of a LLJ destabilizes the atmosphere and increases convective activity and thunderstorm activity. They found that this is more likely to increase over wet soils than over dry soils. Kang and Bryan (2011) found consistent increased cooling and moistening in the PBL from wet soils with earlier convective activity than over dry soils. In contrast, Taylor *et al*. (2012) found convective precipitation to fall preferentially over dry soils in the Sahel region of Africa. This occurs because dry soils are associated with larger sensible heat flux, which destabilizes the atmosphere in the PBL and increases the likelihood of convective activity.

While many modeling studies support soil moisture-precipitation coupling, few have exclusively identified soil moisture's impact on precipitation and even fewer studies have used observed *in situ* soil moisture measurements. The purpose of this research is to better understand land-atmosphere coupling by using *in situ* soil moisture measurements. This study will focus on convective events that occurred when the atmosphere was relatively stable with no LLJ present. These criteria allow for the analysis of events that may have strong feedbacks between soil moisture and the atmosphere. The classification system and criteria are described in Section II. Results from the case studies are explained in Section III. A discussion and summary are presented in Section IV.

CHAPTER II

DATA AND METHODOLOGY

Soil moisture data

Soil moisture data were obtained from the Oklahoma Mesonet (Illston *et al*., 2008). The network is a state-wide monitoring system providing real-time data of air temperature, wind speed, and rainfall from 115 stations. Over 100 soil moisture stations were installed recording *in situ* soil moisture measurements at 5 depths: 5, 25, 60, and 75 cm. Volumetric water content is estimated using the thermal matrix potential, measured by Campbell 229-L heat dissipation sensors. Soil moisture data used in this study were from the 5 cm measurements taken at 0600 UTC or 1:00 am CST. The station-based soil moisture measurements were converted into a $1/2^{o}$ resolution gridded dataset. Soil moisture is identified as volumetric water content and is calculated as the percent volume of water in a given volume of soil. Soil moisture percentiles were calculated using the empirical cumulative distribution function from each observation station(s) within every grid cell. The percentiles are a standardized measurement of soil water content that is based on comparing conditions to the entire record. A value of 1 (or 100%) indicates that the maximum soil water content during the period of record, 0.5 (or 50%) indicates the median soil water content and 0 (0%) is the minimum soil water content. Soil moisture percentiles will be used instead of volumetric water content because it allows measurements to be compared across Oklahoma regardless of variations in soil characteristics.

Precipitation dataset

The precipitation dataset used in this study is the Climate Prediction Center Morphing Method (CMORPH, Joyce at al., 2004). CMORPH combines data from passive microwave sensor satellites with thermal-infrared data from geostationary satellite data and has a spatial resolution of $1/4^{o}$ resolution. The grid point which we identity to be the location of the convective precipitation represents the point of maximum precipitation rate during the event. Each event and corresponding grid point of maximum precipitation rate is matched with the corresponding soil moisture value grid point from the soil moisture observations. Convective events during the warm season (April-September) from 2002- 2011 were identified for a total of over 3,000 events. Only 193 of those events were analyzed in this study.

Synoptic environment

Land-atmosphere interactions are defined as the local land surface influencing the energy and heat fluxes in the atmosphere. This study focuses on events that caused convective precipitation, as opposed to stratiform precipitation that are largely influenced by frontal passes and larger atmospheric processes. We characterized all events into one of the 4 categories based on synoptic conditions. This classification is adopted from Frye and Mote (2010) who used a modified convective trigger potential (CTP, Findell and Eltahir, 2001). Daily 1200 UTC atmospheric sounding temperature profiles from six stations (Amarillo, TX, Fort Worth, TX, Norman, OK, Lamont, OK, Dodge City, KS) were used to characterize the stability of the atmosphere. The modified CTP is calculated based on the lapse rate of the atmospheric sounding temperature profile between 850 and 700 hPa. If the lapse rate is less than 6.0°C/km, the atmosphere was considered to be synoptically stable or synoptically benign (SB). If the lapse rate is greater than 6.0°C/km, the synoptic environment is considered to be synoptically unstable or synoptically primed (SP).

An account of the Great Plains low-level jet (LLJ) is also taken into consideration as part of the classification method. The LLJ is a large-scale feature in the lower atmosphere that greatly affects the weather patterns in the central United States (Bonner, 1968). This fast-moving ribbon of air can carry warm Gulf moisture and warm temperatures in the low levels of the atmosphere northward. The LLJ has a large influence on the influx of moisture can greatly influence the stability of the lower atmosphere and cause conditions to be more favorable for convective precipitation in the Great Plains (Higgins *et al.* 1997; Wu and Raman, 1998). The presence of the LLJ was determined by using daily 1200 UTC winds at 850 hPa and 700 hPa level wind vectors from the North American Regional Reanalysis (NARR, Mesinger et al., 2006). Like in Frye and Mote (2010), we identified the LLJ if vector winds from the Gulf of Mexico were greater than 12 m/s (Bonner, 1968). The four different categories within the synoptic environment classification system are: synoptically primed –LLJ present (SP-LLJ), synoptically benign – LLJ present (SB-LLJ), synoptically primed – no LLJ present (SP-noLLJ), synoptically benign – no LLJ present (SB-noLLJ).

Each convective event was classified into one of these 4 categories. By doing this, we are able to discern how soil moisture influences convective precipitation under different atmospheric conditions. This study will only focus on events that are considered to be SB-noLLJ since the atmosphere would not be previously unstable and there would not be a dominant influence of moisture from the Gulf that could mask the local moisture conditions.

Classified events and cluster analysis

The 193 SB-noLLJ events were divided into 5 different groups using cluster analysis. These events were most likely under relatively stable atmospheric conditions with little to no moisture advection from the Gulf of Mexico LLJ. These events were divided using Ward's Method of cluster analysis based on 3 characteristics: normalized lapse rate, humidity index, and volumetric water content. Normalized values were calculated as the ratio of the standard deviation of each characteristic to the mean of each characteristic. 5 clusters were chosen because it showed the best division of grouped events without having many groups with only a few events. The most representative (e.g., closest to the mean) case within each cluster was chosen and each of those events was analyzed for similar and different storm characteristics.

HYSPLIT analysis

The National Oceanic Atmospheric Administration (NOAA) HYSPLIT (Hybrid Single-Particle Lagragian Integrated Trajectory) trajectory model is a useful tool to see the backward trajectory of an air parcel (represented in the model as a single particle) at multiple heights. The model for events after 2004 used the EDAS40 (Eta Data Assimilation System) for events and events that took place during 2003 and 2004 used the EDAS80 model. The duration of the backward trajectory was 72 hours ending at the closest hour prior to the event occurring. The backward trajectory was done at two heights: 1000 m and 500 m above the ground.

Radar data

Radar data were obtained through the HDSS Access System of NEXRAD Level III from multiple stations in Oklahoma, Kansas, and Texas. In this study, 30 events recorded by KTLX (Oklahoma City, Oklahoma) station were used to analyze the point of convective initiation for each of the storms. The point of convective initiation was identified using the following criteria: 1) convective event occurred within a 1° difference in latitude and longitude of Oklahoma City (35.48° N, 97.530° W), 2) initiation occurred between 13:00L and 19:00L, and 3) the convective cell was isolated. Cells in a cluster were eliminated as well events only showing traces of accumulated precipitation. Following evaluation of all the events, four different days (9 CMOPRH events) were selected for further study. Additional radar data were obtained from the National Center for Environmental Prediction (NCEP) / Environmental Modeling Center (EMC) 4 km gridded Stage IV data. The analysis is based on a multi-senior 6-hourly 'Stage III' analyses produced by the 12 river forecasting centers in the continental United States. These radar images are mosaics done by NCEP from the Stage III analyses. Radar data of the five days found from the NEXRAD Level III radar data will be the case studies events in this paper. Figure 1 shows how the case study events were chosen.

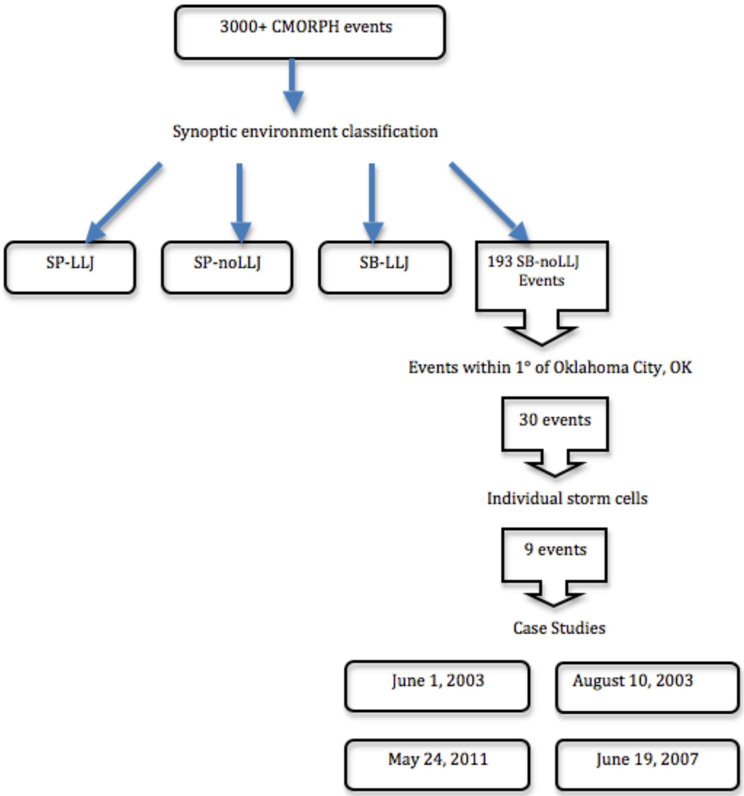

Figure 1. Schematic diagram showing the breakdown of choosing the 4 case studies.

NARR data

3-hour composite plots of a number of atmospheric variables were created to better understand the atmospheric environment before the start of precipitation. The variables that were examined included: PBL, sensible heat flux at the surface, latent heat flux at the surface, 850 mb vector winds, 500 mb vector winds, and Convective Available Potential Energy (CAPE) at the surface. The NARR data is reported in 3-hour composites beginning at 00Z. Therefore, if the event occurred within a 3-hour interval, the previous 3-hour average was chosen.

Storm Prediction Center (SPC) mesoscale discussions

Mesoscale discussions from NOAA'S National Weather Service Storm Prediction Center were used to understand the mesoscale atmosphere conditions on the day of the event. These reports can be accessed at: www.spc.noaa/gov/archive.

Weather Prediction Center (WPC) national forecast charts

WPC national forecast charts are issued every morning. They can be found at: http://www.wpc.ncep.noaa.gov/noaa/noaa_archive.php.

CHAPTER III

RESULTS

Cluster groups

By cluster analysis, the 193 events were divided into 5 different clusters. Cluster 1 had 27 events, Cluster 2 had 34 events, Cluster 3 had 62 events, Cluster 4 had 36 events, and Cluster 5 had 34 events. The purpose of cluster analysis was to further subdivide the convective events in the SB-noLLJ category and to objectively select a small number of events for the case study analysis.

Oklahoma City events

30 events out of the 193 in the SB-noLLJ category occurred within a 1° latitude and longitude distance from Oklahoma City (35.5° N, 97.53° W). Radar data for each event were used to visually analyze the storm development. Events that were part of a larger system (e.g., cold front, mesoscale convective system (MCS), etc.) were excluded. Eventually, 9 events from 4 days (some days had multiple events) were selected for further analysis. These events occurred on June 1, 2003, August 10, 2003, May 24, 2011, and June 19, 2007. Multiple events occurred during these days and some of the events on the same day were clustered into different groups. On June 1, 2013 two events were recorded and were both in Cluster 4. On August 10, 2003 there was one event from Cluster 3 and one event from Cluster 4. On May 24, 2011 there were three events, two of which were in Cluster 1 and one in Cluster 3. On June 19, 2007 there were two

events that are in Cluster 3. One of the events on June 19, 2007 was the representative site for Cluster 1 mentioned earlier. These separate days are discussed as case studies.

Case study 1: June 1, 2003

The synoptic patterns over the Great Plains and the overall atmospheric conditions during the events are important to study so that the robustness of the 4-category synoptic classification system can be evaluated. The Weather Prediction Center (WPC) forecast for June 1, 2003 indicated that flash flooding and severe thunderstorms were possible (Figure 2). A surface trough positioned over the Colorado-Kansas border created low-level convergence and caused the atmosphere to become moderately unstable. The stationary front shown in Figure 1 transitioned into a warm front as it pushed northward to the Oklahoma-Texas border (Figure 3) in the early afternoon. There was enough convective available potential energy (CAPE) to support convective development as the mid-level convective inhibition weakened.

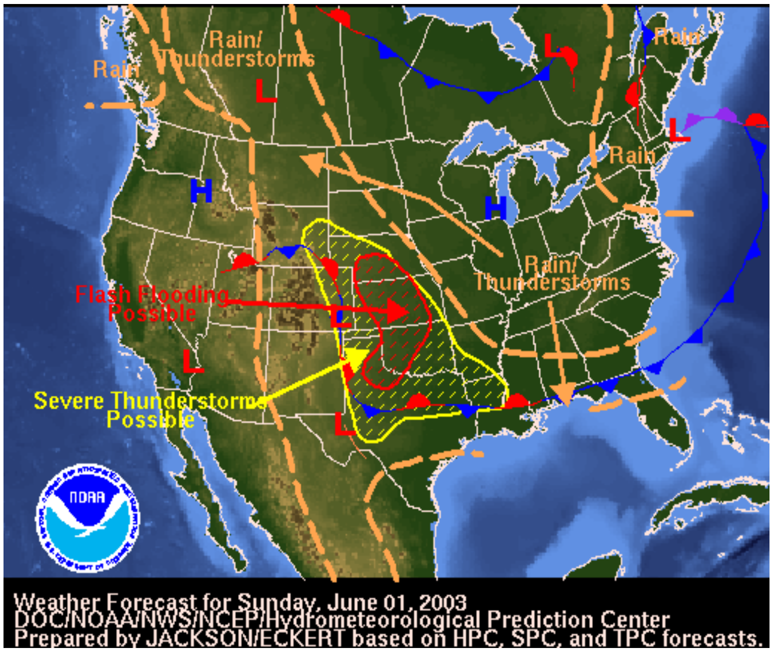

Figure 2. WPC weather forecast map from the morning of June 1, 2003.

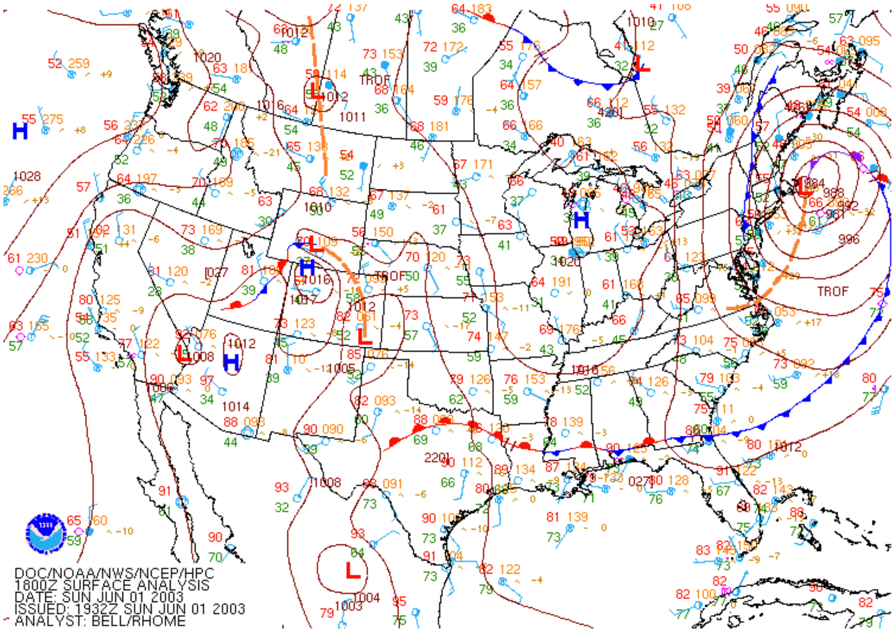

Figure 3. National Weather Service (NWS) surface analysis at 1800Z (13:00L) on June 1, 2003.

Divergent flow near the Rockies associated with mid- and upper-level vertical motion and a sharp short-wave trough also enhanced thunderstorm activity in the Great Plains (SPC Mesoscale Report #1182). Super-cell thunderstorms began forming around 14:30L as the cap began to erode and temperatures warmed. Strong instability caused large hail and damaging wind gusts to be the main threat. The MCS moving southeastward stretched from Kansas to Texas by 17:50L (Figure 4).

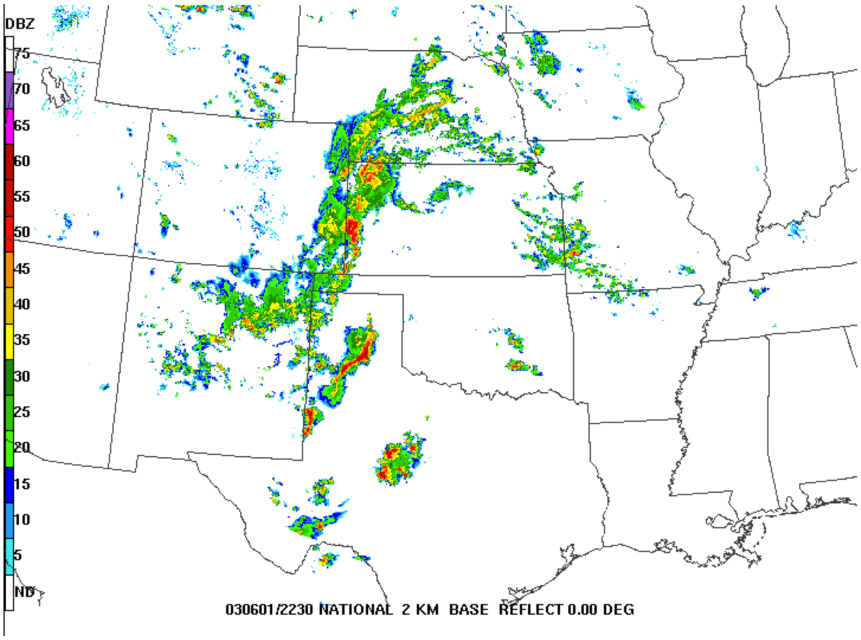

Figure 4. Storm Prediction Center (SPC) National 2 KM base reflectivity over the Great Plans at 2230Z (17:30L) on June 1, 2003.

Two CMORPH events [(A) 35.125˚ N, 97.125˚ W; (B) 35.375˚ N, 97.375˚ W] were recorded within the study region on June 1, 2003 (Figure 5). The point of initiation (POI #1) (34.775˚ N, 97.179˚ W) was identified to be roughly 80 miles away from the CMORPH event locations occurring at 15:15L as noted in Figure 5 by the red arrow. It should be noted that in this particular case, the point of initiation for the thunderstorm is different and independent of the two CMORPH events listed above. This highlights one of the limitations of subjectively choosing a point of initiation for events, which will be discussed in detail later in the thesis.

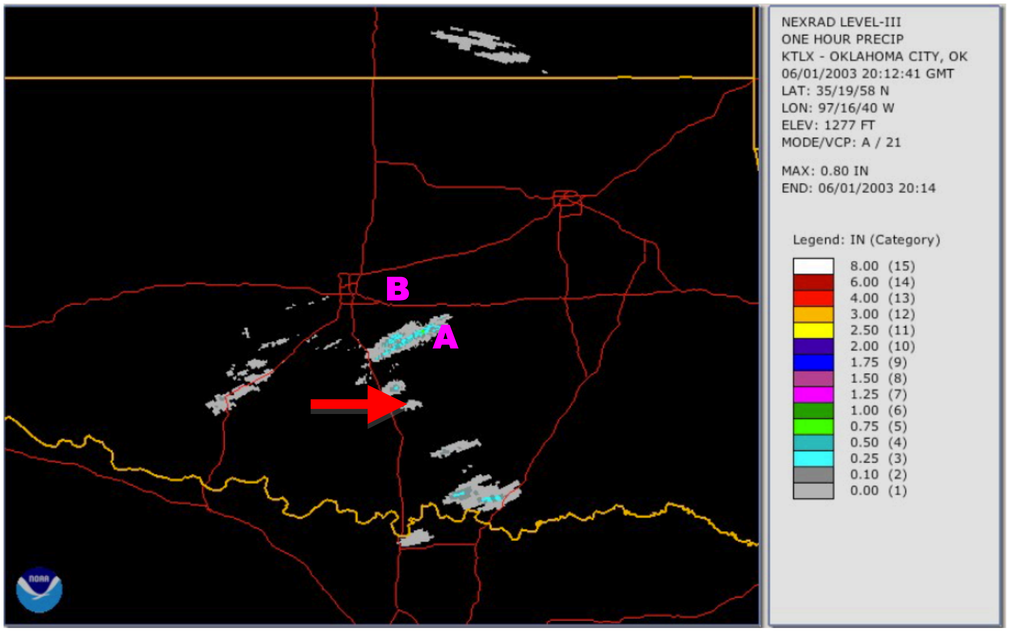

Figure 5. NEXRAD Level-III One hour precipitation taken from KTLX – Oklahoma City at 15:14L on June 1, 2003. Red arrow denotes event of interest and point of initiation.

The NOAA HYSPLIT model shows both the 1000 m and 500 m air parcels backtrack trajectories (Figure 6). The distance and direction of travel during the 72 hours prior to the time of the point of initiation are shown. The 1000 m air parcel shows a northward path from the Gulf of Mexico moving into Oklahoma. There was also gradual decrease in height until 0000Z June 1st (19:00L May 30th) when the air parcel rises rapidly higher during the 6-hour period over central Texas. Then it proceeds northward into southern Oklahoma. The 500 m air parcel initially began at the surface and remained at a consistent height until 0600Z June 1st (0:00L) when it was lifted to 500 m right over central Arkansas. The direction of movement for the 500 m air parcel is quite different than the 1000 m air parcel. It loops clockwise in Missouri and then moves southward into Arkansas before turning in Oklahoma. During the hours prior to convective initiation both air parcels are lifted. This lifting is potentially caused by land-atmosphere interactions due to sensible heating in the afternoon.

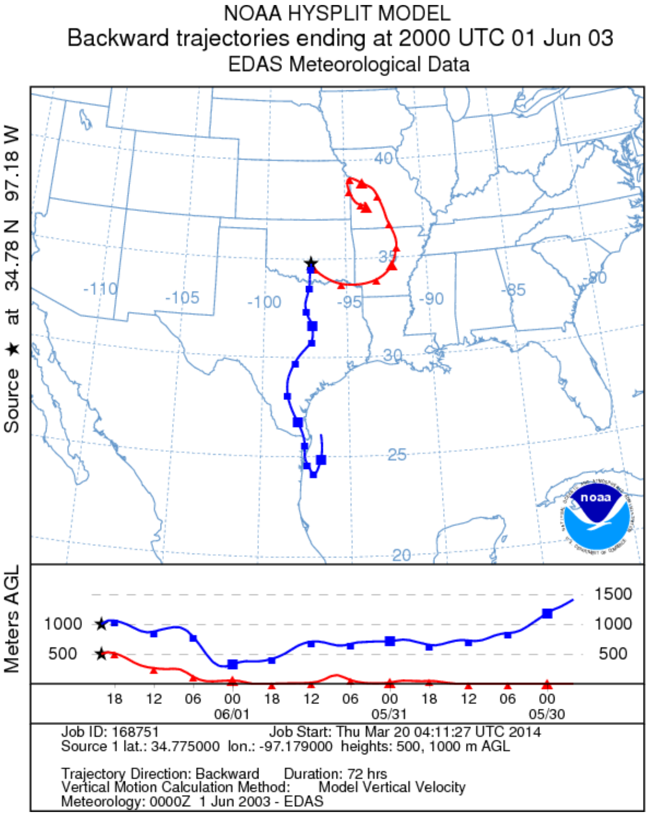

Figure 6. Backtrack trajectory of two air parcels on June 1, 2003: Blue line represents the air parcel that is 1000 meters above ground level (AGL) and the red line represents the air parcel 500 meters AGL.

The 850 mb vector winds map shows the vector winds averaged between 10:00L – 13:00L (Figure 7). The 850 mb vector winds show the general circulation of the low centered over

Colorado. Vectors winds in Texas and Oklahoma are from the north, but vectors winds in Missouri and Arkansas are moving from the south and east. The wind speeds in Oklahoma and parts of the Panhandle of Texas and north Texas are less than 6 m/s. The 500 mb vector winds map shows mid-level winds around 12 m/s, twice as fast as 850 mb winds, moving in a zonal pattern (Figure 8). There is prominent speed and wind shear located from the surface to 500 mb. Warm air advection likely took place in the afternoon as seen by the veering of winds with height. This thermal advection increased the instability in the atmosphere causing multiple cells to fire up in the afternoon.

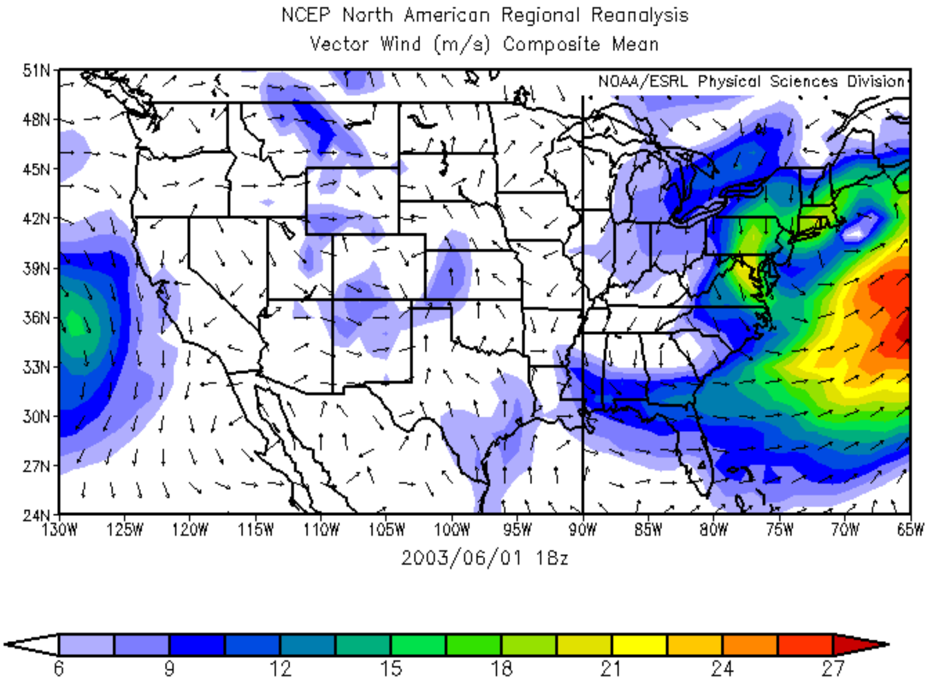

Figure 7. 850 mb vector wind (m/s) composite mean between10:00L-13:00L on June 1, 2003.

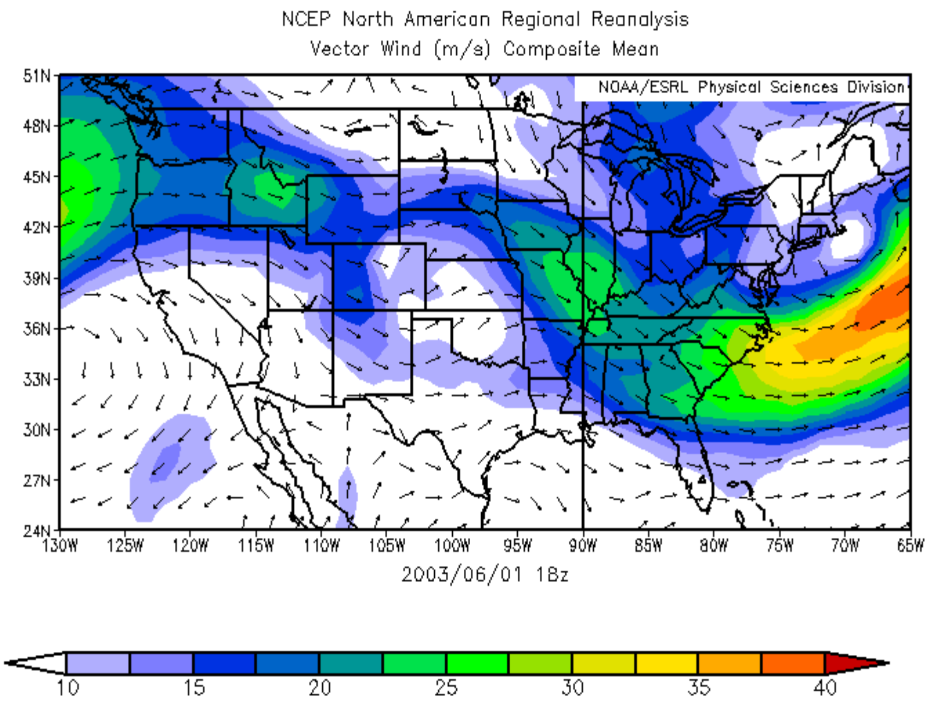

Figure 8. 500 mb vector wind (m/s) composite mean between 10:00L-13:00L on June 1, 2003.

High CAPE indicates a greater chance for severe weather in the case of hail, frequent lightning, and downdrafts. The values are related to the maximum potential velocity of the updraft speed. In an environment where CAPE is high, storms tend to develop vertically very quickly. 3-hour prior to the initiation of this event, CAPE values were relatively order of 750 J/kg (Figure 9). Parts of Colorado, Nebraska, and Wyoming and especially west Texas had large CAPE values exceeding 3000 J/kg.

Land surface conditions also have an influence on the initiation of convective storms. Latent heat flux plays a large role in creating more instability in the atmosphere. A larger latent heat flux adds to the instability and can cause storms to become severe. On days with high humidity and an abundance of water vapor in the air, the potential for latent heat release to cause development of thunderstorm increases. The mean composite surface latent heat flux and sensible heat flux were around -300 W/m^2 implying the transfer of heat from the ground to high levels in the atmosphere (Figure 9). Comparing the two flux maps, the regions with the highest latent heat flux (e.g., southeastern United States) differ from the regions with the highest sensible heat flux (e.g., southwestern United States). Oklahoma happens to be in the middle of these two regions and overlaps in both greater values of latent and sensible heat fluxes.

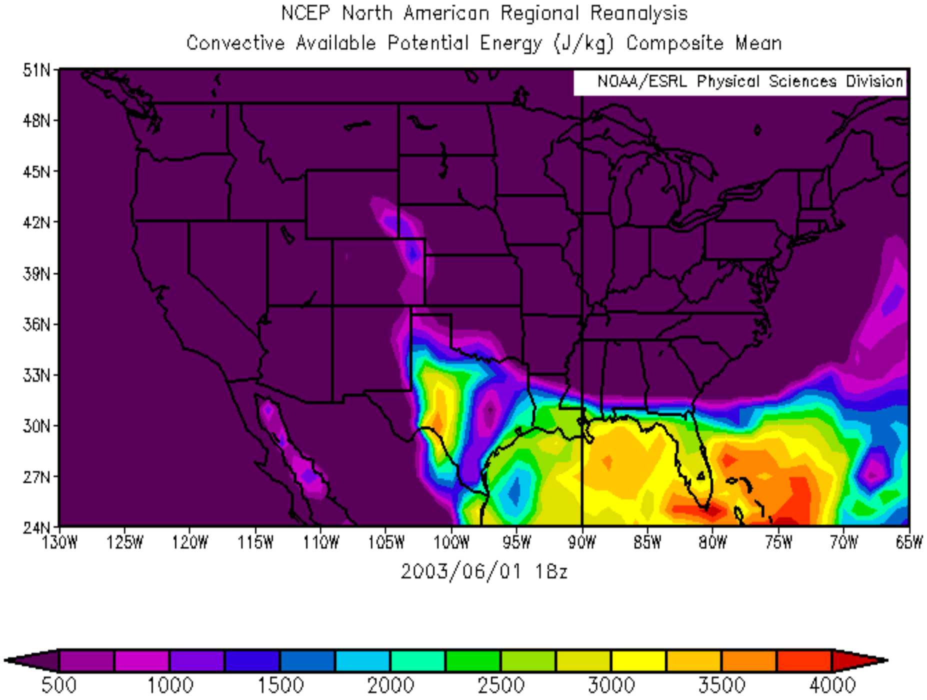

Figure 9. Convective available potential energy (CAPE) composite mean between 10:00L-13:00L on June 1, 2003.

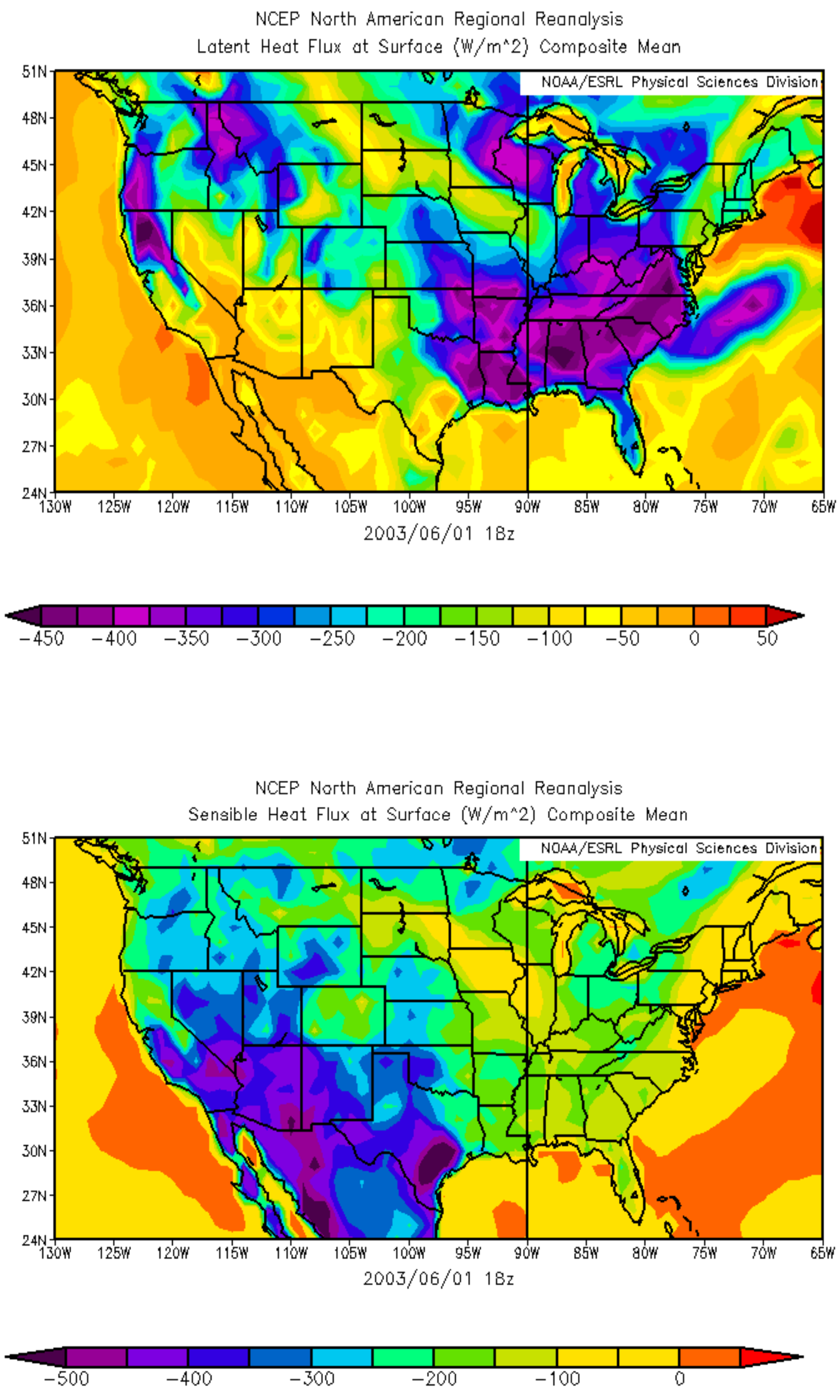

Figure 9. (Top) Latent heat flux at the surface (W/m^2) composite mean on June 1, 2003. (Bottom) Sensible heat flux (W/m^2) composite mean on June 1, 2003.

The soil moisture percentiles for CMORPH events A and B were 0.24 and 0.47 respectively. Soil moisture data was not available for POI #1. Soil moisture data are gridded from stations at a 25 km resolution. This makes about 400 grid cells over Oklahoma, but there are only 113 stations. Therefore the majority of grid cells will not have a soil moisture station in them. Nonetheless, both locations are considered to have dry soil moisture conditions. Temperature and humidity anomalies are listed in Table 1. Both locations have negative temperature anomalies. Event A had high humidity anomalies at both the surface and mid-levels. Event B had slightly lower anomalies and negative humidity anomaly at mid-levels.

Table 1. Temperature and humidity anomalies and VWC and percentiles for June 1, 2003.

Event	Temp (1000-900 mb)	Temp (850-700 mb)	Humidity 1000-900 mb)	Humidity (850-700 mb)	Soil Percentiles
A	-0.88	-0.75	0.87	0.46	0.24
B	-0.66	-0.21	0.22	-0.51	0.47

Case study 2: August 10, 2003

Rain and thunderstorms with a chance of severe thunderstorms were forecasted for much of the Great Plains and Oklahoma on August 10, 2003. A stationary front was present over Oklahoma and a cold front was to the north stretching from Nebraska up into Minnesota (Figure 10). A large MCS formed in northern Oklahoma around noon and traveled southward into central and southern Oklahoma. SPC reports mentioned a chance for isolated large hail and damaging winds were possible. A small supercell formed in the southeastern corner of Oklahoma, which will be the main focus of this case study (Figure 11).

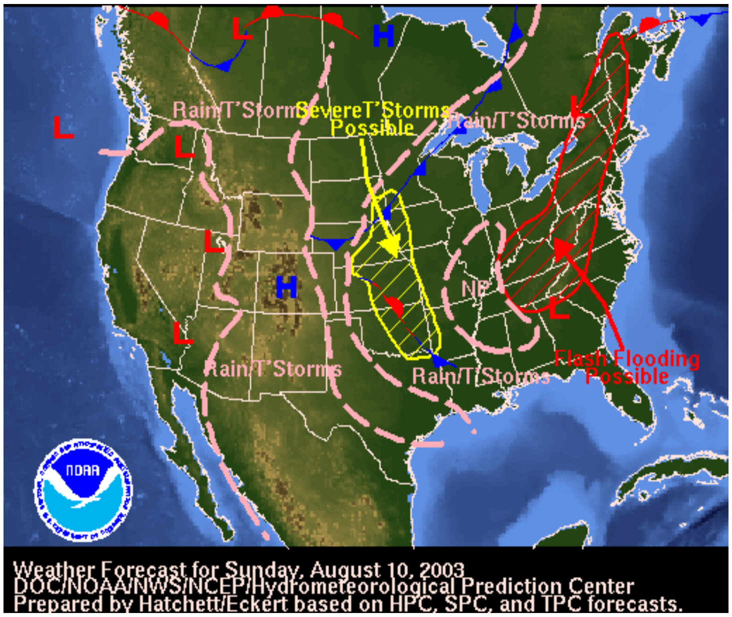

Figure 10. WPC weather forecast map from the morning of August 10, 2003.

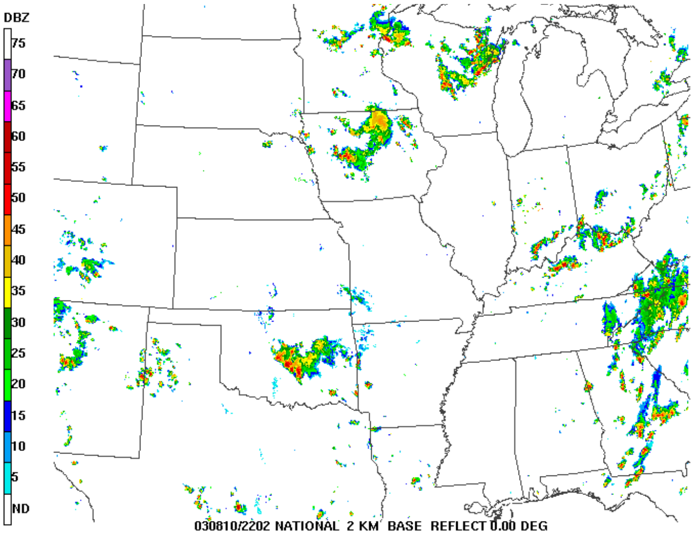

Figure 11. SPC National 2 KM base reflectivity over the Great Plans at 2230Z (17:30L) on August 10, 2003.

The surface analysis from SPC shows a surface low over central Oklahoma, but also has a surface high to the east of this low pressure (Figure 12). This surface trough signifies lifted and rising air, which acts as the mechanism for convective activity to form. This trough is also present in upper-levels (e.g., 250 mb) as well (Figure 13). Strong ridging to the west was present due to a strong high-pressure system centered over Colorado.

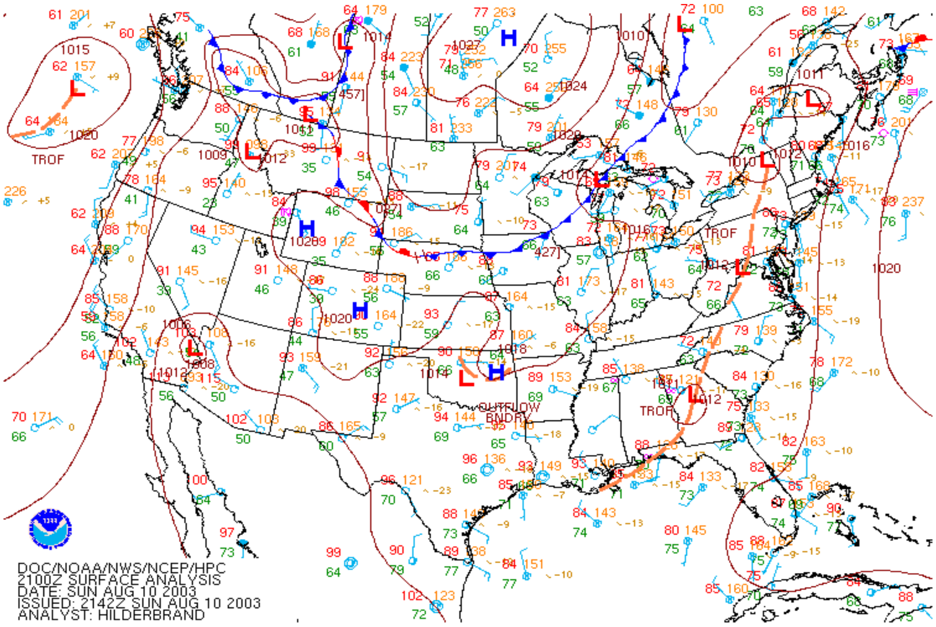

Figure 12. NWS surface analysis at 1800Z (16:42L) on August 10, 2003.

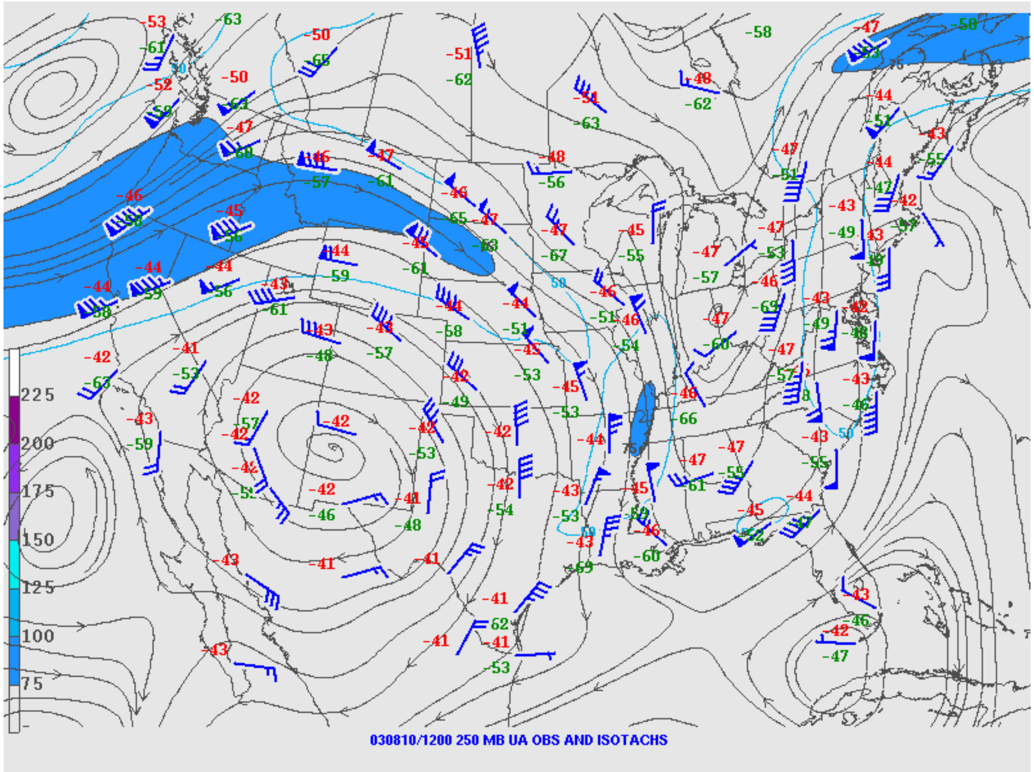

Figure 13. SPC 250 mb upper-air analysis at 7:00L on August 10, 2003.

Two CMORPH events [(C) 35.125˚ N, 96.875˚ W; (D) 35.125˚ N, 95.625˚ W) were recorded on this day (Figure 14). Event C was in cluster 3, while Event D was grouped into Cluster 4. The point of initiation (POI #2) (34.27˚ N, 95.415˚ W) for a different supercell thunderstorm was roughly 115 miles away from the two CMORPH events and occurred around 17:00L. This supercell formed apart from the large MCS that traveled southward.

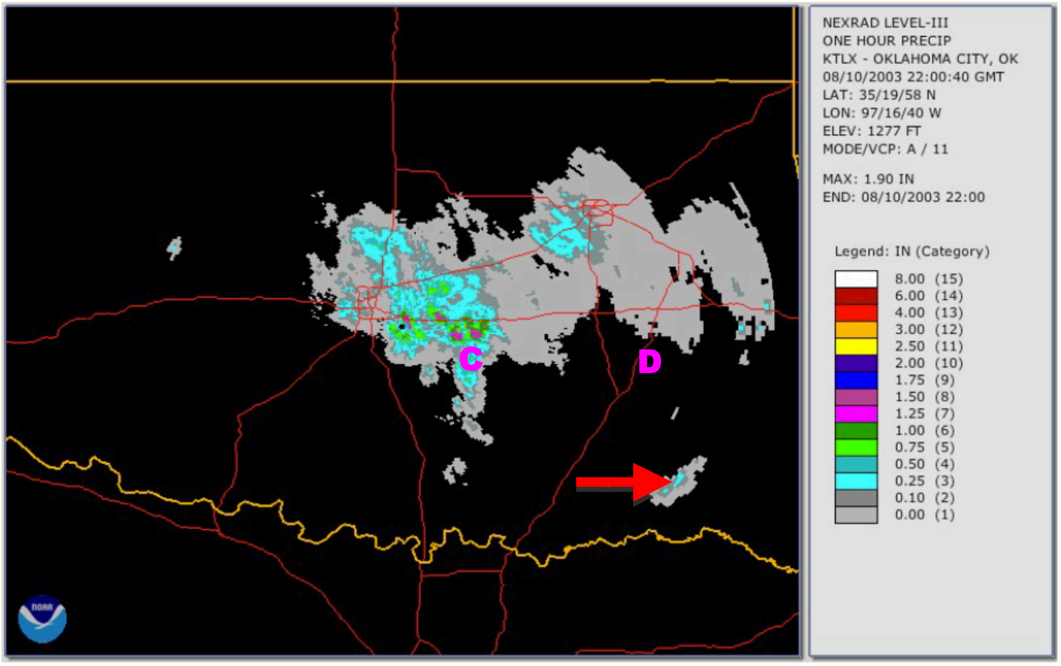

Figure 14. NEXRAD Level-III One hour precipitation taken from KTLX – Oklahoma City at 15:14L on August 10, 2003. Red arrow denotes event of interest and point of initiation.

The HYSPLIT model shows the two air parcels to be slowly moving from Arkansas into Oklahoma (Figure 15). The two air parcels traveled less than 500 miles over the course of 72 hours. It is very likely there was strong land-atmosphere coupling in southeastern Oklahoma due to strong latent and sensible heating and the destabilizing profile of the planetary boundary layer. Both air parcels move southwest, but eventually curve northward into Oklahoma and makes a small loop before moving south to the point of initiation. Around 12Z (0700L) on August 9th, both air parcels are lifted just as both they cross into Oklahoma. They were likely lifted because the planetary boundary grew quickly over Arkansas and strong southerly vector winds in the mid-levels created an area of positivity vorticity advection (Figure 16).

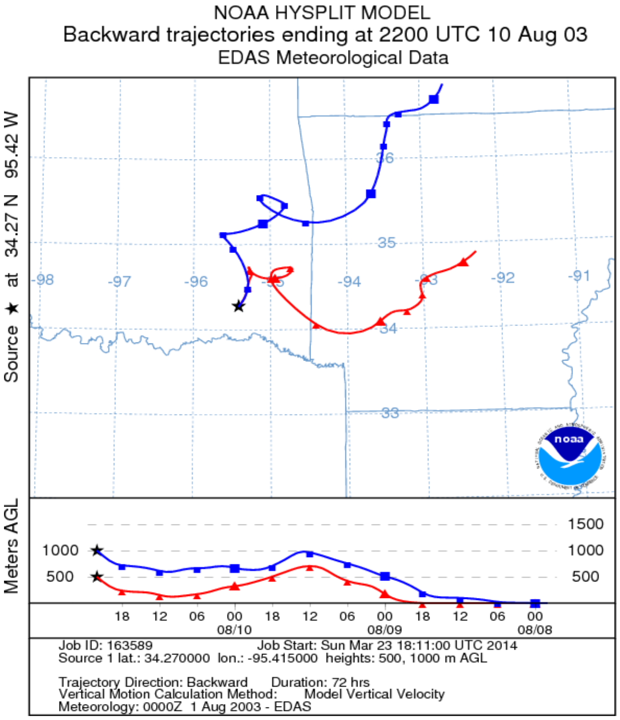

Figure 15. Backtrack trajectory of two air parcels on August 10, 2003. Blue line is for the air parcel 1000 meters above ground level (AGL) and the red line is for the air parcel 500 meters AGL.

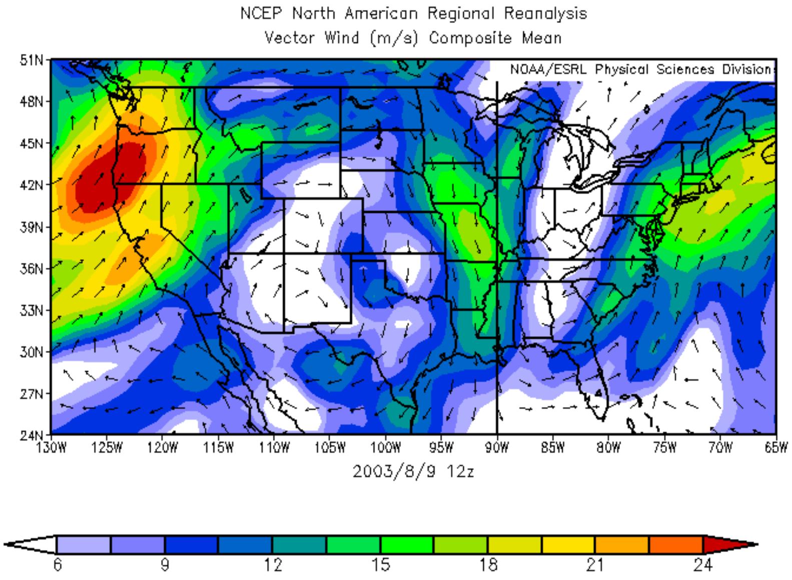

Figure 16. 500 mb vector wind (m/s) composite mean between 07:00L-10:00L on August 3, 2003.

The 850 mb vector winds show light winds less than 4 m/s flowing from the northeast over southern Oklahoma (Figure 17). The 500 mb vector winds show a much different story (Figure 18). Strong vector winds are prominent in Nebraska and they continue into Kansas and eventually start to weaken closer into Oklahoma, but values are still around 10 m/s. Very strong winds from the south on the west coast contrasts with the strong northerly winds in the Midwest illustrating the strong ridge and subsequent trough pattern across the United States. Southeastern Oklahoma is on the downward side of trough meaning there was convergence of air motion. Winds from the lower levels to the mid-levels are backing meaning they are moving counterclockwise with height.

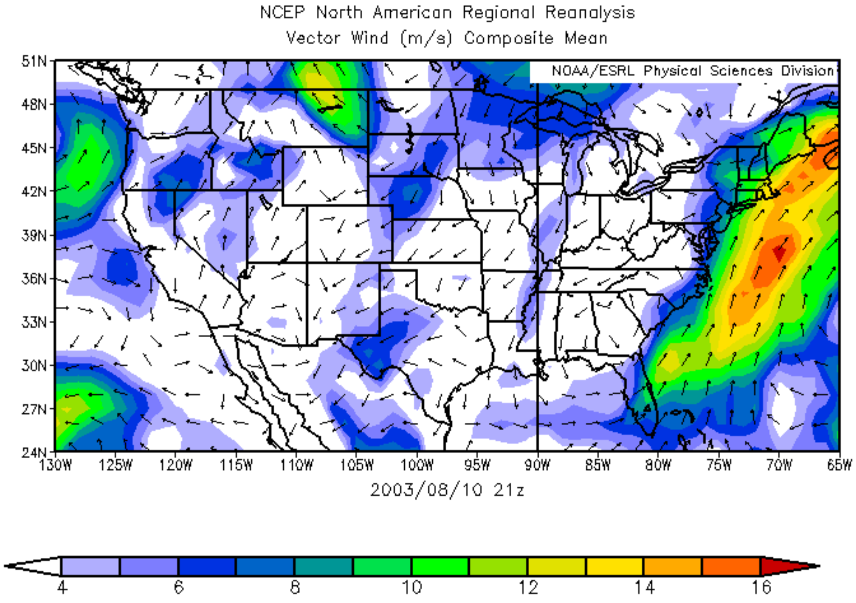

Figure 17. 800 mb vector wind (m/s) composite mean between 13:00L-16:00L on August 10, 2003.

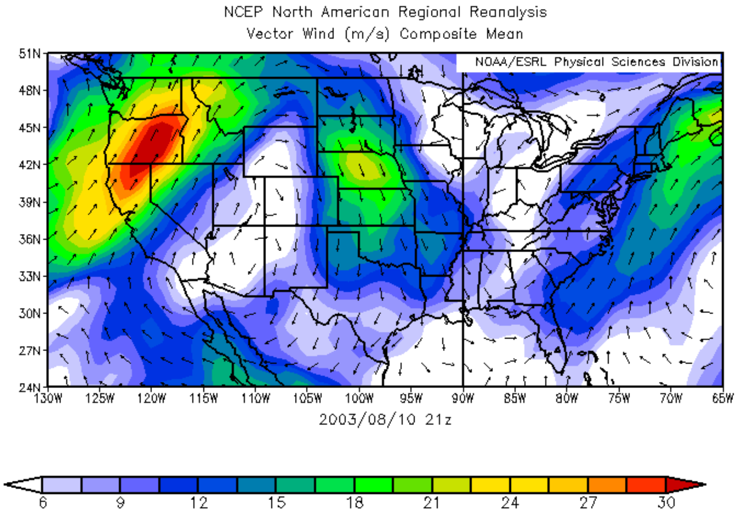

Figure 18. 500 mb vector wind (m/s) composite mean between 13:00L-16:00L on August 10, 2003.

CAPE values on August 10, 2003 were on the order of 750 J/kg (Figure 19). Farther north into northeastern Oklahoma and parts of southern Kansas and Missouri, CAPE values were even lower.

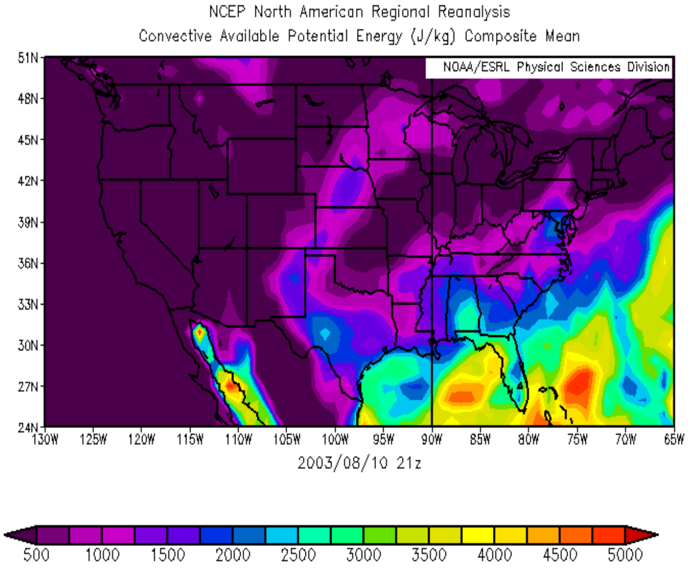

Figure 19. CAPE composite mean between 13:00L-16:00L on August 10, 2003.

Moderate values of surface latent heat flux and sensible heat flux were available in the hours before the thunderstorm initiated. The mean composite latent heat flux was on the order of -180 W/m^2 and the sensible heat flux was about -100 W/m^2. These negative values indicate a transfer of energy from the surface to the atmosphere. In comparison to case study 1 from June 1, 2003, these heat fluxes are about 200 W/m^2 larger. Based on the heat fluxes, the June 1, 2003 case had a stronger land-surface forcing than this event. It is interesting to note that latent heat flux values over parts of Kansas, northern Missouri, and Iowa, were hovering around 0 to -10 W/m^2. There is a stark contrast between these values and the heat flux over central Arkansas where latent heat flux values were on the order of -200 W/m^2. The contrast between these two areas is also shown in the sensible heat flux map. Values of sensible heat flux are less than 100 W/m^2 in western Oklahoma and in central Oklahoma, where the MCS was strongest, sensible heat flux values were near 0 W/m^2 (Figure 20).

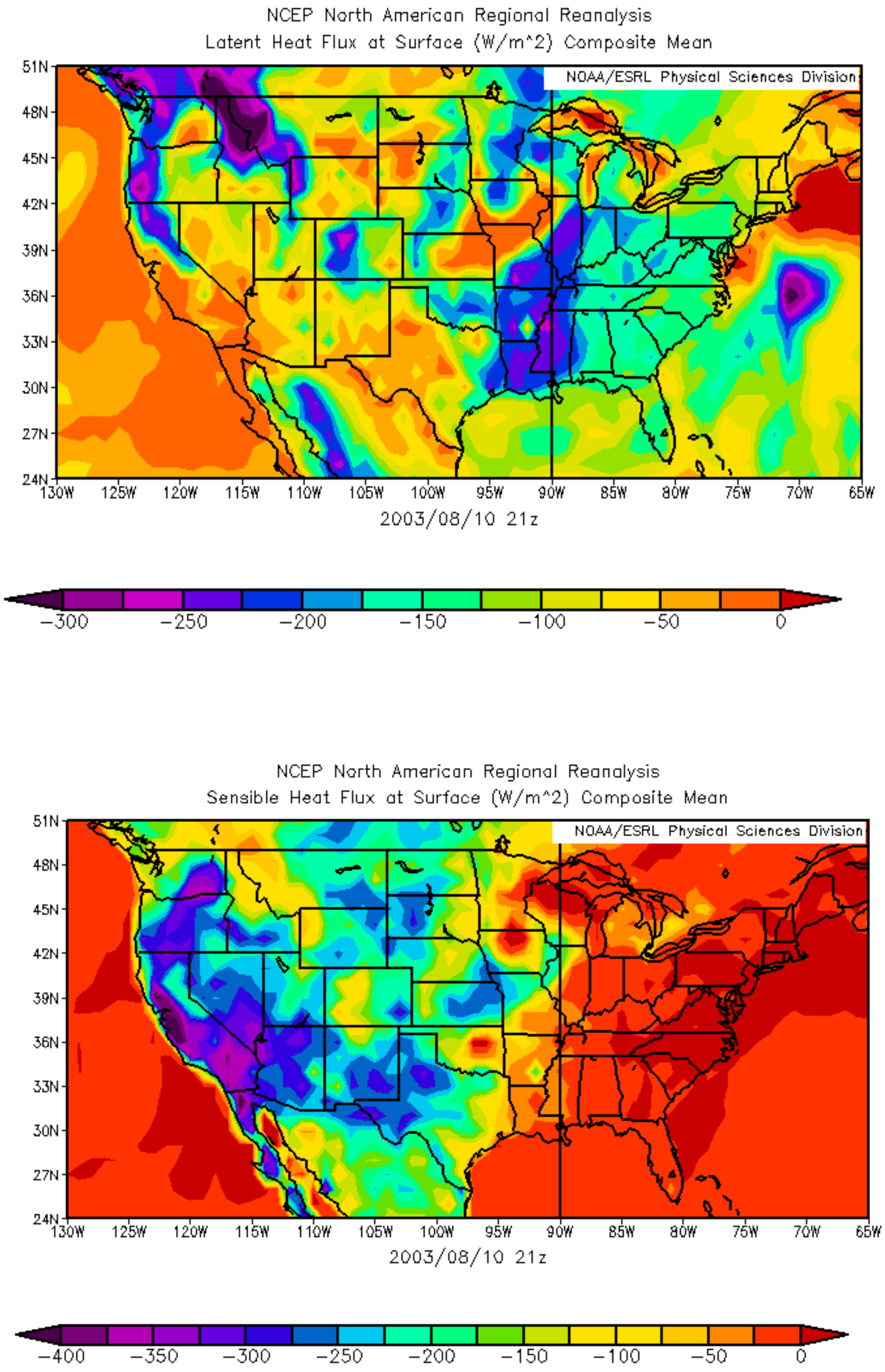

Figure 20. (Top) Latent heat flux at the surface (W/m^2) composite mean. (Bottom) Sensible heat flux (W/m^2) composite mean on August 10, 2003.

The soil moisture percentiles for events C and D were 0.36 and 0.52, respectively. The soil moisture percentile was 0.413. These events are considered to have occurred over dry soils for Event C, Event D and the point of initiation. Temperatures anomalies for events C and D were very low at the surface and were a little higher in the mid-levels. Humidity anomalies were negative indicating less than normal atmospheric moisture. These humidity anomalies contrast Event A from the June 1, 2003 event. The lack of moisture from the Gulf of Mexico is likely the reasoning behind the contrasting humidity anomalies and the much slower moving air parcels.

Table 2. Temperature and humidity anomalies and VWC and percentiles for August 10, 2003.

Event	Temp (1000-900 mb)	Temp (850-700 mb)	Humidity 1000-900 mb)	Humidity (850-700 mb)	Percentiles
C	-0.04	-0.12	-0.46	-0.28	0.36
D	-.002	-0.13	-0.66	-0.40	0.52
POI #2	N/A	N/A	N/A	N/A	0.41

Case study 3: May 24, 2011

The morning of May 24, 2011 the SPC forecast an outbreak of super cell thunderstorms. They also indicated that severe thunderstorms were possible throughout the lower Great Plains and across much of the eastern United States. Multiple low-pressure systems were present over the Rockies along a stationary front (Figure 21). The 18Z (13:00L) surface analysis shows a low-pressure system with a dry line in place over western Oklahoma that extends down into Texas (Figure 22). The warm front accompanied with the system shifted winds to flow from the south in Oklahoma and bringing warm moist air from the Gulf of Mexico into the area. Forecasters were also prepared after watching this area days in advance and forecasted for a severe weather outbreak across Kansas, Oklahoma, and Texas. According to SPC reports, a 997 mb low pressure was situated over the Texas Panhandle accompanied by a dryline that extended from far western Oklahoma into west Texas (SPC Mesoscale report #0925, 0934, 0938). The atmosphere destabilized in the early afternoon as temperatures began to warm and dew point temperatures climbed to 20º C.

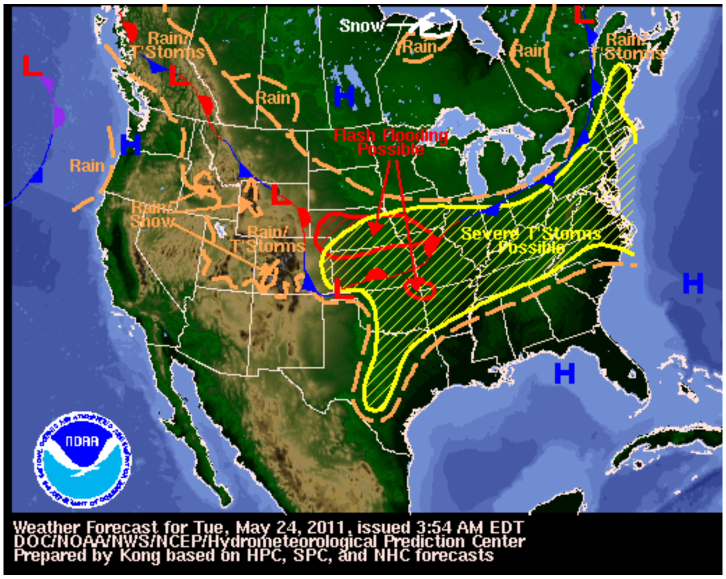

Figure 21. WPC weather forecast map from the morning of May 24, 2011.

The cap eventually eroded and rapid cell development occurred along the dryline (Figure 23). Multiple Severe thunderstorm watches and warnings were issued along with tornado watches across the Great Plains.

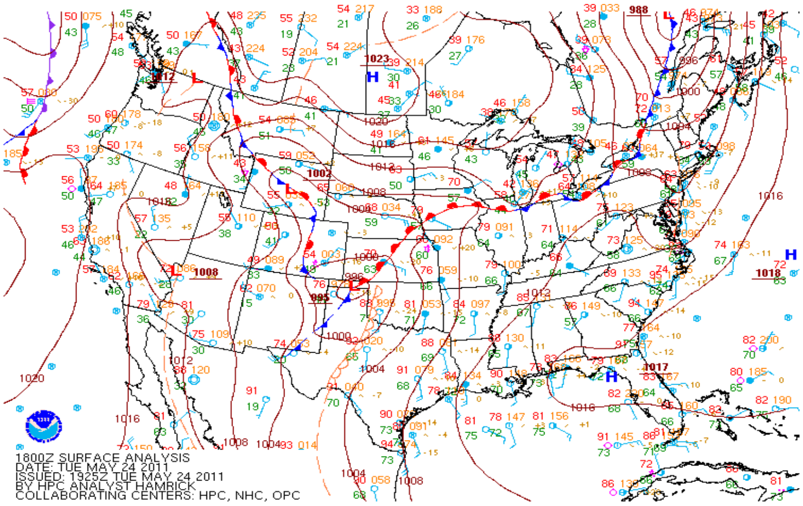

Figure 22. NWS 1925Z (14:25L) Surface Analysis on May 24, 2011.

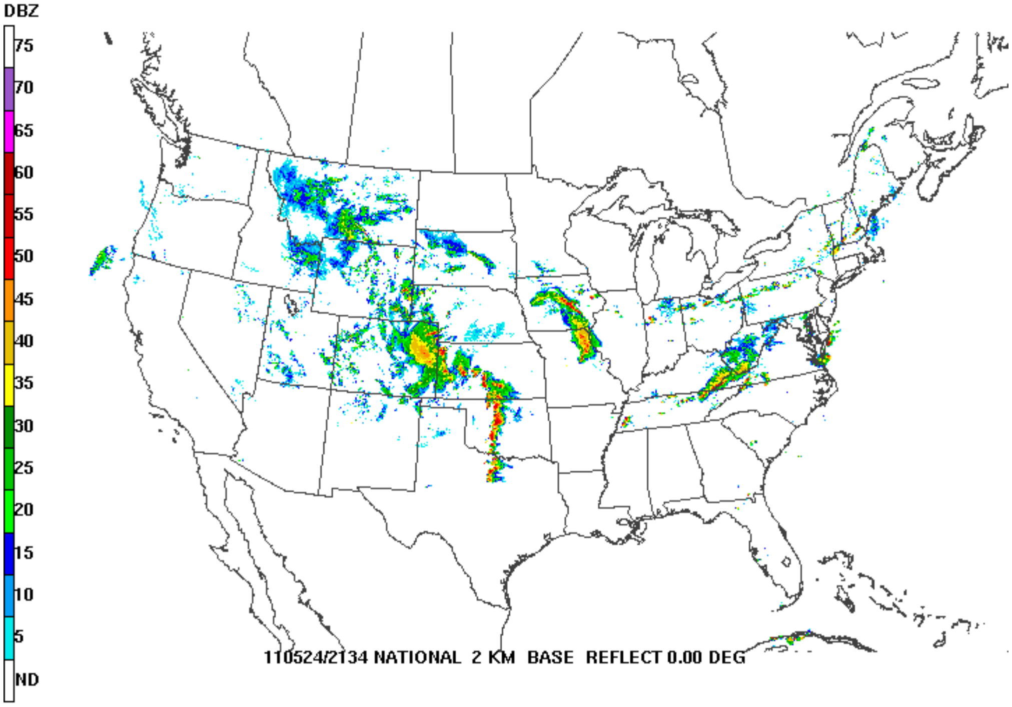

Figure 23. SPC National 2 KM base reflectivity over the Great Plans at 2134Z (16:34L) on May 24, 2011.

Three CMORPH events [(E) 34.875˚ N, 97.125˚ W; (F) 35.125˚ N, 98.375˚ W; (G) 36.123˚ N, -98.125˚ W) were recorded on this day (Figure 24). Events E and G were grouped into Cluster 1, while event F was placed in Cluster 3. The point of initiation (POI #3) (34.60˚ N, 98.75˚ W) was roughly 150 miles away from the 3 CMORPH events. Unlike the previous case studies, the point of initiation is related to the CMORPH events. The point of initiation occurred to the west of all of the CMORPH events, indicating that the highest point of precipitation occurred to the west of the point of initiation as the super cells were moving east.

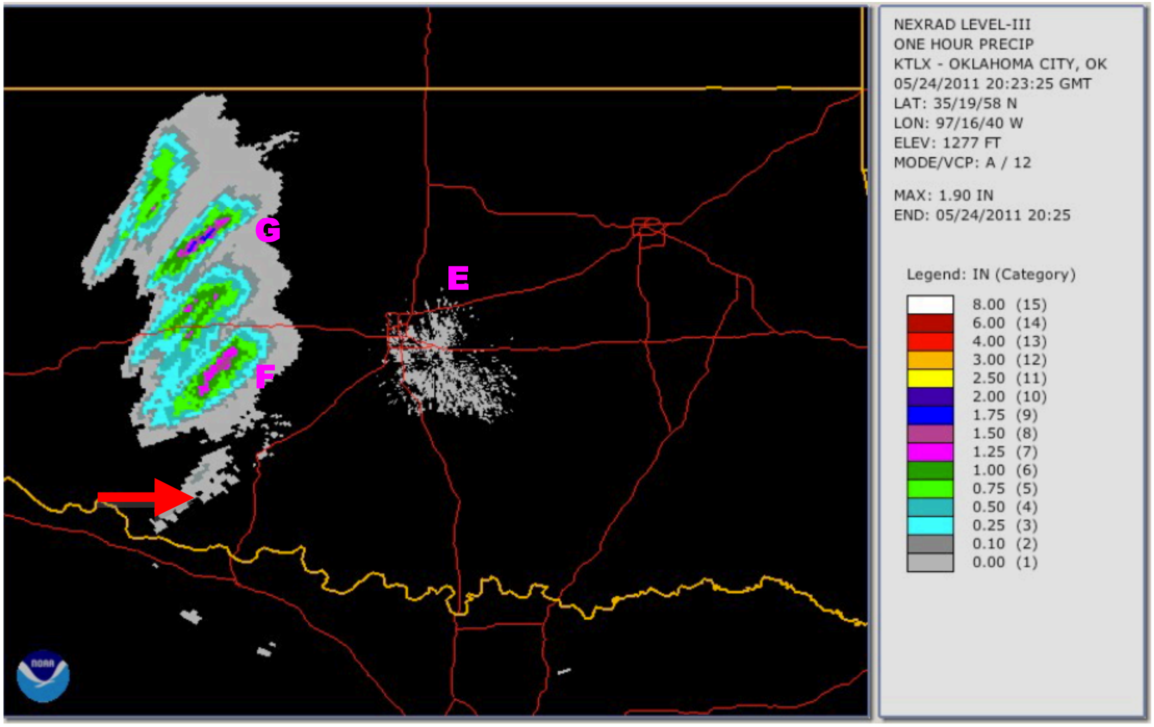

Figure 24. NEXRAD Level-III One hour precipitation taken from KTLX – Oklahoma City at 15:35L on May 24, 2011. Red arrow denotes event of interest and point of initiation.

The HYSPLIT model shows both air parcels moved quickly from the Gulf of Mexico through Texas and into southwestern Oklahoma (Figure 25). From the trajectory of these air parcels, it is evident moist air likely traveled with these air parcels. Both air parcels traveled in a similar pattern curving to move towards Texas without crossing into Mexico. Both air parcels were lifted around over southern Texas at 6Z (01:00L) the day of the event. Prior to that, the 500 m air parcel stayed at the surface and the 1000 m air parcel received a little lifting at 00Z (19:00L May 22nd) on May 23rd.

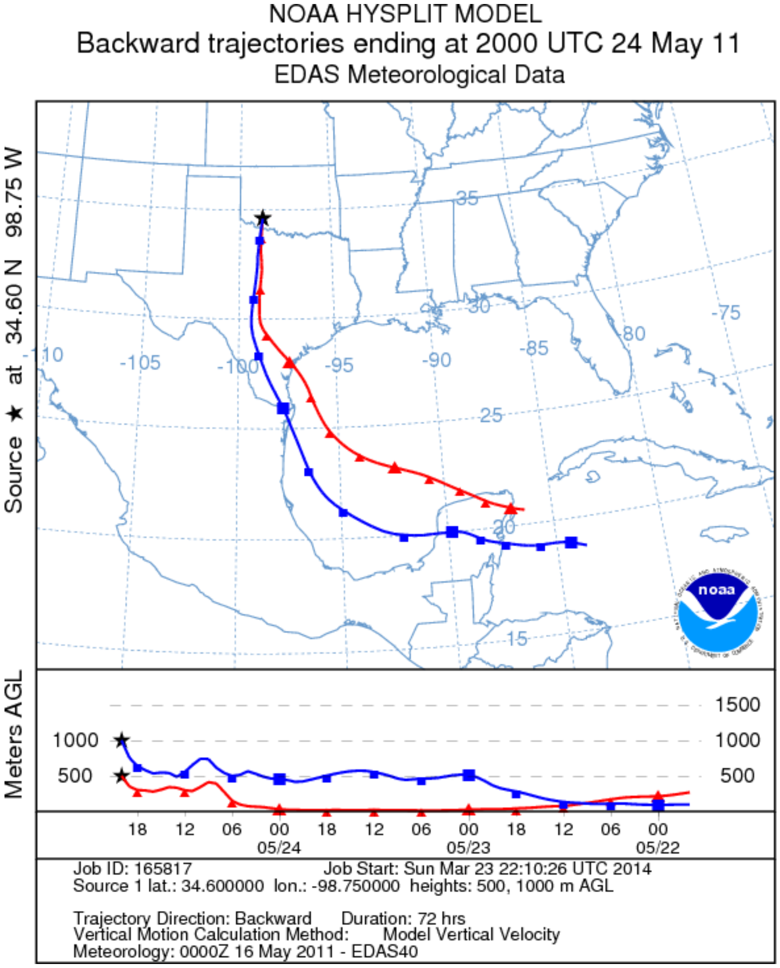

Figure 25. Backtrack trajectory of two air parcels on May 24, 2011. Blue line represents the air parcel that is 1000 meters above ground level (AGL) and the red line represents the air parcel) 500 meters AGL.

Very strong 850 mb winds from the south indicate the presence of LLJ (Figure 26). Although this day's atmosphere is not supposed to have a LLJ present based on the criteria, this is an example of how the classification system can be flawed. 850 mb vector winds vary above 15 m/s and reach as high as 20 m/s in some areas. These strong winds flowed from the south, which match the pattern of the air parcels as noted in the backtrack trajectory.

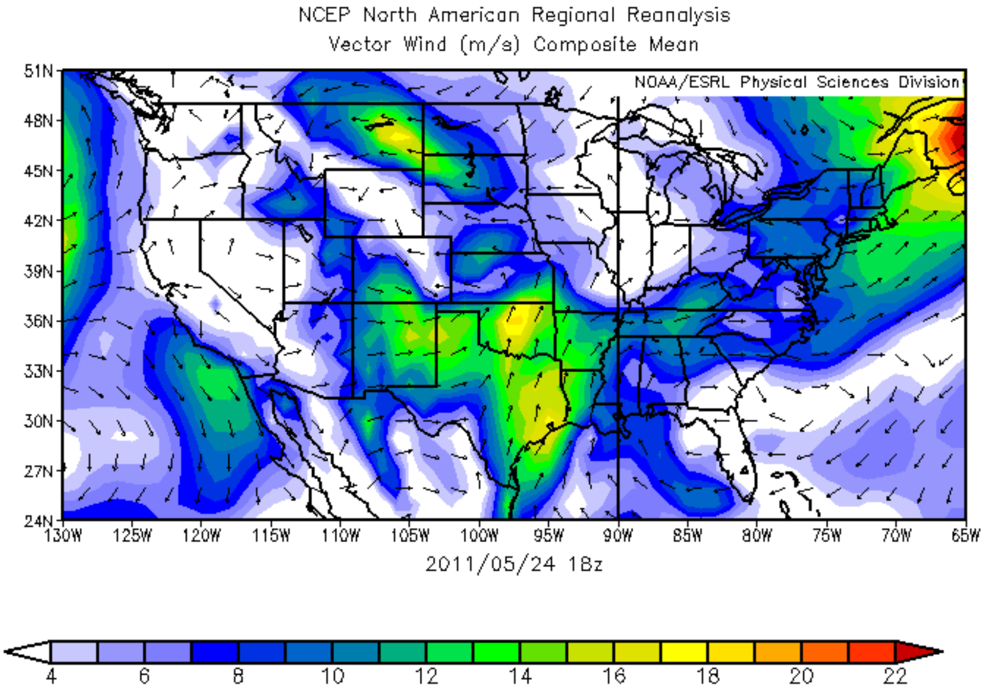

Figure 26. 850 mb vector wind (m/s) composite mean between 10:00L-13:00L on May 24, 2011.

500 mb winds, on the other hand, had a very strong zonal flow (Figure 27). The strongest vector winds were noticed over the west Texas and southern New Mexico. In addition, this pattern shows a mid-level trough over Oklahoma and the upward side of the trough creates divergence and rising air aloft. Rising air was likely enhanced because winds were veering with height and

warm air advection was present in the low-levels. This mid-level jet created very deep shear layers that were conducive to the development of super cell storms.

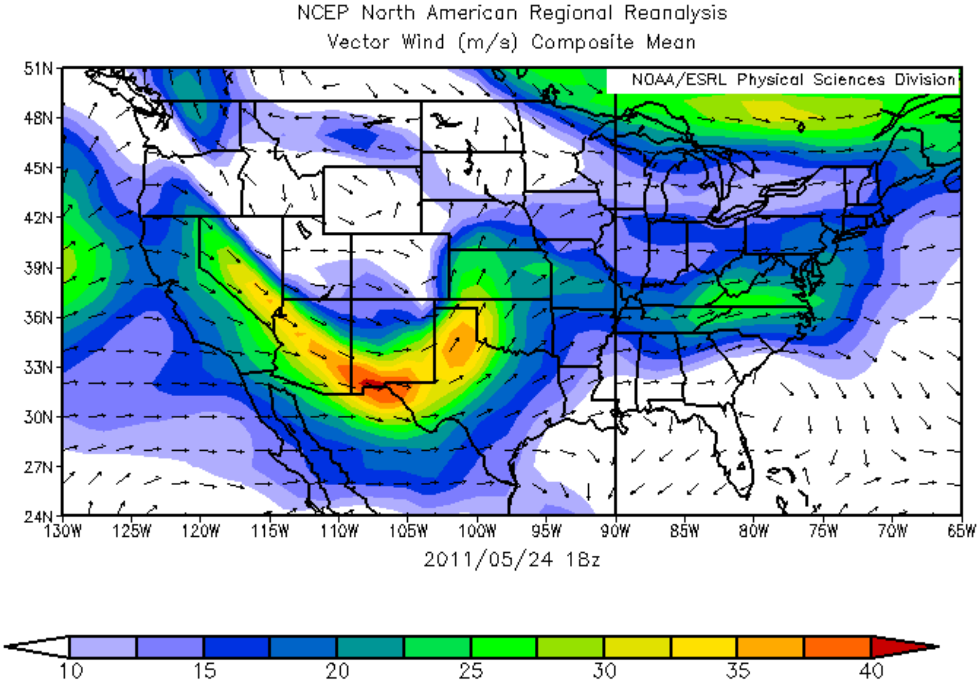

Figure 27. 500 mb vector wind (m/s) composite mean between 10:00L-13:00L on May 24, 2011.

In addition to the 800 mb and 500 mb vector maps, the 250 mb map also shows the presence of a very strong jet streak making its way to Oklahoma at 13:00L on May 24th (Figure 28). Southwestern Oklahoma was on the very edge of the left flank region of the jet stream, the region known to have lift due to positive vorticity advection and rising air aloft. Greater divergence aloft and weaker convergence at the surface and a drop in surface pressure means the low-pressure center will intensity and deepen.

High CAPE values were present on the order of 3200 J/kg. The downstream atmosphere accompanied by very high CAPE values, steep lapse rates, and a moist boundary layer were the essential ingredients for supercells to form along the dry line as it pushed eastward.

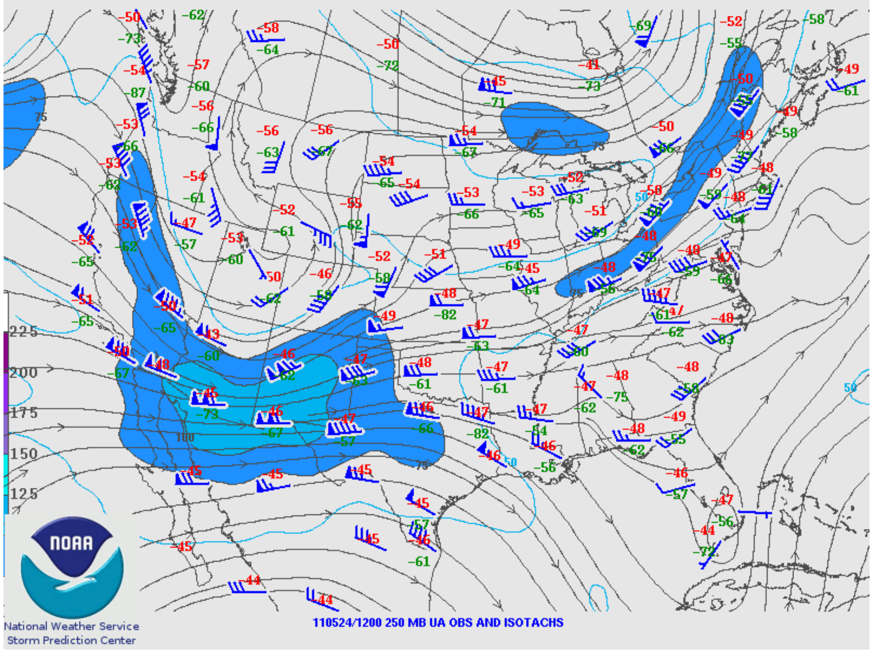

Figure 28. SPC 250 mb upper-air analysis at 13:00L on May 24, 2011.

Figure 29 shows the high CAPE values in Texas, Oklahoma, and parts of Kansas, Arkansas and Missouri. The highest CAPE values were in central and southern Oklahoma, and northern parts of Texas by the Red River. The CAPE values show a gradient similar to the pattern of the supercells that formed along the dry line. Based on preliminary data, over 50 tornadoes were reported and there were several hundred reports of wind and hail.

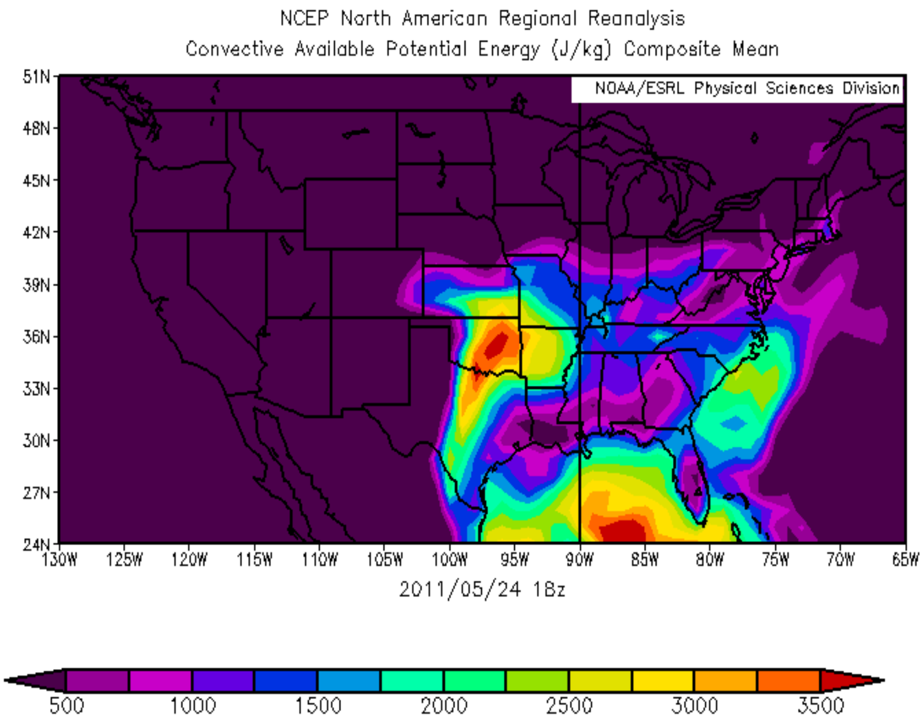

Figure 29. CAPE composite mean between 10:00L-13:00L on May 24, 2011.

This case event acts as a counter example to the previous two events because the LLJ is present on this day (even though this day was classified as SB-noLLJ). Nonetheless, the latent heat and sensible heat fluxes were still large enough for the possibility of some coupling between the land-surface and atmosphere (Figure 30). The highest latent heat flux values were found in far eastern Oklahoma and much of Arkansas and Missouri. The latent heat flux in western Oklahoma was about -300 W/m^2. There is a clear distinction between this region and Texas. Much of Texas experienced 0-10 W/m^2 latent heat flux values. This is likely due to the extremely dry air over this region. In contrast, the sensible heat flux over Texas and New Mexico are very high and values in Oklahoma were around -350 W/m^2. The latent heat and sensible heat fluxes on May 24, 2011 were higher than the values on August 10, 2003 (Case #2).

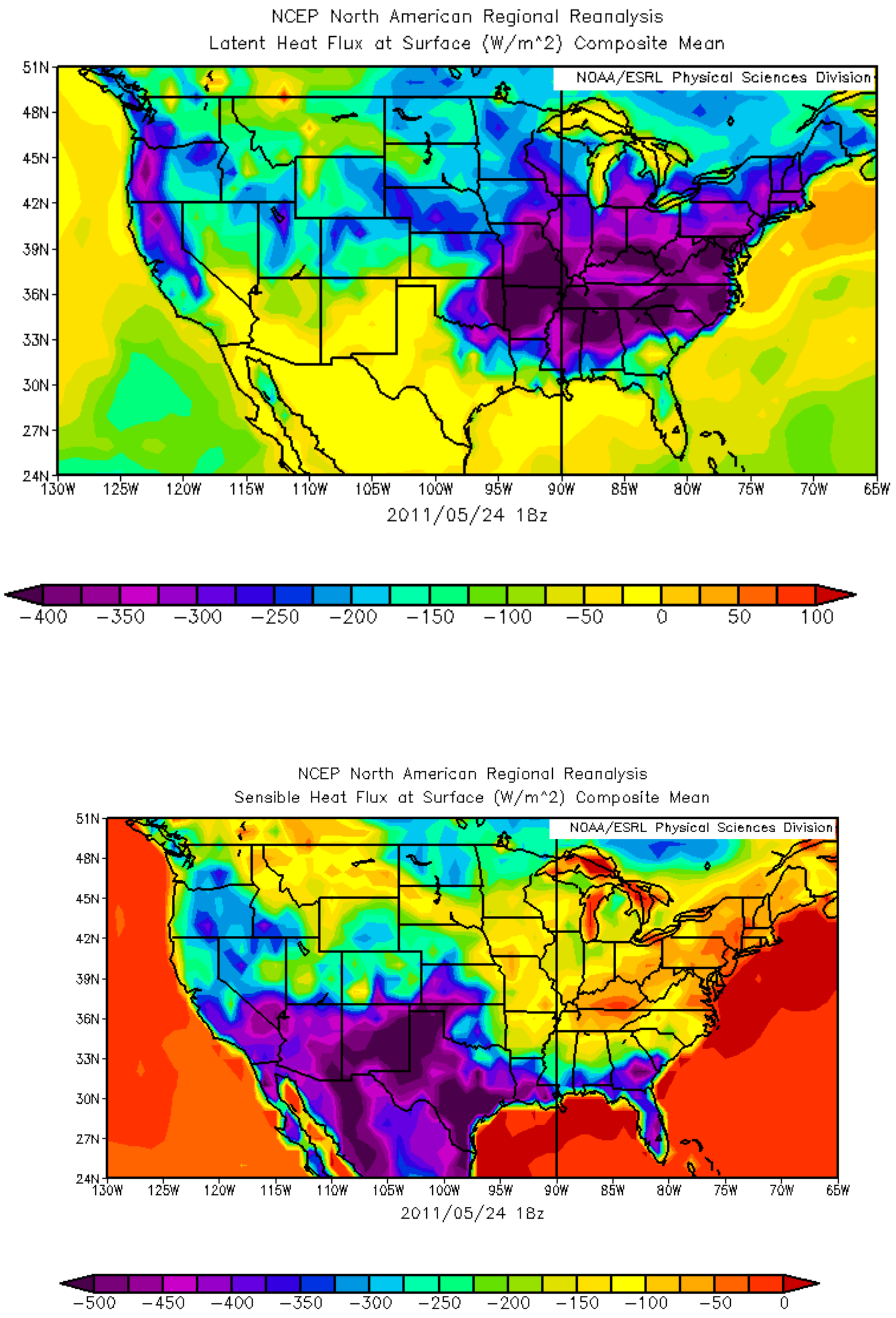

Figure 30. (Top) Latent heat flux at the surface (W/m^2) composite mean. (Bottom) Sensible heat flux (W/m^2) composite mean on May 24, 2011.

Soil moisture percentiles are considered to be wet for the CMOPRH events, 0.71, 0.80, 0.98, respectively. However, where the point of convective initiated is only considered as dry. A strong soil moisture gradient on this day may be the reason for the stark contrast. Nonetheless, it is more likely atmospheric conditions overpowered the land-atmospheric coupling on this day. With the LLJ presence, it's difficult to pinpoint factors that could contribute to possible land surface and atmosphere interactions. This event shows that the synoptic classification developed by Frye and Mote (2010) does not work perfectly. There are some days that are misclassified. In this case, the LLJ was present and therefore this event is not one that is only due to local land-surface forcing. This event is able to show the number of atmospheric conditions that were present and created the perfect environment for a severe weather event.

Table 3. Temperature and humidity anomalies and VWC and percentiles for May 24, 2011.

Event	Temp (1000-900 mb)	Temp (850-700 mb)	Humidity 1000-900 mb)	Humidity (850-700 mb)	Percentiles
E	0.83	0.80	1.89	1.83	0.71
F	0.91	0.85	1.72	1.79	0.80
G	0.942	0.90	1.75	1.70	0.98
Actual	N/A	N/A	N/A	N/A	0.51

Case Study 4: June 19, 2007

The environmental conditions on June 19, 2007 were very favorable for severe thunderstorms according to the SPC (Figure 31). A mesoscale low-pressure system centered over northern

Colorado accompanied by a dry line and a quasi- stationary front running through Kansas were the main focuses on this day. Severe thunderstorms were expected to develop due to the combination of deep-layer shear and extreme instability during the warm afternoon hours. Rapid cell development was expected in Northern Oklahoma and the Texas Panhandle with substantial destabilization. A diffuse warm front move northward around 16:00L (Figure 32). SPC reported extreme instability in areas south of the front and CAPE values in excess of 5000 J/kg (SPC Mesoscale report #1202, 1206, 1207). Several clusters of severe storms developed and propagated southwestward late in the afternoon. These clusters collided with several other severe storms and an upscale convective evolution was formed at 22:00L (Figure 33).

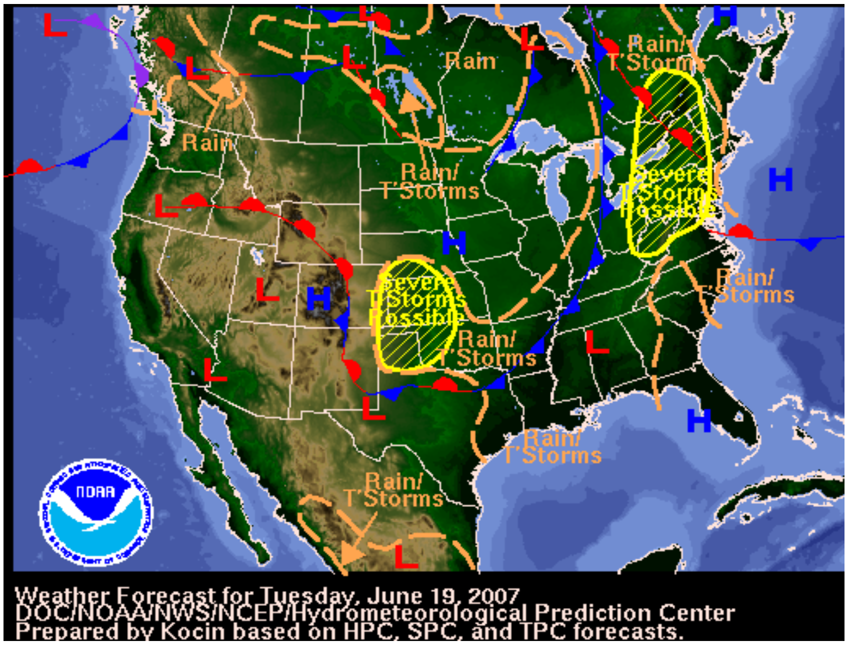

Figure 31. WPC weather forecast map from the morning of June 19, 2007.

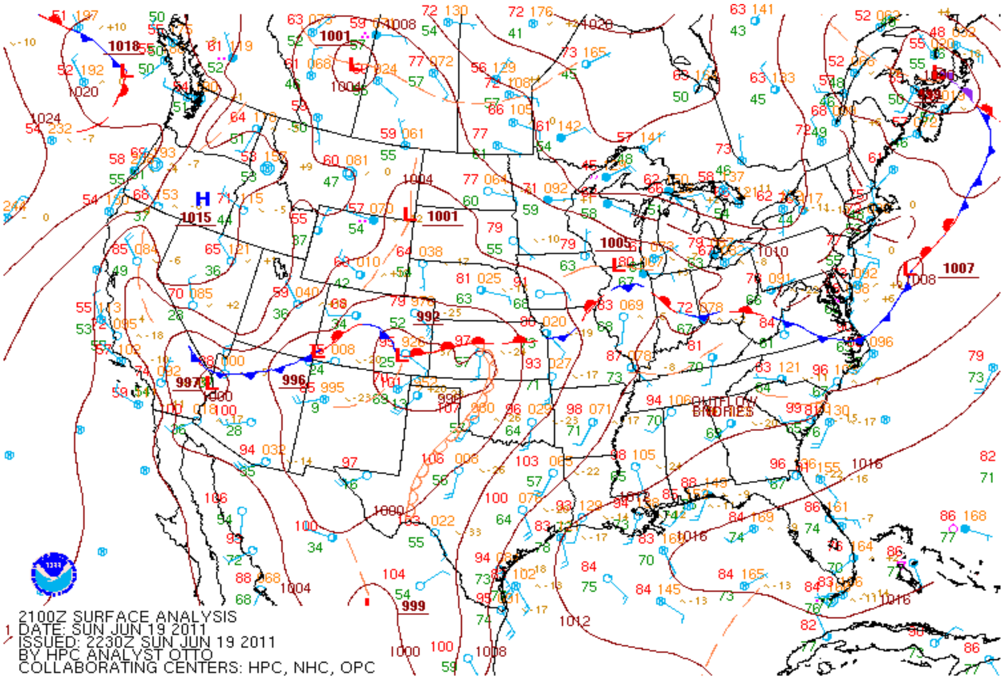

Figure 32. NWS Surface Analysis at 1958Z (14:25L) on June 19, 2007.

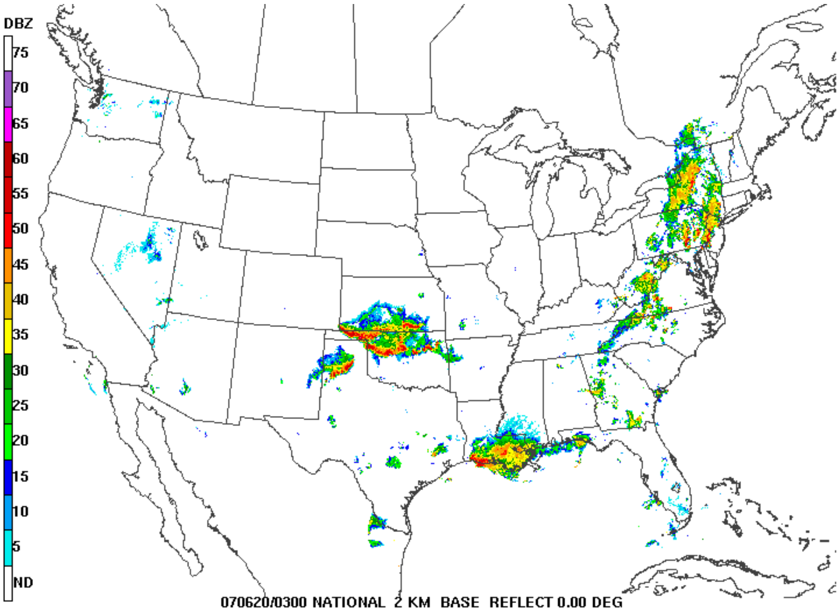

Figure 33. SPC National 2 KM base reflectivity over the Great Plans at 0300Z (22:00L) on June 19, 2007.

Two CMORPH events [(H) 35.125˚ N, 98.125˚ W; (I) 36.375˚ N, 97.875˚ W] took place on this day (Figure 34). Both events H and I were grouped into Cluster 3. The point of initiation (POI #4) (37.557˚ N, 98.0872˚ W) occurred at 22:00L and was closest to event I. Most of the supercell thunderstorms developed and strengthened over the same area and moved south very slowly.

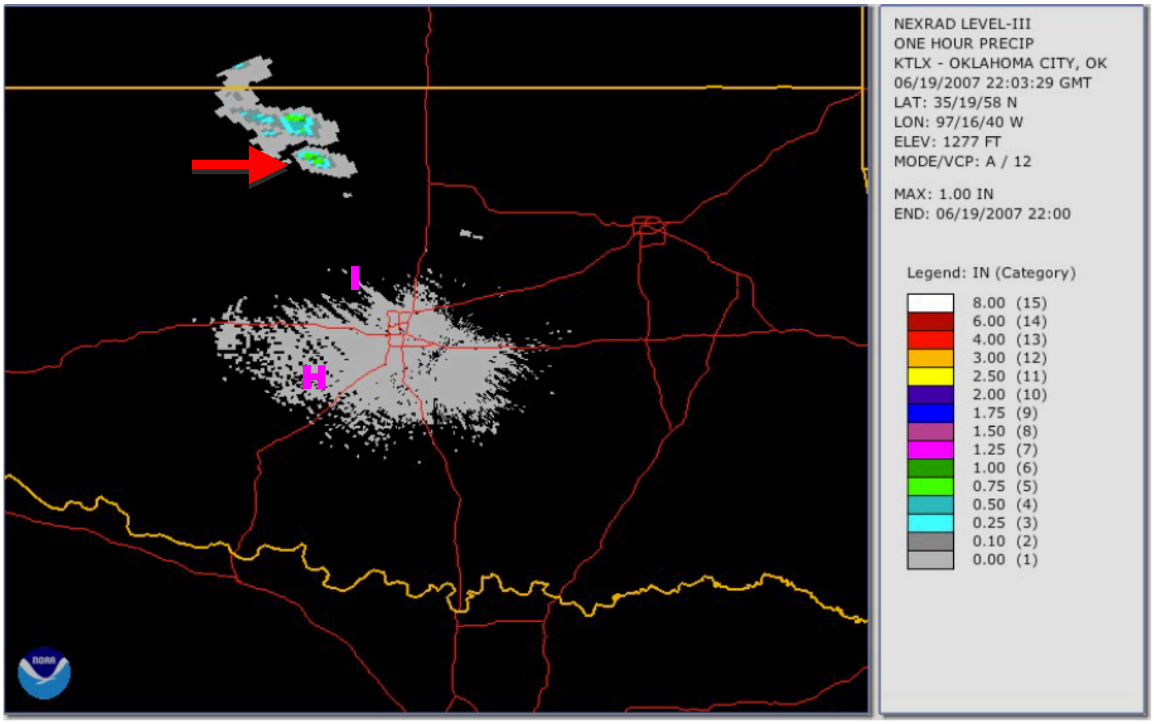

Figure 34. NEXRAD Level-III One hour precipitation taken from KTLX – Oklahoma City at 17:00L on June 19, 2007. Red arrow denotes event of interest and point of initiation.

The HYSPLIT model shows both air parcels moving in from the Gulf of Mexico (Figure 35). Unlike case study 3 on May 24, 2011, the air parcels did not travel as quickly or as far as the air parcels that afternoon. The atmospheric environment became very unstable as the afternoon continued and as temperatures climbed, supercells formed along the dry line. The 500 m air parcel stayed close to the surface until 00Z June 19th and then slowly began to rise. The 1000 m air parcel is a slightly more variable over the past 72 hours. It began rising about the same time as the 500 m air parcel and this occurred in North Texas almost 24 hours before the point of initiation.

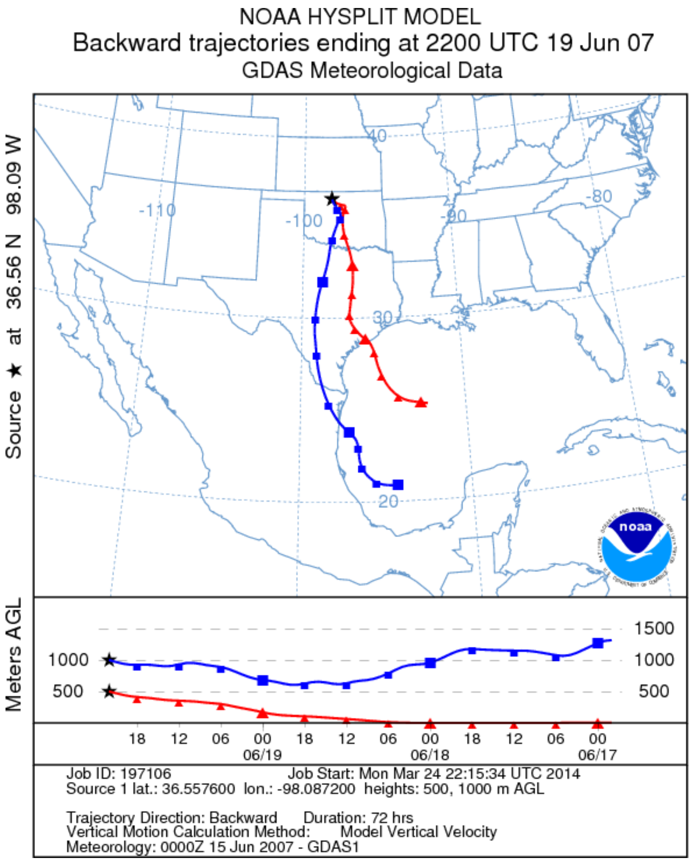

Figure 35. Backtrack trajectory of two air parcels on June 19, 2007: Blue line represents the air parcel that is 1000 meters above ground level (AGL) and the red line represents the air parcel) 500 meters AGL.

The 850 mb winds flowed from the southwest around 10 m/s before the event initiated (Figure 36). Winds in Texas flowed from the south bringing in warm moist air to the area. There were weak 850 mb winds through out much of the Great Plains. Western parts of Texas, Oklahoma, and Kansas had higher 850 mbs winds around 7 m/s, but for the most part, the lower-level winds were calm. The 500 mb winds were flowed much faster around 12 m/s and flowed zonally (Figure 37). Winds were definitely veering with height. Between the two maps, it is clear there was deep shear hours before the supercells rapidly formed.

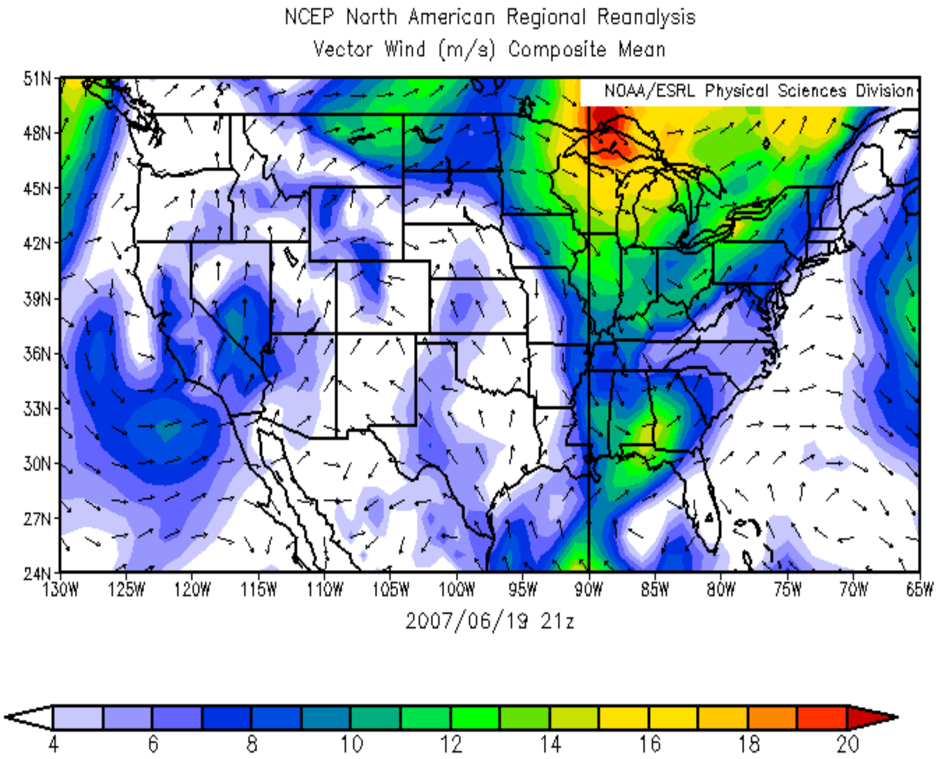

Figure 36. 850 mb vector wind (m/s) composite mean between 13:00-16:00L on June 19, 2007.

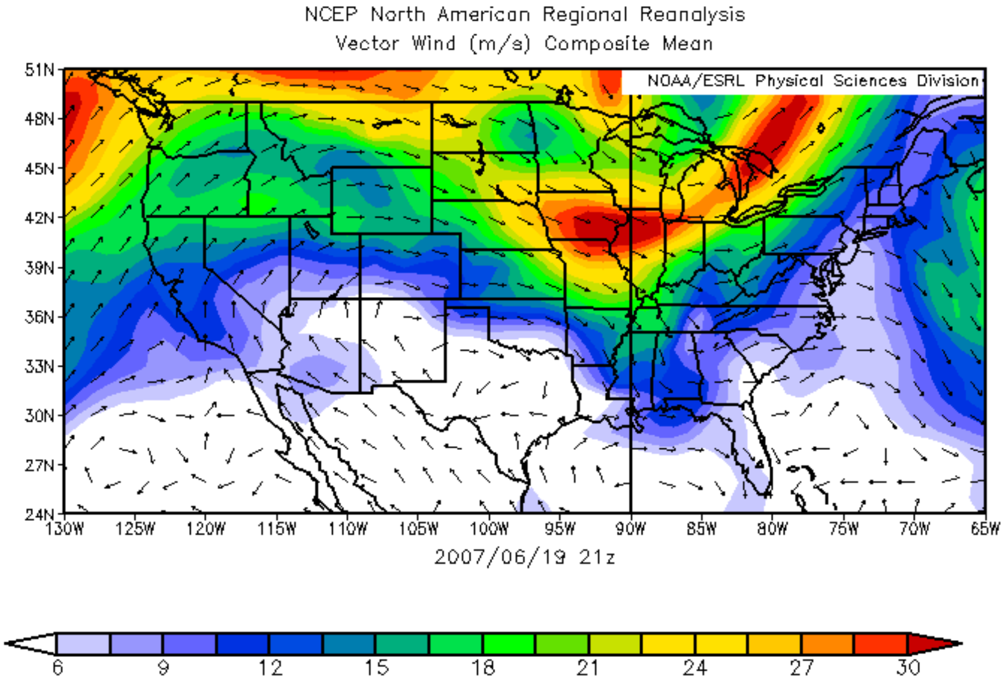

Figure 37. 500 mb vector wind (m/s) composite mean between 13:00-16:00L on June 19, 2007.

The CAPE values on this day were the greatest out of all of the case studies. CAPE values were already greater than 3000 J/kg by the early afternoon. The 3-hour mean composite of CAPE before the event was 5000+ J/kg (Figure 38). Extreme instability with CAPE values of 5000 J/kg and supporting shear were both supportive of rapid development of supercells with a high chance for large hail and damaging winds.

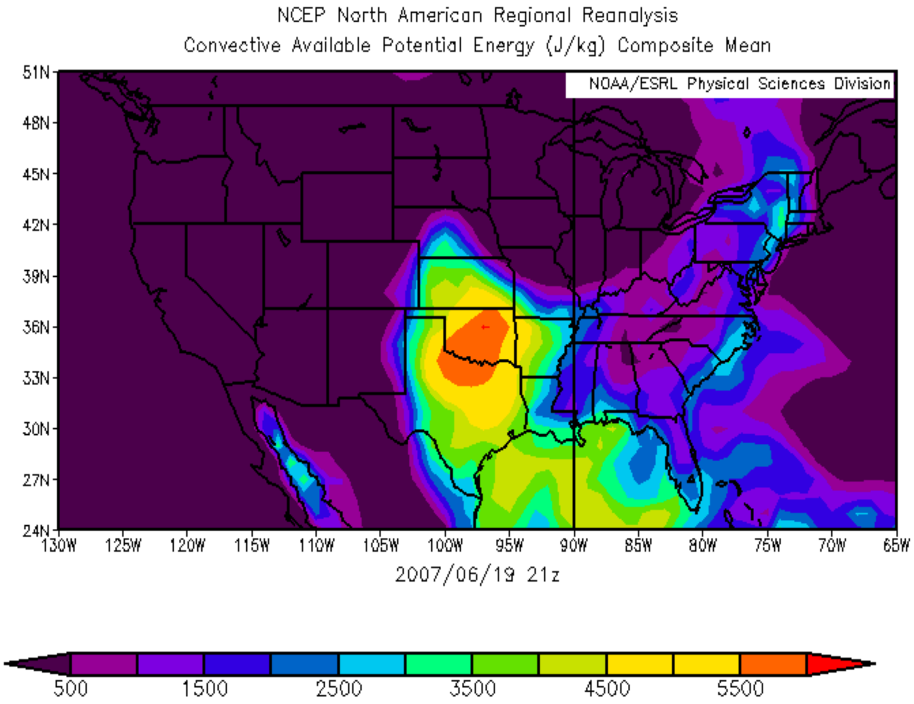

Figure 38. CAPE composite mean between 10:00L-13:00L on June 19, 2007.

Latent heat flux values were on the order of -275 W/m^2 in central and eastern Oklahoma (Figure 39). Latent heat fluxes increase farther north in southern Kansas and Missouri and northward. Towards the west into the Panhandle and far western Oklahoma, latent heat flux values were between -250 W/m^2 and -100 W/m^2 heat flux. Sensible heat flux was only about -50 W/m^2.

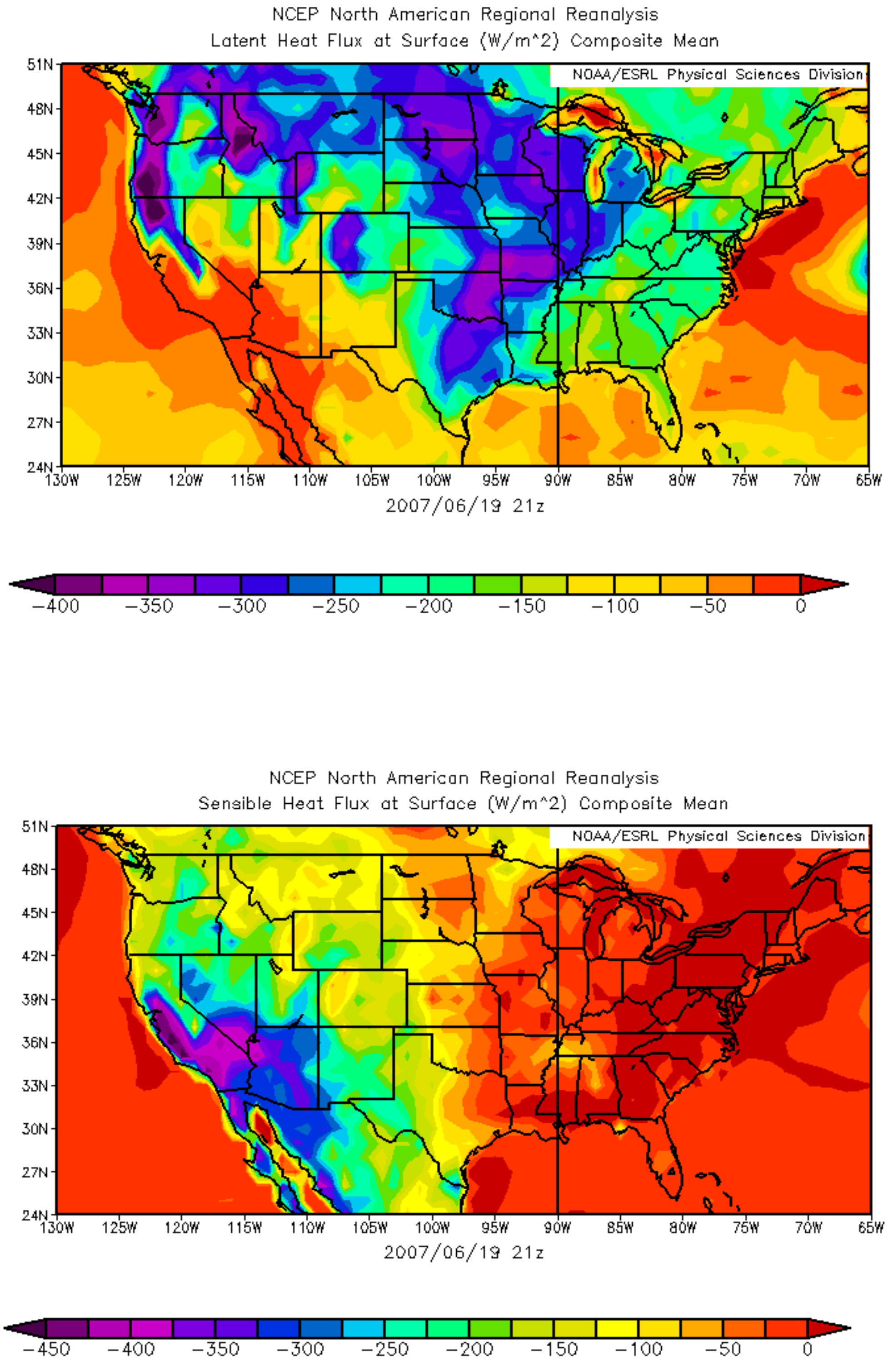

Figure 39. (Top) Latent heat flux at the surface (W/m^2) composite mean. (Bottom) Sensible heat flux (W/m^2) composite mean on June 19, 2007.

Soil moisture percentiles for CMORPH events H and I were 0.90 and 0.88, respectively. The percentile for the grid point closest to the location of the point of convection was 0.86 and matches closely with the percentiles from the CMORPH events. These soils would be described as wet soils. Temperature anomalies were slightly negative, except for Event I's temperature between 850-700 mb (Table 4). Humidity anomalies were higher than the other case studies. This suggests that a LLJ was present during the time of initiation. SPC did report there was a nocturnal development of a modest LLJ (SPC Mesoscale Discussion #1207). The land-atmosphere coupling for this event is slightly ambiguous, because of the atmosphere conditions during this event. The atmosphere was already unstable hours before any thunderstorm development. If there were any coupling between the two, it would have probably been small.

Table 4. Temperature and humidity anomalies and VWC and percentiles for June 19, 2007.

Event	Temp (1000-900 mb)	Temp (850-700 mb)	Humidity 1000-900 mb)	Humidity (850-700 mb)	Percentiles
H	-0.32	-0.05	2.81	2.04	0.90
I	-0.08	0.27	0.74	2.31	0.88
POI #4	N/A	N/A	N/A	N/A	0.86

CHAPTER IV

DISCUSSION AND SUMMARY

Case study 1, 2, and 4 represent cases that have moderate to strong land-atmosphere coupling. Many factors must be considered to determine whether or not the initiation of precipitation was mainly forced by atmospheric conditions or by land-surface conditions. A soil moisture classification based on quartiles for such a small number of events would not be ideal for this study. The medium calculated from these 9 events do not fully represent soil moisture conditions across Oklahoma and may not share the same criteria for drier than normal or wetter than normal soil conditions for all the events in Oklahoma. Therefore, soil conditions are based on soil percentiles and the medium value of 0.5 (50%) represents the normal soil moisture value. Based off of this classification, CMORPH event A and event B have drier than normal soil conditions. We expect there were strong land surface interactions with the atmosphere for case study 1. The very weak 850 mb winds eliminates the presence of a LLJ and the speed, path, and distance of the 500 m air mass allows us to believe there were interactions with the surface as it traveled (Table 6). The cooler temperatures based off temperature anomalies from June 1, 2003 is also related to the drier soils. It is expected that drier soils correspond warm temperatures and drier humidity conditions and wetter soils correspond with cooler temperatures and higher humidity anomalies. The humidity anomalies were hovering around the average value with humidity from event 1 slightly wetter than event 2 (Table 5).

Case study 2 also shows strong surface-atmospheric interactions. Like case study 1, the 850 mb winds in study case 2 were very low. In addition, the characteristics of the 2 air parcels as shown in the HYSPLIT models show similar patterns to the 500 m air mass from case study 1. Because these air parcels were moving very slowly, it is likely they were influenced by the land surface conditions. The CAPE values for case study 2 were the lowest among all of the case studies. These factors reinforce the conclusion that these two effects were impacted by ground conditions. CMORPH events 3 and 4 and the point of initiation on August 10, 2003 are all in the medium quartile meaning these soils are drier than average.

Case study 3 is the counter example to the other case studies. A LLJ was not present at 9:00L, however, the large line of supercell thunderstorms formed late in the afternoon. From the time the 850 mb vector winds were recorded in the morning to the vector winds three hours before the storms initiated, the atmospheric conditions changed. The 850 mb winds were just under the threshold for the LLJ to be present around 10 m/s (Figure 40). 6 hours later, the 850 mb winds grew stronger and were well above the required 12 m/s minimum vector winds. The percentiles for CMORPH events E, F, G had wetter than normal soil conditions. However, the soil percentile where the individual cell developed was over drier than normal soils. Although this case study does not represent an environment with no LLJ present, it does show the point of initiation occurred over drier than average soil conditions. The CMORPH events may have occurred over wet and very wet soils, but CMORPH events only represents the grid points where the highest precipitation rate occurred.

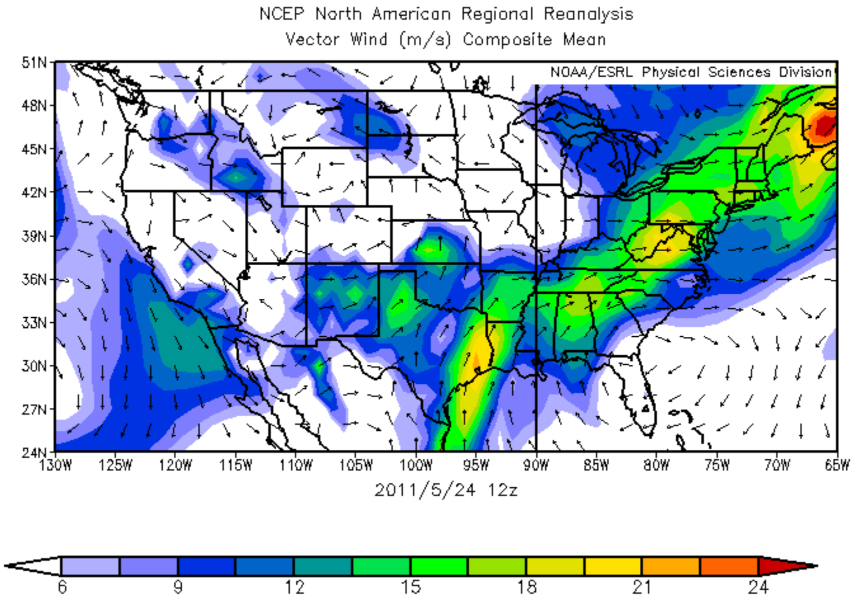

Figure 40. 850 mb vector wind (m/s) composite mean between 7:00-10:00L on May 24, 2011.

Case study 4 was chosen based on the same criteria as case study 1 and 2. However, there are multiple characteristics about the storms that developed on June 19, 2007 compared to the other two days. The 850 mb vector winds were weak, which followed the LLJ criteria. The very high CAPE values are a concern; because it is possible the atmospheric conditions (e.g., extreme CAPE values and severe instability) were suitable for rapid development of thunderstorms without the influence from surface conditions. Nonetheless, the high latent heat flux values are still important to consider. The large energy exchange from the ground to the atmosphere does illustrate the possibility of moderate land-atmosphere interactions. The soil percentiles from events H and I are both in the upper quartile. At the point of initiation, the soil percentile represented wetter than normal soil conditions.

We expect that above (below) normal temperatures and below (above) normal humidity to correspond with dry (wet) soils. Temperature anomalies from CMORPH events H and I were slightly cooler than average, but had very high soil percentiles. Higher temperature anomalies from CMORPH events E, F, and G are also associated with high soil percentiles. Humidity anomalies and soil percentiles demonstrate the expected positive trend. Further work outside of this study will need to be done to see if the temperature-soil moisture relationship found in this thesis is robust once more events are analyzed.

Table 5 shows a compilation of the 9 CMORPH events as well as the 4 points of initiation from the 4 days. Also listed are the temperature and humidity anomalies taken at multiple levels and soil percentiles. Table 6 shows all of the atmospheric variables during the 4 days.

Table 5. Temperature and humidity anomalies shown with soil percentile for all events.

Event	Date	Latitude	Longitude	Temp 1000-900 mb	Temp 850-700 mb	Humidity 1000-900 mb	Humidity 850-700 mb	Soil Percentile
A	06/01/03	35.125	-97.125	-0.88	-0.75	0.87	0.46	0.24
B	06/01/03	35.375	-97.375	-0.66	-0.21	0.22	-0.51	0.47
POI #1	06/01/03	34.775	-97.179	N/A	N/A	N/A	N/A	N/A
C	08/10/03	35.125	96.875	-0.04	-0.12	-0.46	-0.28	0.36
D	08/10/03	35.125	-95.625	-.002	-0.13	-0.66	-0.40	0.52
POI #2	08/10/03	34.27	95.415	N/A	N/A	N/A	N/A	0.41
E	5/24/11	34.875	97.125	0.83	0.80	1.89	1.83	0.71

F	5/24/11	35.125	98.375	0.91	0.85	1.72	1.79	0.80
G	5/24/11	36.123	-98.125	0.942	0.90	1.75	1.70	0.98
POI #3	5/24/11	34.60	-98.750	N/A	N/A	N/A	N/A	0.51
H	06/19/07	35.125	-98.125	-0.32	-0.05	2.81	2.04	0.90
I	06/19/07	36.375	-97.875	-0.08	0.27	0.74	2.31	0.88
POI #4	06/19/07	37.557	-98.087	N/A	N/A	N/A	N/A	0.86

Table 6. Sensible and latent heat fluxes, 850 mb and 500 mb vector winds, CAPE for all event days.

Event	Sensible (W/m^2)	Latent (W/m^2)	850 mb (J/kg)	500 mb (J/kg)	CAPE (J/kg)
06/01/03	-350	-275	<6	10	~750
08/10/03	-100	-175	<4	12	~500
05/24/11	-300	-280	~17	25	~3200+
06/19/07	-60	-360	4	12	~5500+

Based on the 13 cases (9 CMOPRH and 4 initiation points) examined in this study, rain falls preferentially over dry (or drier than normal) soils rather than wet soils. It is difficult to compare the soil moisture percentiles from CMORPH events, because these percentiles only represent the location (grid point) with highest rainfall rate. That does not imply the storm initiated over that grid point. Therefore, the percentiles for the CMORPH events may not accurately represent the soil conditions when convective initiation occurred Except for POI #4 from June 19, 2007, the soil conditions for the other points of initiation occurred over drier soils. More events will need to be analyzed to determine whether thunderstorms are more likely to develop over drier soils. These case studies only represent a small number of events classified as SB with no LLJ present.

It is necessary to examine other events and see whether there are any reoccurring patterns between 850 mb and 500 mb vector wind patterns and the path and speed of air parcels hours before an event. This study has helped create one methodology to determine the land-atmospheric coupling by examining the initiation of thunderstorms.

Limitations

While this study answered the main research question, there are limitations to this study that will need to be addressed in the future. Some of the limitations of this study include:

i. The synoptic environment classification: Atmospheric conditions between 0900UTC and when the points of initiation occurred may have changed
ii. Subjectively choosing a specific station, e.g. Oklahoma City station, and choosing events within a certain distance away from the radar site
iii. Subjectively choosing unique and "interesting" events
iv. CMORPH events only describes grid point of maximum precipitation rate: This does not describe the point of initiation
    a. Soil moisture measurements may not be available for specific point of initiation
v. Only analyzed 9 CMORPH events out of 193 events (4 days)

Future work

Future work is needed to determine how well the cluster analysis performed. One issue that remains unresolved is whether events within a cluster share similar storm characteristics. For example, most of the events within Cluster 3 could have all formed outside of a large stratiform event or they could be associated with an extensive squall line. Daily weather maps will also be useful to see whether a frontal system or a pressure system influenced these convective events. Further work includes analyzing more cases from each cluster to establish characteristics of each cluster. Understanding the storm characteristics will be helpful in determining how accurate the classification is.

In addition to completing more case studies, I am interested in classifying all the SB-noLLJ events based on storm type and humidity and temperature anomalies. Lastly, soil moisture gradient maps would be useful to determine whether there was a large soil moisture gradient present during these events. This would help explain why soil conditions for CMOPRH events differed than the soil conditions at the points of initiation. There is still a lot of work that can be done with these events, but this research project has gotten me one step closer.

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