

AN EMPIRICAL STUDY OF THE RELATIONSHIP BETWEEN SOIL MOISTURE
AND CONVECTION IN THE SOUTHERN GREAT PLAINS

by

JOHN DALE FRYE

(Under the Direction of Thomas L. Mote)

ABSTRACT

Land surface properties, particularly soil moisture, have been shown to alter the atmosphere's planetary boundary layer (PBL) at many spatial and temporal scales. Changes in the PBL can lead to conditions that promote or inhibit the development of convective thunderstorms. This dissertation examines the relationship between soil moisture and two aspects of the convective environment in the southern Great Plains from 1998 to 2004: (1) diurnal growth of the planetary boundary layer, and (2) measures of atmospheric stability, including (convective available potential energy (CAPE), lifted index (LI), and convective inhibition (CIN)). This work also examines the relationship between soil moisture, gradients in soil moisture and the location of convective development. The synoptic-scale environment can also promote or inhibit convective development. Therefore, this work also examines how these relationships change under various synoptic-type days. This research is enhanced by the use of soil moisture estimates from the Tropical Rainfall Measuring Mission Microwave Imager and atmospheric soundings from the North American Regional Reanalysis.

Moderate soil moisture (15-30%) and moderate soil moisture gradient (1.5-2.0% km⁻¹) are shown to be critical values when examining the role of this surface property on

convection. The diurnal growth of the boundary layer is greatest within this range of soil moisture values, allowing more turbulent thermals to reach the level of free convection. Within this range of soil moisture values, CAPE is lower and LI is higher than over wetter and drier soils and the CIN values are highest. The increase in CIN indicates a stronger cap to convection exists over areas with moderate soil moisture, allowing a greater accumulation of convective energy during the day. Once the stronger caps are eroded, the convection tends to develop more quickly and become more organized. The moderate soil moisture and soil moisture gradient values are also shown to represent a “tipping point” for the probability of convection initiation. These elements of convective development are also related to the synoptic-scale environment, particularly the presence or absence of the low-level jet (LLJ).

INDEX WORDS: Convection, Soil Moisture, Planetary Boundary Layer, Convective Initiation, Atmospheric Stability, Great Plains

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DEDICATION

I would like to dedicate this dissertation to my wife, Shannon, sons, Broderick and Camden, and my daughter, Adalynn. Each of you has given me the encouragement, strength, and inspiration needed to complete this task. Thank you for sacrificing all that you have to help me accomplish this dream.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1. Introduction

Land surface characteristics have been shown to influence weather patterns at multiple spatial and temporal scales (Pielke and Segal 1986, Lanicci et al. 1987, Chen and Avissar 1994, Kunkel et al. 1994, Pan et al. 1995, Emori 1998, Baker et al. 2001, Koster et al. 2003, Capehart et al. 2004). One such characteristic that has been investigated is soil moisture. Results from multiple atmospheric general circulation models show soil moisture has a positive feedback on moisture characteristics in the planetary boundary layer (PBL) and precipitation patterns at continental scales (Koster et al. 2003). The effects of soil moisture on precipitation at smaller spatial scales (i.e., meso-alpha to meso-beta) vary greatly based on location of the study region and meso- to synoptic-scale atmospheric conditions (Barnston and Schickedanz 1984, Fast and McCorcle 1991, Chen and Avissar 1994, Findell and Eltahir 1997, Pielke 2001, Findell and Eltahir 2003a, Findell and Eltahir 2003b, Cook et al. 2006, Taylor and Ellis 2006, Wu et al. 2007, Meng and Quiring 2008).

Two extreme climatic events that have been associated with soil moisture in the last 20 years occurred during the summers of 1988 and 1993 in the Midwestern United States. These two seasons have been shown to have a positive feedback between soil moisture and precipitation that created prolonged drought and flood conditions, respectively (Atlas et al. 1993, Kunkel et al. 1994, Pan et al. 1995, Bates et al. 2001,

Dominguez and Kumar 2005). Dry soil conditions in the Midwest during 1988 enhanced the prolonged drought by limiting the amount of moisture available for evapotranspiration into the lower portion of the atmosphere (Atlas et al. 1993). The conditions during the summer of 1993 were the opposite; the region experienced above average precipitation since the summer of 1992, which led to anomalously high soil moisture content. With soils already saturated from the previous year, the above average precipitation in the summer 1993 caused flood waters to rise and affected cities all along the Missouri and Mississippi River Valleys (Kunkel et al. 1994). While these two seasons highlight the relationship between soil moisture and precipitation, Oglesby and Erickson (1989) showed the lack of soil moisture is a key component to a majority of persistent droughts.

Recently, Koster et al. (2004) identified a “hot spot” in soil moisture feedback within the Great Plains of the United States (Fig. 1.1), including and within proximity to the regions affected by the 1988 drought and 1993 floods. In addition to the hot spot found in the Great Plains, Koster et al. (2004) found similar locations around the world (i.e., the Sahel in Africa, India, and South America). The hot spots are areas where an ensemble of atmospheric general circulation models (AGCMs) indicated a strong land-atmosphere coupling between soil moisture and summer precipitation values. The locations of the hot spots are not unexpected due to the regions experiencing drier climates where evaporation rates are sensitive to soil moisture conditions (Koster et al. 2004).

Some of the hot spots around the world (identified by Koster et al. 2004) are in areas where short-term, observation-extensive field campaigns (e.g., HAPEX-Sahel,

IHOP-2002) were conducted to determine the role soil moisture has on atmospheric conditions that lead to convection (Taylor et al. 1997, Taylor and Lebel 1998, Weckworth et al. 2004, Weckworth and Parsons 2006). These field campaigns typically lasted one convective season or less, covered only a small spatial area (i.e., HAPEX-Sahel covered a $1^\circ \times 1^\circ$ area), and had small number of stations that measure soil moisture content (Taylor et al. 1997, Taylor and Lebel 1998, Robock et al. 2000). The data collected in these field campaigns have helped to develop parameterization schemes for atmospheric models to better handle variations in soil moisture and its effect on convective precipitation patterns.

1.2. Literature Review

a. Planetary Boundary Layer

The boundary layer is defined as the lowest layer of the atmosphere which is directly influenced by the Earth's surface (Stull 1988, Arya 2001). According to Stull (1988), the forcing mechanisms within the boundary layer operate on the order of minutes to an hour and include: frictional drag, heat transfer, evaporation and transpiration, and modifications of flow by the terrain. This layer is also unique due to its diurnal evolution, especially over land surface; however, this evolution is not fully understood (Teixeira et al. 2008). The evolution of the boundary layer has been shown to be influenced by numerous factors including, but not limited to: synoptic scale pressure systems, moisture conditions above the boundary layer, and land surface properties such

as soil moisture distribution (Stull 1988, Chang and Wetzel 1991, Ek and Mahrt 1994, Arya 2001, Taylor et al. 2003).

Alterations in the soil moisture cause changes in the sensible and latent heat fluxes. Areas with high soil moisture will have lower sensible heat flux and thus lower temperature than areas with drier soil. Theoretically, the growth of the planetary boundary layer is dependent on these heat fluxes (Pielke 2001) and thus the diurnal change in planetary boundary layer height can be an accurate proxy for changes in the atmospheric properties in the lower levels. An increase in the sensible heat flux (i.e., higher air temperatures) creates a thicker boundary layer. According to theoretical models and results from short-term field campaigns, regions that lack soil moisture experience an increase in the sensible heat flux and an increase in boundary layer height (McCumber and Pielke 1981, Zhang and Anthes 1982, Ookouchi et al. 1984, Lanicci et al. 1987, Fast and McCorcle 1991, Segal and Arritt 1992, Liu et al. 1999, Chang et al. 2000, Berbery et al. 2003, Trier et al. 2004, Betts and Viterbo 2005, Douglas et al. 2006, Betts 2007).

b. Pre-Storm Environments

There are multiple metrics used to determine the convective nature of the atmosphere. Three of the most widely used are convective available potential energy (CAPE), lifted index (LI), and convective inhibition (CIN). LI is a measure of the temperature difference at 500-hPa between the environmental air and of an air parcel that is lifted adiabatically from the surface to that level (Galway 1956). While LI only measures stability at one level, CAPE and CIN are measures of atmospheric stability

throughout a layer of the atmosphere. These two measures utilize the principle of buoyancy to determine the stability of the atmosphere (Weisman and Klemp 1982, Djuric 1994). To determine CAPE and CIN the environmental temperature profile is compared to the temperature profile of an air parcel lifted adiabatically from the surface. The levels where the parcel temperature is less than the environmental temperature have negative buoyancy and thus inhibit convection (i.e., CIN). However, if the parcel temperature is warmer than the environmental temperature the atmosphere is positively buoyant and shows that the warmer air parcel will rise thus create convection (i.e., CAPE).

All the above measures compare parcel temperatures and environmental temperatures; thus, they are highly dependent on the vertical profile of the environmental temperature. Not quite as apparent is the control the low-level moisture levels have on these convective metrics (Pielke 2001, Donner and Phillips 2003). All the metrics lift a parcel adiabatically to determine stability. When a parcel starts its ascent from the surface it is lifted dry adiabatically (i.e., with constant potential temperature) until it reaches saturation. Thus, the closer the parcel is to saturation at the surface (i.e., the closer the dew point temperature is to the air temperature), the sooner it will reach saturation as it is lifted through the atmosphere. Once the parcel reaches saturation, it is then lifted moist adiabatically (i.e., with constant equivalent potential temperature) until it completes its ascent through the atmosphere. Pielke and Zeng (1989) and Pielke (2001) have shown that increases in soil moisture and low level dew point temperatures create a more unstable atmosphere (i.e., higher CAPE values and lower LI values).

c. Convective Initiation

Variations in soil moisture create discontinuities in boundary layer height (i.e., higher heights over drier soils) and discontinuities in potential energy for convection in an area (i.e., drier soils tend to create less potential energy for convection). Thus, the sign of the feedback of soil moisture on convective initiation at small scales (i.e., meso and storm scale) is unclear. The soil moisture feedback on convective initiation has been shown to vary by region, pre-existing synoptic-scale processes, and atmospheric model used in simulations (Rabin et al. 1990, Ek and Mahrt 1994, Taylor et al. 1997, Taylor and Lebel 1998, Taylor et al. 2003, Findell and Eltahir 2003a, Findell and Eltahir 2003b, Taylor and Ellis 2006). Ek and Mahrt (1994) found that convection initiates first over regions with a large sensible (latent) heat flux when the synoptic conditions above the boundary layer were drier (wetter) and had strong (weak) stratification. Conversely, Taylor et al. (2003) found that the development of convection typically occurs where there is an abundance of moisture over wet soils due to the lowering of the lifting condensation level (LCL) and level of free convection (LFC).

Another area that has been a focus of convective development is along the boundary between two dissimilar air masses (Maddox et al. 1980). Multiple modeling studies have shown that changes in land properties can create mesoscale circulation patterns that can influence the low-level heat and moisture fields and help focus convective activity into a certain area (Sun and Ogura 1979, Ookouchi et al. 1984, Pielke and Segal 1986, Nicholson 1988, Avissar and Pielke 1989, Fast and McCorcle 1991, Chang and Wetzel 1991, Segal and Arritt 1992, Emori 1998, Liu et al. 1999, Pielke 2001, Carleton et al. 2001, Holt et al. 2006, Niyogi et al. 2006).

d. Synoptic-Scale Influences

An underlying theme in the above topics is the influence of the synoptic-scale weather patterns on the relationship between soil moisture and convection. When the area is influenced by a synoptic-scale baroclinic environment the relationship might be different versus when it is in a barotropic environment. Another feature that also influences the study region is a low-level jet (LLJ) originating from the Gulf of Mexico (Bonner 1968, Vasquez 2002). There have been multiple studies that have examined the influence that the synoptic-scale patterns have on mesoscale features, some of which are the focus of this dissertation (Stull 1988, Rabin et al. 1990, Ek and Mahrt 1994, Taylor et al. 1997, Taylor and Lebel 1998, Arya 2001, Pielke 2001, Findell and Eltahir 2003a, Findell and Eltahir 2003b, Taylor et al. 2003, Trier et al. 2004, Weaver 2004a, Weaver 2004b, Taylor and Ellis 2006). The relationship between soil moisture and the mesoscale features investigated in this dissertation will be examined based on the presence of a barotropic or baroclinic atmosphere at the synoptic-scale as well as if there is a LLJ present.

e. Soil Moisture Retrievals

Traditional techniques used to measure soil moisture (e.g., gravimetric, neutron probe, heat dissipation sensors) only provide point measurements (Hollinger and Isard 1994, Robock et al. 2000). However, soil moisture has large temporal and spatial heterogeneity that is not adequately captured with the point measurements (Engman and Chauhan 1995). In order to better assess variability in soil moisture, remote sensing techniques have been developed to provide a more extensive coverage temporally and

spatially (Wetzel et al. 1984, Wetzel and Woodward 1987, Jackson 1993, Engman 1995, Engman 1996, Walker and Houser 2001, Adegoke and Carleton 2002, Jackson et al. 2002, Bindlish et al. 2003, de Jeu and Owe 2003, Njoku et al. 2003, Vicente-Serrana et al. 2004, Walker and Houser 2004, Cashion et al. 2005, Jackson et al. 2005, Bindlish et al. 2006, Gao et al. 2006.)

Wetzel et al. (1984) developed an algorithm to infer soil moisture content using infrared (IR) data from geosynchronous satellite systems (e.g., Geostationary Operational Environmental Satellite [GOES]). The algorithm was developed based on the daily surface temperature change that resulted in the partitioning of latent and sensible heat over dry versus wet soils. Wetzel and Woodward (1987) utilized soil moisture measurements, computed from rain gauge data, to test this algorithm for a 5-day period. From this 5-day study it was concluded that applications using soil moisture data from IR remote sensing techniques should be limited to averaged values over larger (spatial and temporal) scales. Rabin and Schmit (2006) also found similar results utilizing GOES sounder IR data to measure changes in surface temperatures to calculate soil moisture values. Wetzel and Woodward (1987) found that normalized vegetation index (NDVI), which utilizes visible and near-infrared satellite data, had higher correlation with soil moisture than using temperature measurements to obtain soil moisture. Adegoke and Carleton (2002) also found similar results comparing NDVI and fractional vegetation index (FVC) to soil moisture measurements from stations in Illinois. The results showed averaged area values of NDVI and FVC had a higher correlation to soil moisture content and a lag period up to eight weeks existed between the NDVI/FVC and soil moisture. Sandholt et al. (2002) also utilized the NDVI combined with surface temperature

measurements to retrieve soil moisture information. The results mirrored those of Wetzel and Woodward (1987) and Adegoke and Carleton (2002) in that the measurements averaged over a larger spatial area had higher correlation to soil moisture.

While useful for inferring soil moisture, IR satellite data does have limitations and inherent errors. The main limitation is that no measurements are possible where cloud cover is present, because the cloud cover obscures the surface. The basis for the measurement is the change in surface temperatures throughout the day due to different partitioning of sensible and latent heat under dry or moist soil conditions (Wetzel et al. 1984, Wetzel and Woodward 1987, Adegoke and Carleton 2002, Sandholt et al. 2002). Errors in soil moisture measurements can also occur due to instrument error, atmospheric attenuation of the IR radiation, and low-level thermal advections influencing local surface temperatures (Wetzel et al. 1984). Some of these limitations/errors can be minimized or eliminated with the use of other remote sensing platforms. The development of microwave sensors aboard space-borne platforms has been shown to improve soil moisture measurements (Schmugge et al. 1980, Owe et al. 1988, Jackson and Schmugge 1989, Jackson 1993, Engman 1995, Owe et al. 1999, Walker and Houser 2001, Jackson et al. 2002, Bindlish et al. 2003, de Jeu and Owe 2003, Njoku et al. 2003, Vicente-Serrana et al. 2004, Cashion et al. 2005, Jackson et al. 2005, Bindlish et al. 2006, Gao et al. 2006).

Cashion et al. (2005) found, in a review of previous studies, that a lower frequency microwave channel (6.6 GHz), brightness temperatures showed the strongest relationship with soil moisture. They also showed that at 19 GHz there is a linear relationship between brightness temperatures and soil moisture. The findings in de Jeu

and Owe (2003) validated the use of the lower frequency microwave band to detect soil moisture utilizing the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) 6.6 GHz frequency brightness temperatures. Additional studies have been conducted using lower frequency synthetic aperture radar (SAR) and precipitation radars aboard satellite platforms (e.g., Tropical Rainfall Measurement Mission [TRMM], European Remote-Sensing Satellites [ERS]) (Shi et al. 1997, Moran et al. 1998, Moran et al. 2000, Oki et al. 2000, Kelly et al. 2003, Seto et al. 2003a, Seto et al. 2003b). Passive microwave techniques will be commonly employed until future soil moisture missions like Hydros become viable alternatives using L-band (1.25 GHz) radar techniques. Soil moisture retrievals from passive microwave instruments are also dependent on both sensor characteristics (i.e. polarization direction, observation angle, and frequency of bands) and characteristics of the material being sensed (i.e. electrical and thermal properties, surface roughness [including vegetation] and particle size, and vertical distribution) (Barrett and Curtis 1982, Engman and Chauhan 1995, Shi et al. 2002, Moran et al. 1998).

Techniques for estimating soil moisture with microwave remote sensing are based on the significant contrast in the dielectric characteristics between water and dry soil (Engman and Gurney 1991, Jackson 1993). According to Engman and Gurney (1991) the dielectric constant for water is significantly higher than the dielectric constant for dry soil. Consequently, as a dry soil has moisture added to it, the dielectric constant would increase and thus decrease the emissivity and brightness temperature, which is measured by the sensor aboard the satellite, due to less reflectivity of a wetter soil.

Another aspect that has been shown to be useful in determining the soil moisture content using microwave sensors is the separate horizontal and vertical polarizations. Cashion et al. (2005), in a study for the Little River Watershed in Tifton, GA, found that the differences between the horizontal and vertical polarization measurements can be utilized to determine the volumetric soil moisture using the TRMM Microwave Imager's (TMI) 10.65 GHz band. Polarization differences are used to determine soil moisture except when the vegetation cover was significant, as determined by NDVI. This led Cashion et al. (2005) to conclude, when determining soil moisture, TMI data alone are not very useful but when combined with ancillary data [i.e. Advanced Microwave Scanning Radiometer (AMSR) aboard AQUA and vegetation data from Moderate Resolution Imaging Spectroradiometer (MODIS)] the quality of the soil moisture information is greatly improved.

One disadvantage to microwave remote sensing of soil moisture is the depth into the ground that moisture is detected. The soil moisture product from TMI measures the top 0.5 cm (Gao et al. 2006). Despite the limited depth measured, Gao et al. (2006) found a strong correlation between the measurements of remotely sensed data and soil moisture from 5 cm neutron probes utilized by the Oklahoma Mesonet sites. Other studies have also shown moisture in the top soil layers have a higher correlation to convection in shorter temporal scales (i.e., 1-2 days); while deeper moisture in the soil is more critical after a long period without precipitation (Ek and Mahrt 1994, Taylor et al. 1997, Taylor et al. 2003, Taylor and Ellis 2006).

1.3. Research Questions

The primary objective of this research was to investigate the role of soil moisture on convection in the southern Great Plains (Fig. 1.2) to determine if a positive or negative feedback exists between soil moisture and convection at the regional and smaller scales. The study region is located within one of the hot spots identified by Koster et al. (2004) (Fig 1.1). To acquire a more thorough understanding of the effect soil moisture has on convection, the following research questions are posed:

- How do alterations in soil moisture influence the height of the planetary boundary layer?
- What is the relationship between soil moisture and various metrics used to describe the convective nature of the atmosphere [i.e., convective available potential energy (CAPE), convective inhibition (CIN), and lifted index (LI)]?
- Is convection more likely to initiate over wet soils, dry soils, or the transition areas?
- How are the above relationships altered by changes in the synoptic-scale weather patterns that influence the southern Great Plains region?

In the first manuscript (Chapter 2), the relationship between soil moisture and diurnal growth in the planetary boundary layer is investigated. It is hypothesized that under similar synoptic-scale conditions the boundary layer growth will be greatest over the dry soils.

The second manuscript (Chapter 3) mainly focuses on the relationship between changes in soil moisture and the changes in the stability conditions as measured by CAPE, CIN, and LI. A secondary focus of that manuscript is to establish the synergistic

relationship between soil moisture and the larger synoptic-scale patterns, mainly the presence of a moist low-level jet. It is hypothesized that under similar synoptic conditions, instability will be greatest over regions over wetter soils.

The final manuscript (Chapter 4) further reinforces the relationship between soil moisture and convection by examining the locations of convective initiation (using ground-based weather radar) and its relationship between the soil moisture fields. It is hypothesized that under synoptically benign days, the convection will be more focused on the regions of transitions between wet and dry soils (i.e., where the mesoscale circulation patterns are established); and on days where the synoptic conditions are more favorable for widespread convection, the focus for convective initiation will be over wet soils.

All aspects of the present research are using newly developed data products to determine the relationships between soil moisture and convection. The first data product is daily soil moisture from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) (Gao et al. 2006). These data use microwave remote sensing platforms and other ancillary data to obtain a daily soil moisture product for the southern portion of the United States (Fig. 1.3). Additionally, the study uses the newly developed reanalysis data from the North American Regional Reanalysis (NARR) (Mesinger et al. 2006). This data set has a higher spatial resolution (32 km) and temporal resolution (3 hours) than the National Centers for Environmental Prediction (NCEP) Global Reanalysis data set. This data set allows users to perform a reanalysis of events at finer temporal and spatial resolutions.

The development of the TMI soil moisture data set and NARR data set has also allowed land-surface-atmosphere interactions, including soil moisture, to be investigated further. While there are multiple studies that have examined the influence of soil moisture on convection these studies have been: (1) modeling studies, (2) short-term field campaigns, and (3) case studies of past extreme weather events. What has been lacking is a long-term observational study. This dissertation fills the void in the research by examining the relationship between soil moisture and convection over a relatively long period (1998-2004).

1.4. Summary

Soil moisture has been shown to influence temperature and moisture fields in the lower part of the atmosphere in various case studies, modeling studies, and short-term field campaigns. The present study builds on this research by establishing a much needed long-term, observational-intensive study to examine the role of soil moisture on convection in the southern Great Plains. This is one of the first observational studies conducted on this area since the region was identified by Koster et al. (2004) as a hot spot for precipitation patterns being highly influenced by soil moisture conditions in various climate models. It is also one of the first studies to use the daily soil moisture data developed by the Land Surface Hydrology Group at Princeton University (data available at http://hydrology.princeton.edu/data.sm_tmi.php; also see Gao et al. 2006) and the NARR reanalysis data set to look at convective conditions in the study region. The results should be useful in the development of new techniques in the modeling of the land surface atmosphere interactions, an area that has been of concern in the research

community (Peters-Lidard et al. 2001, Betts 2004, Dirmeyer et al. 2006, Teixeira et al. 2008).

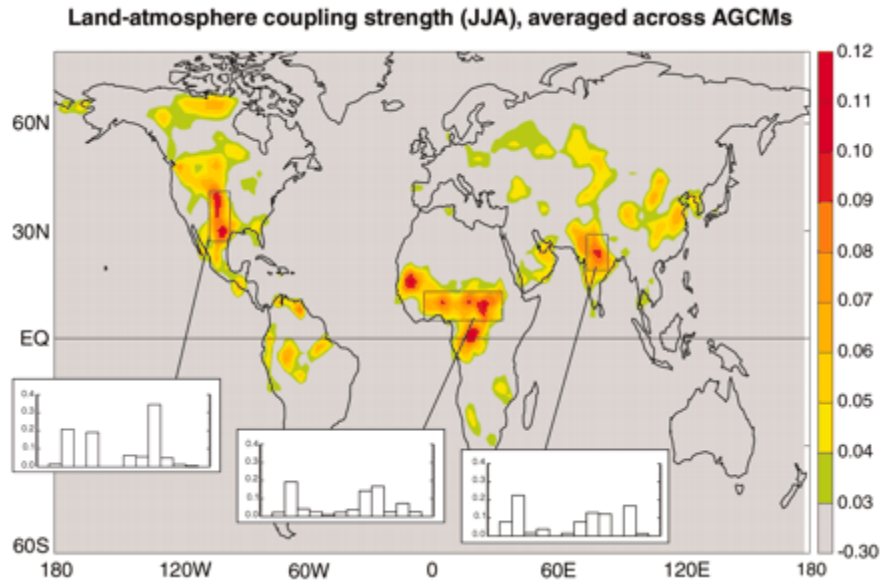


Fig. 1.1. Locations of land-atmosphere coupling hot spots around the world during June, July, August for 12 AGCMs (from Koster et al. 2004). Color scale represents the Ω difference (dimensionless) describing the strength of the soil moisture feedback on precipitation. Insets represent the strength of coupling for the 12 individual AGCMs in each particular hot spot region.

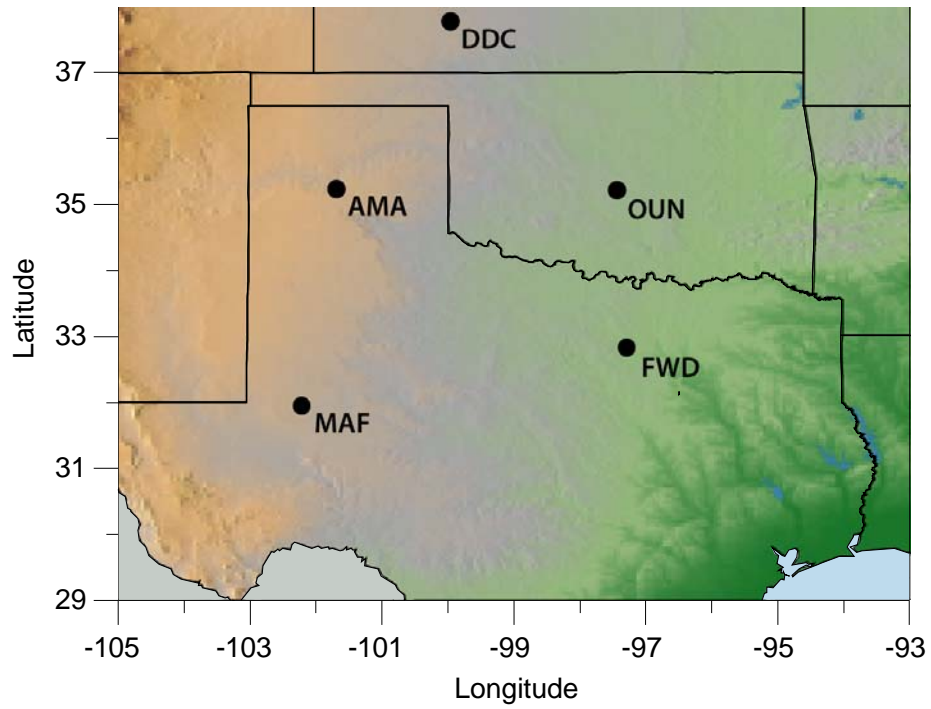


Fig. 1.2. Study region with the locations of radiosonde sites indicated. The radiosonde sites used to determine synoptic-type days were Amarillo, TX (AMA), Dodge City, KS (DDC), Fort Worth, TX (FWD), Midland, TX (MAF), and Norman, OK (OUN). Shaded relief from USGS (2003).

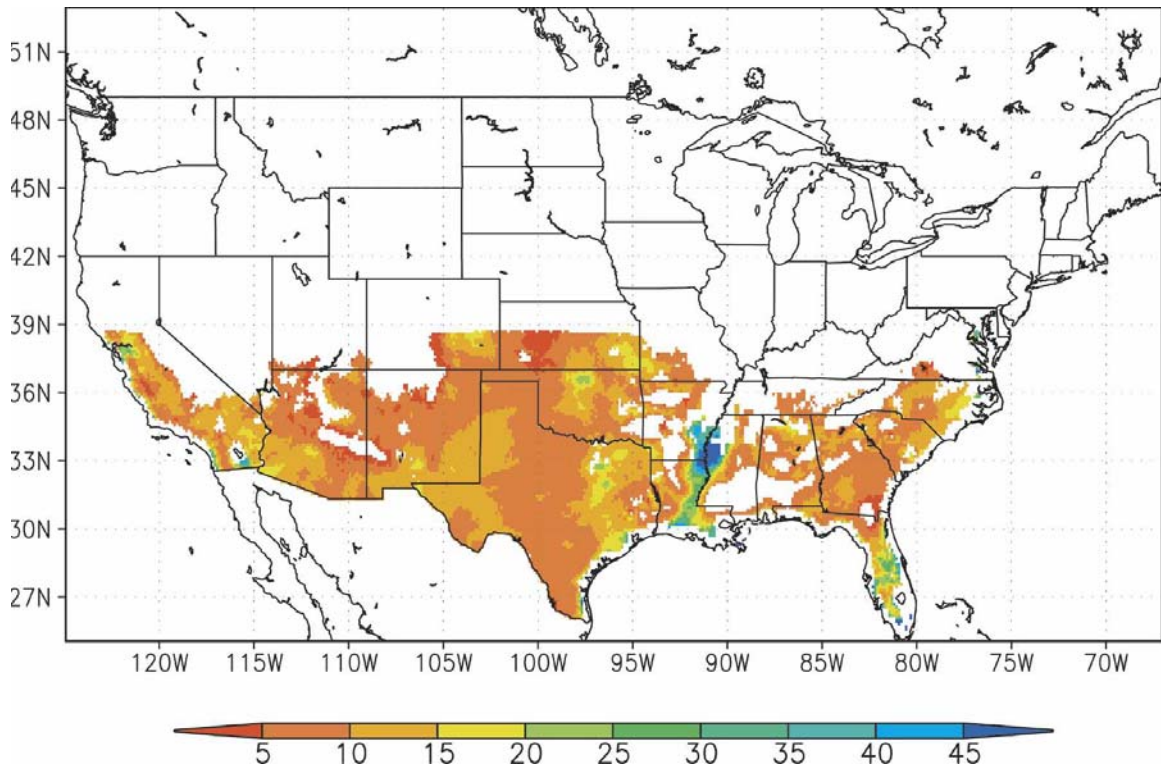


Fig. 1.3. Example of daily retrieved surface (~0.5cm) volumetric soil moisture (%). The map is the Level III product which has contamination masks applied for 01 January 1999 (from Gao et al. 2006).

CHAPTER 2

THE RELATIONSHIP BETWEEN SOIL MOISTURE AND THE DIURNAL CHANGES IN THE PLANETARY BOUNDARY LAYER HEIGHT DURING THE WARM SEASON IN THE SOUTHERN GREAT PLAINS¹

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ABSTRACT

Examination of diurnal boundary layer growth (i.e., boundary layer height differences between 12 UTC and 00 UTC from the North American Regional Reanalysis (NARR) dataset) is used to determine the changes that occur in the planetary boundary layer (PBL). The changes in the PBL are partially caused by variations in the latent and sensible heat fluxes from the surface. Soil moisture is one surface characteristic that has been shown to influence these heat fluxes. Thus, the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) data is used to acquire a daily soil moisture distribution in the southern Great Plains in the U.S. Spearman's Rank correlation is used to determine the relationship between soil moisture and the diurnal PBL growth during the warm season (April-September) for a period from 1998 to 2004 in the southern Great Plains. Depending on the synoptic-type day, the range of Spearman's correlation coefficient was between 0.099 and 0.137, respectively. While Spearman's correlation coefficients were low, all values were statistically significant at the $p=0.01$ level. After classifying soil moisture values into three classes (Wet, Moderate, and Dry Soils based on quartile rankings of volumetric soil moisture content) additional analysis found that diurnal PBL growth was greatest over the Moderate Soils under each synoptic-type day. The mean growth over the Moderate Soils was approximately 900 m greater than over the Dry Soils and 500 m greater than over Wet Soils.

2.1. Introduction

The boundary layer is defined as the lowest layer of the atmosphere which is directly influenced by the earth's surface (Arya 2001). This layer can be characterized by having turbulent flow which helps in the transport of moisture and heat from the earth's surface. The strength of the turbulence within the boundary layer can also influence the height reached by thermals, which transport the heat and moisture. As this depth or boundary layer height grows the thermals are more likely to reach their level of free convection, thus providing heat and moisture to the free atmosphere for the development of convective clouds. The evolution of boundary layer height has been shown to be influenced by numerous factors including, but not limited to: synoptic scale pressure systems, moisture conditions above the boundary layer, and land surface properties such as soil moisture distributions (Zhang and Anthes 1982, Stull 1988, Chang and Wetzel 1991, Ek and Mahrt 1994, Mahrt 2000, Arya 2001, Taylor et al. 2003, Santanello et al. 2005, Maxwell et al. 2007). This work seeks to more clearly define the relationship between soil moisture and the daily evolution of the boundary layer.

The spatial and temporal variations of the boundary layer relate to the variations of the land surface properties that affect the surface energy and moisture budgets. Pielke (2001) defined the surface energy budget as,

$$R_N = Q_G + H + L(E + T), \quad (2.1)$$

where R_N represents the net radiative fluxes, Q_G is the soil heat flux, H represents the turbulent sensible heat flux, and $L(E + T)$ is the turbulent latent heat flux. The turbulent latent heat flux includes two processes important at the surface: E is evaporation, or the

conversion of water to water vapor by nonbiophysical processes, and T is transpiration, which is the conversion of water to water vapor by biophysical processes.

Segal et al. (1988, 1989) investigated how changes to the surface energy budget affect boundary layer growth. According to Segal et al. (1988), a simplification of Equation 2.1 can occur because $Q_G \ll H$ and $L(E+T)$ over vegetated surfaces. Thus, Equation 2.1 can be rewritten as,

$$H \approx R_N - L(E+T), \quad (2.2)$$

where $R_N = (1-\alpha)R_S + LR_N$, where α is the surface albedo, R_S is the incoming shortwave radiation, and LR_N is the net longwave radiation. If R_N is held constant, an increase (decrease) in $L(E+T)$ will result in a decrease (increase) in H . Increases in soil moisture can lead to increases in $L(E+T)$, which leads to decreases in temperature due to the increase in sensible heat. The increases (decreases) in H cause a higher (lower) temperature.

Segal et al. (1988) also related the sensible heat flux to another common measure that is used to compare the amount of latent to sensible heat, the Bowen ratio (B). The Bowen ratio is defined as:

$$B = \frac{H}{L(E+T)}. \quad (2.3)$$

Regions with high soil moisture content have lower B due to portions of net radiation being used to evaporate water, thus increasing $L(E+T)$ compared to regions with drier soils. Segal et al. (1988) showed the relationship between R_N and B (again ignoring Q_G for vegetated surfaces) as:

$$H \cong \left(\frac{1+B}{B} \right) R_N. \quad (2.4)$$

If R_N is held constant over space, areas with a high Bowen ratio would have a larger sensible heat flux and thus a higher temperature.

Thus, an increase in the sensible heat flux (i.e., higher temperatures) creates air parcels which are more buoyant than the surrounding air. The more buoyant warm air rises in the atmosphere allowing for more turbulence or mixing to occur within the boundary layer. This increase in mixing allows the boundary layer to grow (André et al. 1978, Betts 2000). An increase in the boundary layer depth allows the turbulent thermals originating from the earth's surface to carry heat and moisture closer to, and possibly into, the free atmosphere and thus becoming accessible for convective activity. Model results and field observations agree that regions with a lack of soil moisture exhibit an increase in the sensible heat flux and an increase in the boundary layer height (McCumber and Pielke 1981, Zhang and Anthes 1982, Ookouchi et al. 1984, Lanicci et al. 1987, Fast and McCorcle 1991, Chen and Avissar 1994, Betts et al. 1996, Liu et al. 1999, Berbery et al. 2003, Trier et al. 2004).

The growth of the boundary layer can also be influenced by entrainment of air from the free atmosphere as well as synoptic-scale processes (Stull 1988, Arya 2001, Pielke 2001, Findell and Eltahir 2003a, Findell and Eltahir 2003b, Trier et al. 2004). Within the study region, a typical feature present is a moist low-level jet originating from the Gulf of Mexico (Bonner 1968, Vasquez 2002). Boundary layer growth can be limited due to the presence of high amounts of moisture above the growing boundary layer (Ek and Mahrt 1994). The study region also experiences variations in the synoptic-scale flow which can alter the vertical motion fields, thus influencing the growth of the boundary

layer (Ek and Mahrt 1994). The changes in synoptic-scale flow can be determined by identifying the presence of a quasi-barotropic environment (synoptically benign) or baroclinic environment (synoptically primed) (Djuric 1994, Vasquez 2002, Findell and Eltahir 2003a, Findell and Eltahir 2003b).

Previous studies, including those cited in this work, have relied on models or data from short-term, observational-extensive field campaigns (e.g., HAPEX and IHOP) (Taylor et al. 1997, Taylor and Lebel 1998, Weckworth et al. 2004, Weckworth and Parsons 2006). Lacking (in this research area) are long-term observational studies focusing on the aspect of changes in atmospheric conditions due to changes in the sensible and latent heat fluxes caused by variations in the soil moisture content. Adegoke et al. (2007) also identified this lack of long-term observational studies and presented results from an eight-year study in examining the changes of land-cover on the atmospheric conditions in the Midwest region of the U.S. The present study attempts to provide a long-term observational study of the effect that changes in the surface energy fluxes, due to changes in soil moisture, have on the diurnal growth of the boundary layer during the warm season (April-September) over a seven-year period (1998-2004) in the southern Great Plains (Fig. 2.1).

2.2. Data and Methods

a. Soil Moisture

Techniques for measuring soil moisture with microwave remote sensing are based on the significant contrast in the dielectric characteristics between water and dry soil

(Engman and Gurney 1991, Jackson 1993). According to Engman and Gurney (1991) the dielectric constant for water is significantly higher than the dielectric constant for dry soil. Consequently, as a dry soil has moisture added to it, the dielectric constant would increase and thus decrease the emissivity and brightness temperature, which is measured by the sensor aboard the satellite, due to less reflectivity of a wetter soil.

Another aspect that has been shown to be useful in determining the soil moisture content using microwave sensors is the separate horizontal and vertical polarizations. Cashion et al. (2005), in a study for the Little River Watershed in Tifton, GA, found that the differences between the horizontal and vertical polarization measurements can be utilized to determine the volumetric soil moisture. The group utilized the Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager's (TMI) 10.65 GHz band. Polarization differences are used to determine soil moisture except when the vegetation cover was significant, determined by NDVI. This led the authors to conclude that when determining soil moisture, TMI data alone are not very useful but when combined with ancillary data [i.e. Advanced Microwave Scanning Radiometer (AMSR) aboard AQUA and vegetation data from Moderate Resolution Imaging Spectroradiometer (MODIS)] the quality of the soil moisture information is greatly improved.

One disadvantage to microwave remote sensing of soil moisture is the depth into the ground that moisture is detected. Passive microwave sensors typically measure only the top 0.5 cm (Gao et al. 2006). Despite the limited depth measured, Gao et al. (2006) found a strong correlation between the measurements of remotely sensed data and 5 cm neutron probes utilized by the Oklahoma Mesonet sites. Other studies have also shown moisture in the top soil layers have higher correlations to convection on shorter temporal

scales (i.e., 1-2 days); while deeper moisture in the soil is more critical after a long-term period without precipitation (Ek and Mahrt 1994, Taylor et al. 1997, Taylor et al. 2003, Taylor and Ellis 2006).

The present study used soil moisture data obtained from daily soil moisture data archive from the Land Surface Hydrology Group at Princeton University (data available at [http://hydrology.princeton.edu /data.sm_tmi.php](http://hydrology.princeton.edu/data.sm_tmi.php)). The TMI X-band (10.65 GHz) was utilized to develop the daily soil moisture database for the southern United States (Gao et al. 2006). The retrievals from multiple daily satellite passes are input into a land surface microwave emission model, along with ancillary data such as vegetation cover, surface temperature, and soil type data, to construct soil moisture values (Level 1 data). These multiple pass data are joined to create a large-scale daily soil moisture database for the southern United States (Level 2 data). A third level of data was created to mask out areas where problems exist with microwave retrievals of soil moisture (e.g., heavy vegetated areas, snow cover/frozen soils, and water contamination) (for further details on retrieval procedures and the land surface microwave emission model see Gao et al. 2006).

The Level 3 soil moisture data (Daily Volumetric Soil Data) from the Land Surface Hydrology Group at Princeton University and Gao et al. (2006) were used to eliminate any possible contamination from the microwave retrievals. The data are resampled to $1/8^\circ$ (~15 km) resolution for the locations in the United States between 25° and 38° latitude. The daily soil moisture data are available from 01 January 1998 to 31 December 2004; however, for the present study only data from the warm season (April through September) for the seven-year period were utilized. The raw daily soil moisture data were processed using Interactive Data Language (IDL) to create output files which

included latitude and longitude coordinates and the volumetric soil values for each grid point within the study region.

b. Synoptic-Scale Environment

The synoptic conditions in which the soil moisture heterogeneities occur also have an influence on the diurnal growth of the boundary layer. To control for these conditions a modified version of Convective Triggering Potential (CTP) (Findell and Eltahir 2003a, Findell and Eltahir 2003b) and the presence of the low-level jet (LLJ) (as defined by Bonner 1968) were determined for each day throughout the study period and study region.

Findell and Eltahir's CTP is calculated by integrating the area between the environmental temperature and a moist adiabat originating from 100 hPa above the surface to 300 hPa above the surface (Findell and Eltahir 2003a, Findell and Eltahir 2003b) from the early morning (i.e., 12 UTC) modeled atmospheric profile. For the present study a modified version (due to data resolution of sounding data) of the CTP was developed using 12 UTC rawinsonde data from five stations: Amarillo, TX (AMA), Dodge City, KS (DDC), Fort Worth, TX (FWD), Midland, TX (MAF), and Norman, OK (OUN) (Fig. 2.1). For each of these stations, a lapse rate was determined for each profile between 850-hPa and 700-hPa, two mandatory levels for all rawinsonde launches. For each station the modified-CTP was classified synoptically benign (synoptically primed) if the environmental lapse rate of the station was less than (greater than or equal to) $6^{\circ}\text{C}/\text{km}$, a commonly used criteria to distinguish between stable and unstable atmospheres and the average environmental lapse rate (Vasquez 2002). Each day of the

study period was then classified as synoptically benign (synoptically primed) if at least two stations had an environmental lapse rate less than (greater than or equal to) $6^{\circ}\text{C}/\text{km}$.

In addition to subdividing days into synoptically benign and synoptically primed, the moist LLJ originating in the Gulf of Mexico must also be accounted for because it is also an important synoptic-scale condition that can influence boundary layer growth (Ek and Mahrt 1994, Findell and Eltahir 2003a, Findell and Eltahir 2003b). Upper-air data from North American Regional Reanalysis (NARR) data (Mesinger et al. 2006, Ruiz-Barradas and Nigam 2006) were processed using GEneral Meteorological PAcKage (GEMPAK) to determine the presence of the LLJ. NARR was created as a long-term, high-frequency, atmospheric and land hydrology data set for North America (Mesinger et al. 2006). The NARR dataset includes multiple surface and upper-air parameters every three hours at 32 km resolution. According to Mesinger et al. (2006), the NARR dataset has a much improved land-atmosphere interaction component improving on the National Center for Environmental Prediction (NCEP)-National Center of Atmospheric Research (NCAR) Global Reanalysis dataset. Mesinger et al. (2006) also found that NARR temperature and wind data are more accurate than the reanalysis data from NCEP-DOE GR2 data.

For the present study, the LLJ was defined as an area of winds greater than 25 knots (12 m s^{-1}) at the 850-hPa level originating from the Gulf of Mexico (Bonner 1968). When this area of increased winds influenced any portion of the study region at 12 UTC, the day was considered to have a LLJ present.

c. Boundary Layer Height

Planetary boundary layer (PBL) height measurements were obtained from NARR data for the morning (12 UTC) and evening (00 UTC) time period. The PBL height measurements from NARR are calculated using the Eta model's turbulent kinetic energy (TKE) (Black 1994). Since the boundary layer is characterized by turbulent flow, the height in the model is determined by an abrupt decline in TKE in the vertical (Stull 1988; S. Jascourt, pers. comm.). Rogers et al. (2006) found a high correlation between PBL height measurements in NARR and lidar measurements taken in rural and urban settings. Utilizing GEMPAK, the NARR grid was resampled to match the output grid of the daily volumetric soil moisture data. From the morning and evening soundings' times (12 UTC and 00 UTC, respectively) PBL height measurements, a diurnal change of the boundary layer height was obtained for each grid point throughout the study period. The PBL growth is defined as the height change between the morning and evening sounding times.

An independent samples difference of means Student's *t*-test (Rogerson 2001) was utilized to determine if under the various synoptic conditions there were any significant differences in diurnal change of the PBL height. In order to determine if the soil moisture values and PBL heights co-vary, Spearman's Rank Correlation were calculated using volumetric soil moisture and PBL height change (Rogerson 2001). Spearman's Rank Correlation were used because a linear relationship between soil moisture and PBL growth cannot be assumed. A coefficient value was calculated for each synoptic-type day and *t*-statistic was calculated to determine if the correlation coefficient was statistically significant.

2.3. Results

The modified-CTP and the presence of the LLJ were combined to classify days into four different categories. The first synoptic-type day has no LLJ present and is synoptically benign (NoLLJ/SB), the second classification are days with no LLJ present and synoptically primed (NoLLJ/SP), type three days have a LLJ present and is synoptically benign (LLJ/SB), and final classification type are days having a LLJ present and are synoptically primed (LLJ/SP). Table 2.1 shows the number of days in each category by month.

To determine the spatial patterns of soil moisture for the period of record and how those patterns change between the synoptic-type days a series of maps were created (Figs. 2.2-2.4). Examining the average soil moisture conditions for the entire period of record shows that the northeast and southwest portions of the study region have the highest values while the central and southeastern portions of the study region experiences the lowest values (Fig. 2.2). An average soil moisture map was also created for each of the four synoptic-type days (Fig. 2.3a-d). Each of the synoptic-type days has a similar spatial pattern to that of the mean conditions for the entire period of record. The variations between the different synoptic-type days are the due to changes in the percentage of volumetric soil moisture across the domain.

The changes in the percentage between the various synoptic-type days and the mean conditions can be seen in Fig. 2.4. The figure depicts the volumetric soil moisture anomalies between the four synoptic-type days and the mean conditions for the entire period of record. On NoLLJ/SB (Fig. 2.4a) and LLJ/SB days (Fig. 2.4c) the study region is experiencing below normal soil moisture conditions. However, on NoLLJ/SP (Fig.

2.4b) and LLJ/SP (Fig. 2.4d) days the region is experiencing above normal soil moisture conditions. As would be suspected, this suggests that the synoptic-scale patterns are playing a significant role in controlling the weather patterns that would increase soil moisture values (i.e., increases in precipitation).

Maps depicting the mean diurnal growth of the boundary layer (Fig. 2.5) show an east-west gradient under each synoptic-type day. NoLLJ/SP (Fig. 2.5b) and LLJ/SP (Fig. 2.5d) days experience more growth in the western portion of the study area than during NoLLJ/SB (Fig. 2.5a) and LLJ/SB (Fig. 2.5c) days. This suggests that the synoptic-scale patterns play a role in the diurnal growth of the boundary layer. Thus, on days that are synoptically primed the synoptic-scale patterns produce conditions with large regions of vertical ascent that can couple with soil moisture conditions favorable for boundary layer growth.

For each synoptic-type day the mean change in PBL height and standard deviation were calculated in order to determine if there were statistically significant differences between each group. The mean PBL height for each of the synoptic types were NoLLJ/SB) 1702 m, NoLLJ/SP) 2237 m, LLJ/SB) 1816 m, and LLJ/SP) 2166 m (Table 2.2). As was seen in Fig. 2.5 and confirmed in Table 2.2, the synoptically primed days experience more diurnal boundary layer growth (approximately 400 m) than synoptically benign days. The difference between days with the LLJ present and not present is much smaller, yet still significant, at approximately 40 m. Each independent samples *t*-test grouping (i.e., NoLLJ/SB vs. NoLLJ/SP, NoLLJ/SP vs. LLJ/SB, etc.) was statistically significant at the $p=.01$ level (Table 2.3). These results indicate the different synoptic regimes and LLJ conditions do play a role in the diurnal growth of the PBL.

To determine the relationship between soil moisture and diurnal boundary layer growth Spearman's Rank Correlation analysis was conducted for each synoptic-type day (Table 2.4). The correlation coefficients are low for each of the synoptic-type days: NoLLJ/SB) 0.099, NoLLJ/SP) 0.137, LLJ/SB) 0.120, and LLJ/SP) 0.118. While the correlation coefficients for the relationship between soil moisture and PBL growth are low they are all statistically significant at the $p=0.01$ level (Table 2.4). Spearman's correlation coefficients indicate that there is a direct relationship between soil moisture and diurnal boundary layer growth. Thus, as soil moisture increases the diurnal boundary layer growth will be greater. This conflicts with the theoretical framework that over dry soils there would be an increase in the sensible heat flux and in response to that increase a larger growth of the boundary layer. Since the relationships are counter to the theoretical understanding of boundary layer growth and the correlation coefficients are low, additional analysis was conducted by dividing the soil moisture values into three classes.

The three classes of soil moisture are based on the quartile rankings of volumetric soil moisture percentages for each synoptic-type day. Soil moisture was classified Dry Soils if it was in the lowest quartile, Wet Soils if it was in the highest quartile, and Moderate Soils if it was in the middle two quartiles. Table 2.5 shows the mean for each synoptic-type day and soil moisture classification. Over the Dry Soils the mean ranges between 1284 and 1668 m, with the lowest diurnal growth on NoLLJ/SB days and the highest growth on LLJ/SP days. The trend of the lowest values over NoLLJ/SB and highest over LLJ/SP days continues with the Moderate Soils and High Soils with values ranging from 1971 to 2624 m and 1603 to 2126 m, respectively. The change in diurnal boundary layer growth between the different synoptic-type days and soil moisture

classification can also be seen in Fig. 2.6. Fig. 2.6 shows that under each synoptic-type day the mean growth of the boundary layer is smallest over Dry Soils with mean values between 687 and 1005 m less than the largest values over the Moderate Soils. These two soil moisture categories also have the smallest and largest range of values as well. Over the Wet Soils the mean diurnal boundary layer growth and range is between the means and ranges over Dry Soils and Moderate Soils.

Comparing Tables 2.4 and 2.5, as the soil moisture increases from the driest soils to the middle soils there is an increase in the mean PBL growth which corresponds to the results of Spearman's correlation analysis. Again, this runs counter to the theoretical findings that higher boundary layers should be located over the driest soils due to increases in the sensible heat flux. As the soil moisture increases to the wettest soils the mean diurnal boundary layer growth decreases (e.g., mean decrease in PBL growth of 368 m on NoLLJ/SB days, 498 m on NoLLJ/SP, 467 m on LLJ/SB days, and 579 m on LLJ/SP days) (Table 2.5). This relationship in mean boundary layer growth between Moderate to Wet soils contradicts the results of Spearman's correlation analysis; and reflects the theoretical framework that as soil moisture increases the boundary layer height will decrease.

2.4. Conclusion

Soil moisture has been shown to influence temperature and moisture characteristics near the earth's surface in various case studies, modeling studies, short field campaign studies. This study has capitalized on recent developments in microwave remote sensing (e.g., TRMM) and mesoscale reanalysis datasets (e.g., NARR) to improve

fundamental understanding of soil moisture-atmosphere interactions. The current study examined the relationship between soil moisture and diurnal planetary boundary layer growth over seven warm seasons in the southern Great Plains.

High temporal and spatial resolution soil moisture daily data from TRMM illustrated the variability of soil moisture across the study region in the southern Great Plains. The spatial distributions of soil moisture were compared to the spatial patterns of diurnal planetary boundary layer growth under various synoptic-type days. Boundary layer growth is shown to be larger during days under a synoptically primed pattern than days with synoptically benign conditions. These differences between the four synoptic-type days are statistically significant indicating that the larger scale atmospheric patterns do have an impact on the mesoscale patterns of boundary layer growth. However, the diurnal growth of the boundary layer is also explained by the changes in soil moisture values as analyzed by Spearman's Rank Correlation. While all the variations are statistically significant, only a small portion of the variances in boundary layer growth is explained by changes in the soil moisture. These results deviate from other studies that have used short-term field observation periods to show the large impact soil moisture has on properties within the PBL. The low correlation coefficients in the present study could be the result of the large range of variability that can occur in both soil moisture and diurnal PBL growth over a longer period of record and that the data is not rank order.

Under each synoptic-type day, the correlation coefficients between soil moisture and diurnal PBL growth are positive. Thus, as the soil moisture increases boundary layer growth also increases, which counters the findings in modeling and field campaign observations (McCumber and Pielke 1981, Zhang and Anthes 1982, Ookouchi et al.

1984, Lanicci et al. 1987, Fast and McCorcle 1991, Chen and Avissar 1994, Liu et al. 1999, Berberry et al. 2003, Trier et al. 2004). However, comparing means over the Dry, Wet and Moderate Soils show that the PBL growth is greatest over the Moderate Soils and lowest over Dry Soils (Fig. 2.7). This could be the result of the development of mesoscale circulations along transition zones (or boundaries) between the Wet and Dry Soils due to the changes in sensible heat fluxes over extreme soil moisture areas (Ookouchi et al. 1984). These transition zones have been shown to increase vertical velocities at the mesoscale. In Chapter 4, these transition zones between Wet and Dry Soils are examined further by identifying locations of convective initiation and the underlying soil moisture properties.

Despite the low correlation coefficients found between soil moisture and diurnal PBL growth, any changes in the growth can play a significant role on the development on convective activity. This is due to the development of turbulent thermals with the PBL which help transport heat and moisture from the surface upward. The height at which these thermals reach can remain well below the level of free convection in the cases of small diurnal PBL growth. When there is an increase in diurnal PBL growth the heat and moisture associated with these thermals could reach this level and supply the free atmosphere with moisture and heat for convective development. Once convective development is initiated its sustainability can be determined by using various metrics commonly used in thunderstorm forecasting (e.g., convective available potential energy, convective inhibition, and lifted index). In Chapter 3, the variation of these metrics will be examined in order to determine what, if any, influence soil moisture has on them. Combining the results from those two chapters, a relationship of changes in convective

activity due to changes in soil moisture and synoptic-type day will be identified. This relationship will then be examined further, in Chapter 4, by determining the relationship between soil moisture and convective initiation as identified by radar data.

2.5. References

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Table 2.1. The number and percentage of days per month for the four synoptic-type days. Fifteen days were eliminated from the study due to the lack of soil moisture or PBL height data (25 April 1998, 8 Aug 1999, 6 July 2000, 17 September 2000, 18 September 2000, 19 September 2000, 6 April 2001, 13 August 2001, 14 August 2001, 15 August 2001, 17 August 2001, 6 April 2003, and 30 April 2003). NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ/SP are days with no LLJ and synoptically primed, LLJ/SB are synoptically benign days with a LLJ present, and LLJ/SP are synoptically primed days with a LLJ present.

| | April | May | June | July | August | September | Total |
|-----------------|--------------|------------|-------------|-------------|---------------|------------------|---------------|
| NoLLJ/SB | 35 (17) | 30 (14) | 27 (13) | 16 (7) | 13 (6) | 53 (26) | 174 (14) |
| NoLLJ/SP | 57 (28) | 50 (23) | 40 (19) | 103 (48) | 113 (54) | 69 (33) | 432 (34) |
| LLJ/SB | 41 (20) | 56 (26) | 70 (33) | 24 (11) | 12 (6) | 35 (17) | 238 (19) |
| LLJ/SP | 72 (35) | 81 (37) | 73 (35) | 73 (34) | 73 (35) | 50 (24) | 422 (33) |
| Total | 205 (16) | 217 (17) | 210 (17) | 216 (17) | 211 (17) | 207 (16) | 1266 (100) |

Table 2.2. The mean and standard deviation for diurnal PBL growth (m) under each synoptic-type day. NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ/SP are days with no LLJ and synoptically primed, LLJ/SB are synoptically benign days with a LLJ present, and LLJ/SP are synoptically primed days with a LLJ present.

| | Mean | Standard Deviation |
|-----------------|-------------|-------------------------------|
| NoLLJ/SB | 1702 | 1091 |
| NoLLJ/SP | 2237 | 1135 |
| LLJ/SB | 1816 | 1170 |
| LLJ/SP | 2166 | 1216 |

Table 2.3. The t -critical ($p=0.01$), t -observed, and degrees of freedom (DF) for the independent samples difference of means Student's t -test conducted on the diurnal PBL growth between the different synoptic-type days. NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ/SP are days with no LLJ and synoptically primed, LLJ/SB are synoptically benign days with a LLJ present, and LLJ/SP are synoptically primed days with a LLJ present.

| | NoLLJ/SB vs. NOLLJ/SP | NoLLJ/SB vs. LLJ/SB | NoLLJ/SB vs. LLJ/SP | NOLLJ/SP vs. LLJ/SB | NOLLJ/SP vs. LLJ/SP | LLJ/SB vs. LLJ/SP |
|--------------------------------|-----------------------------|---------------------------|---------------------------|---------------------------|---------------------------|-------------------------|
| t-critical | +/- 2.576 | +/- 2.576 | +/- 2.576 | +/- 2.576 | +/- 2.576 | +/- 2.576 |
| t-observed | -438.9 | -83.36 | -359.8 | 385.6 | 74.98 | -304.7 |
| DF | 4352648 | 2854140 | 4227755 | 4889624 | 6263239 | 4764731 |

Table 2.4. Spearman’s correlation coefficients between soil moisture and diurnal PBL growth for each of the synoptic-type days. (* indicates significance at the $p=0.01$ level). NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ/SP are days with no LLJ and synoptically primed, LLJ/SB are synoptically benign days with a LLJ present, and LLJ/SP are synoptically primed days with a LLJ present.

| | Spearman’s Correlation Coefficient |
|-----------------|---|
| NoLLJ/SB | 0.099* |
| NoLLJ/SP | 0.137* |
| LLJ/SB | 0.120* |
| LLJ/SP | 0.118* |

Table 2.5. Mean diurnal PBL growth (m) for each soil moisture category: Dry Soils (lowest quartile), Wet Soils (top quartile), and Moderate Soils (middle two quartiles). NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ/SP are days with no LLJ and synoptically primed, LLJ/SB are synoptically benign days with a LLJ present, and LLJ/SP are synoptically primed days with a LLJ present.

| | Dry Soils | Moderate Soils | Wet Soils |
|-----------------|------------------|-----------------------|------------------|
| NoLLJ/SB | 1284 | 1971 | 1603 |
| NoLLJ/SP | 1668 | 2624 | 2126 |
| LLJ/SB | 1304 | 2163 | 1696 |
| LLJ/SP | 1574 | 2579 | 2000 |

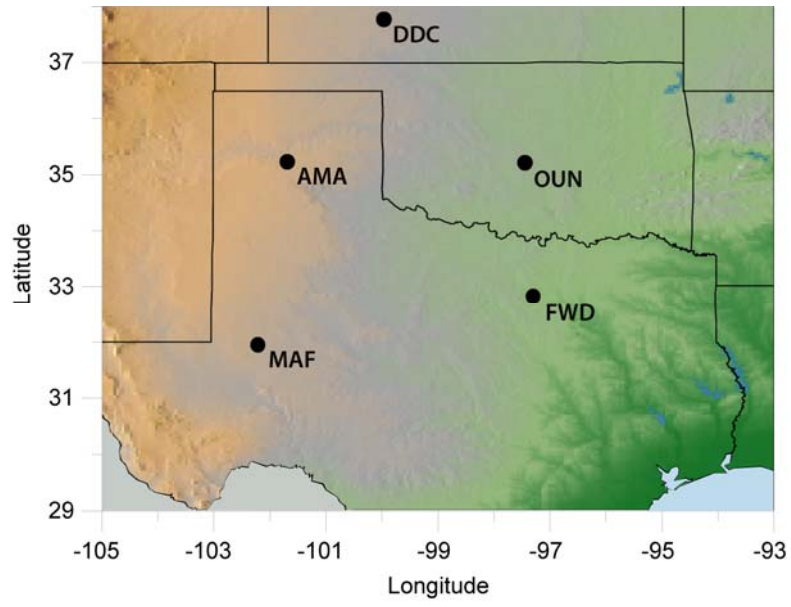


Fig. 2.1. Study region with the locations of radiosonde sites used to determine synoptic-type day. The radiosonde sites include Amarillo, TX (AMA), Dodge City, KS (DDC), Fort Worth, TX (FWD), Midland, TX (MAF), and Norman, OK (OUN). Shaded relief from USGS (2003).

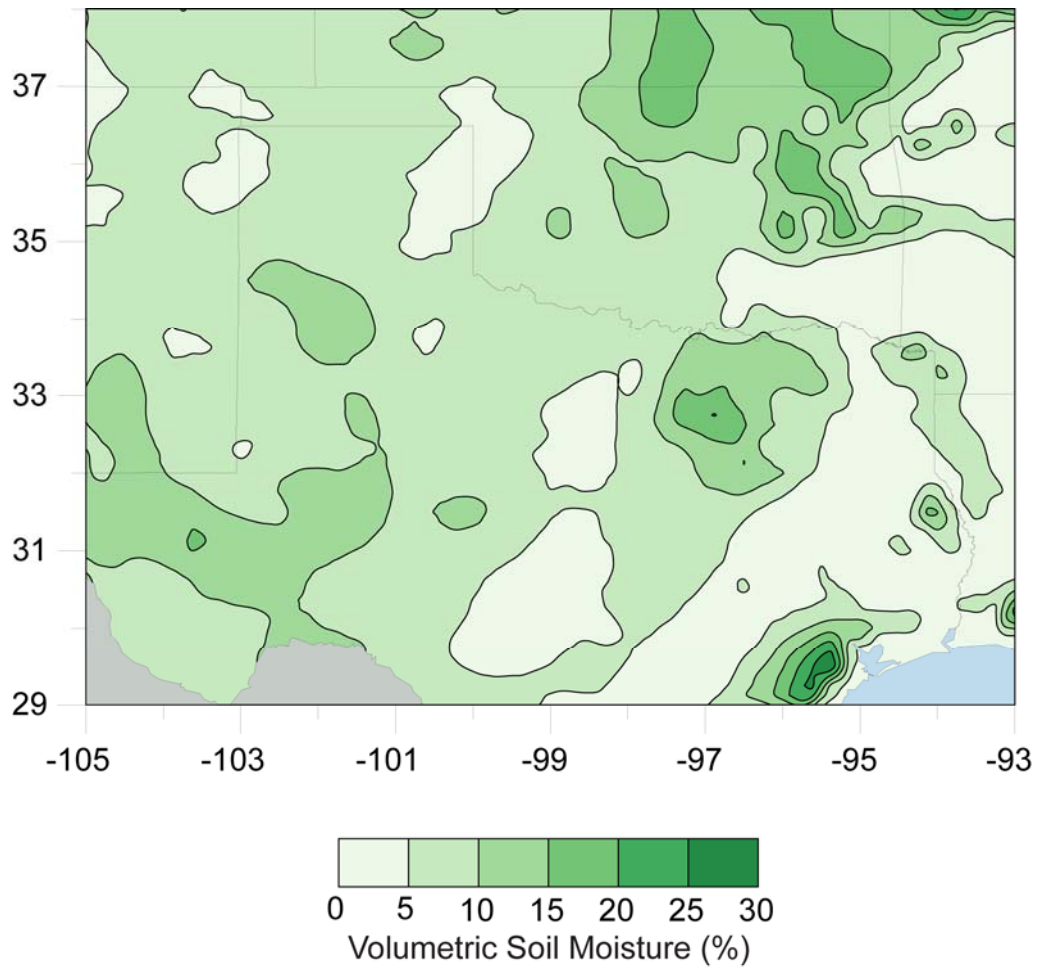


Fig. 2.2. Average volumetric soil moisture (%) for the period of record.

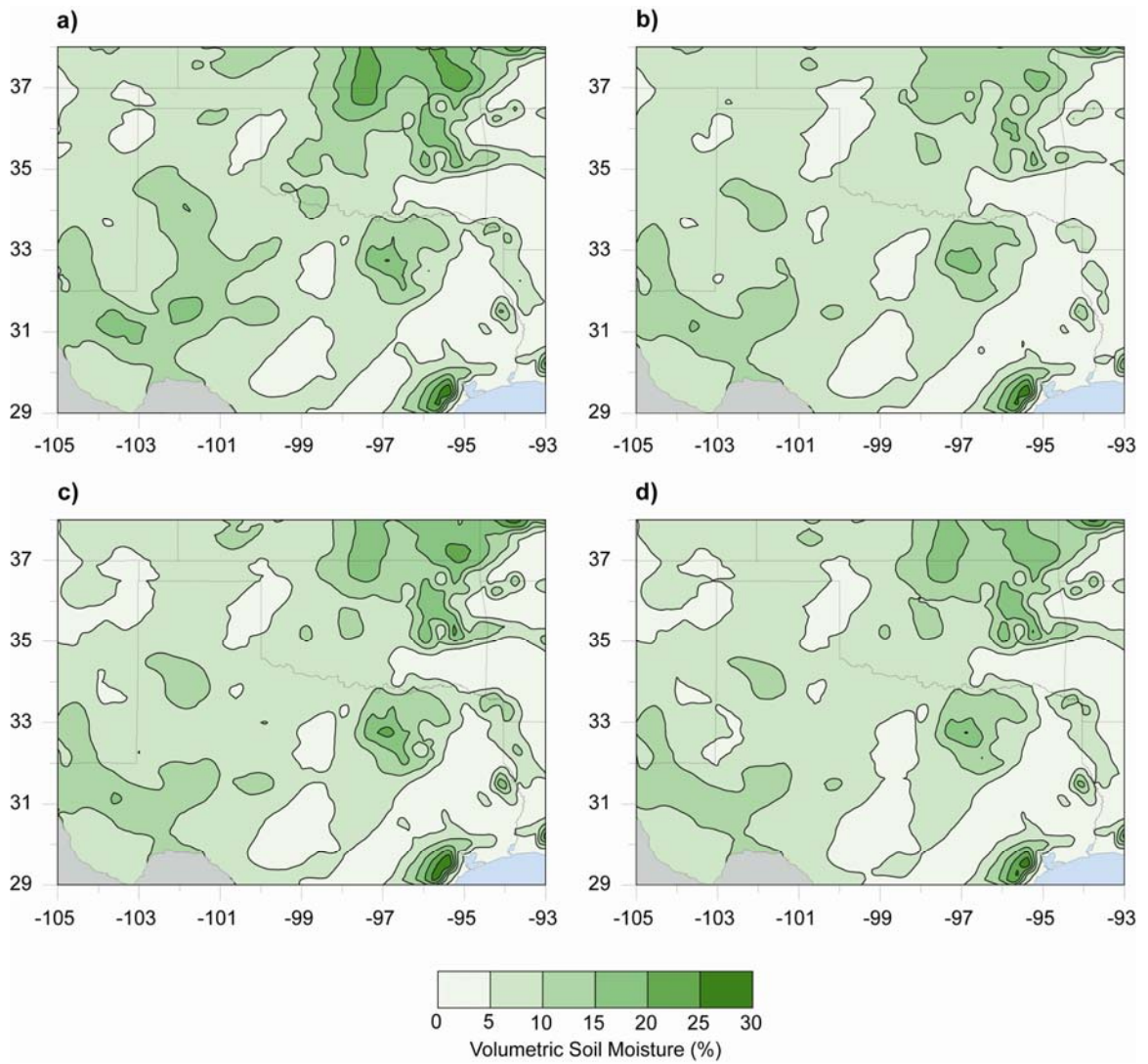


Fig. 2.3. Average volumetric soil moisture (%) for each synoptic-type day: a) NoLLJ/SB days, b) NoLLJ/SP days, c) LLJ/SB days, and d) LLJ/SP days.

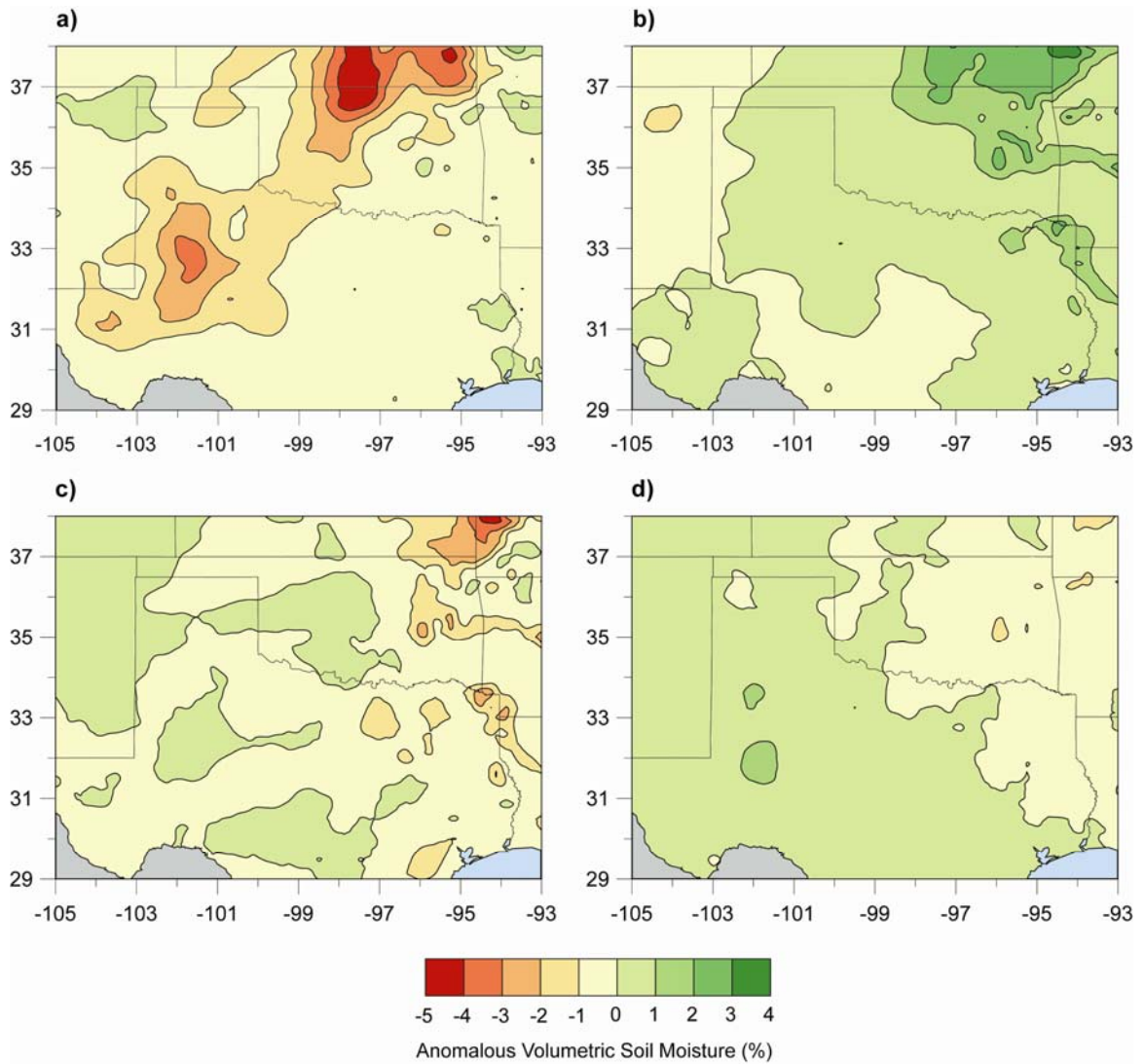


Fig. 2.4. Anomalous volumetric soil moisture (%) for each synoptic-type day: a) NoLLJ/SB days, b) NoLLJ/SP days, c) LLJ/SB, and d) LLJ/SP days.

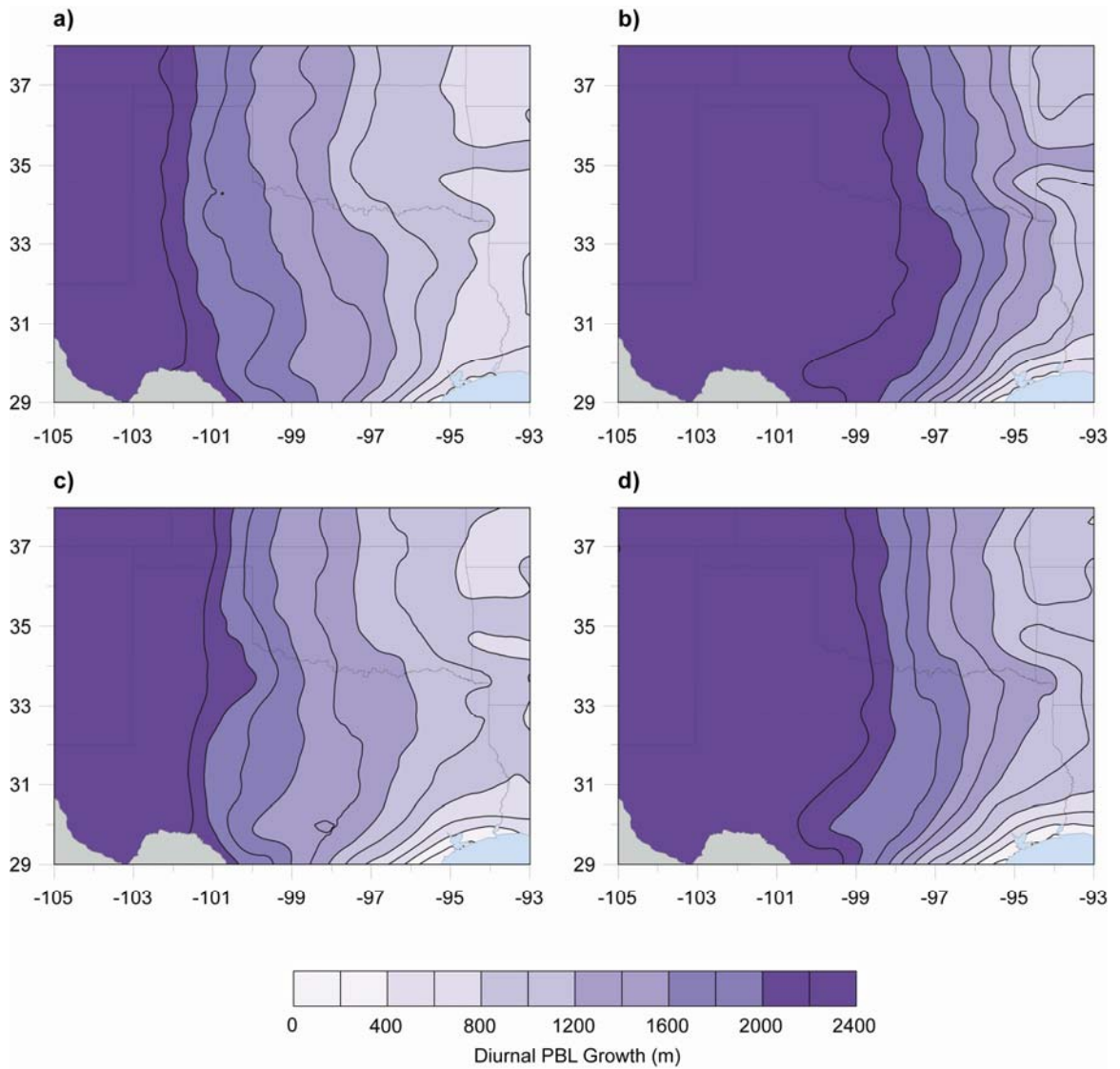


Fig. 2.5. Average diurnal PBL growth (m) for each synoptic-type day: a) NoLLJ/SB days, b) NOLLJ/SP days, c) LLJ/SB days, and d) LLJ/SP days.

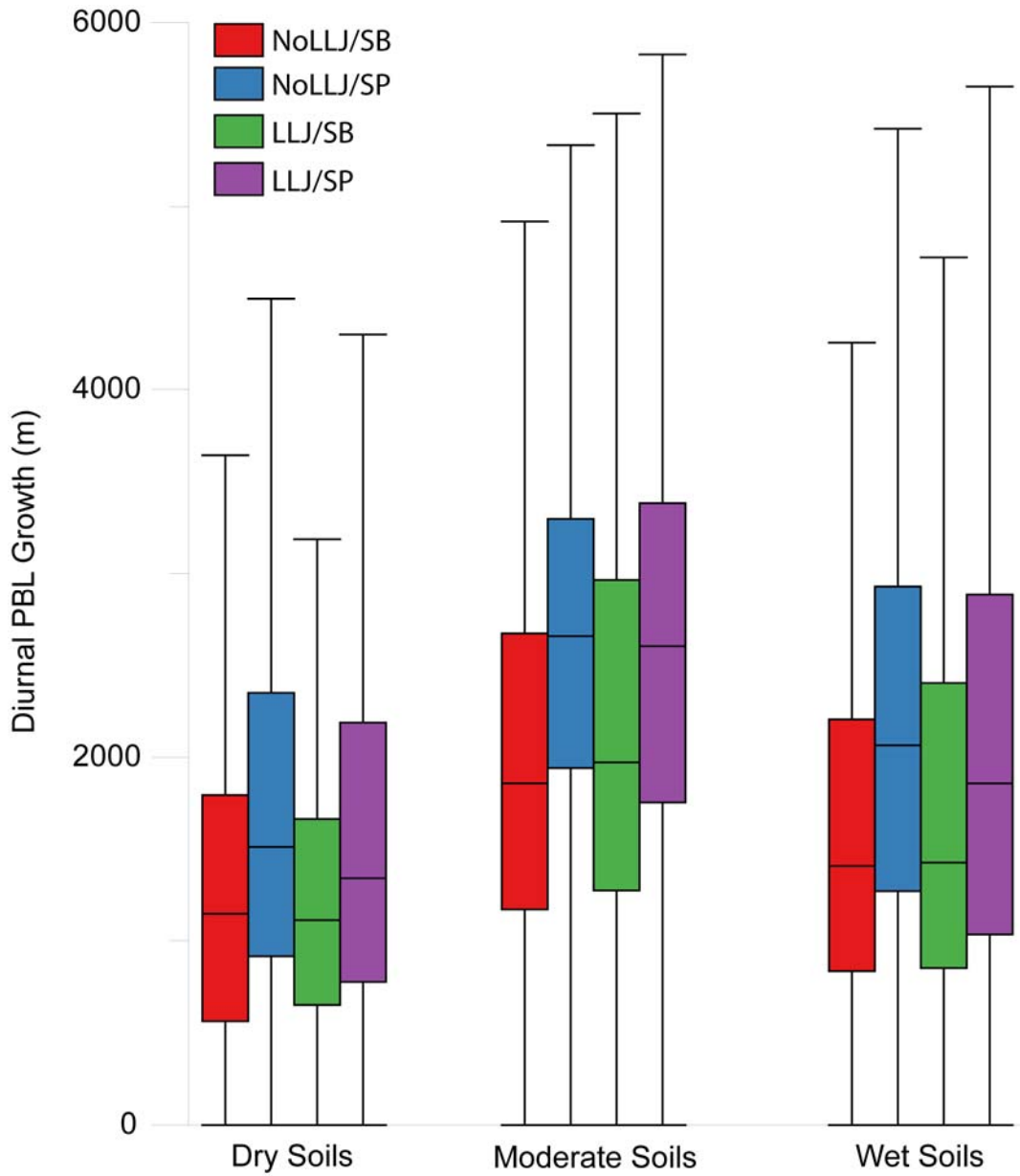


Fig. 2.6. Average and standard deviations of diurnal PBL growth (m) by soil moisture category. Mean is indicated by horizontal line in the shaded box, ± 1 standard deviations (shaded boxes), and ± 2 standard deviations (whiskers). Dry Soils (lowest quartile), Wet Soils (highest quartile) and Moderate Soils (middle two quartiles) for each synoptic-type day.

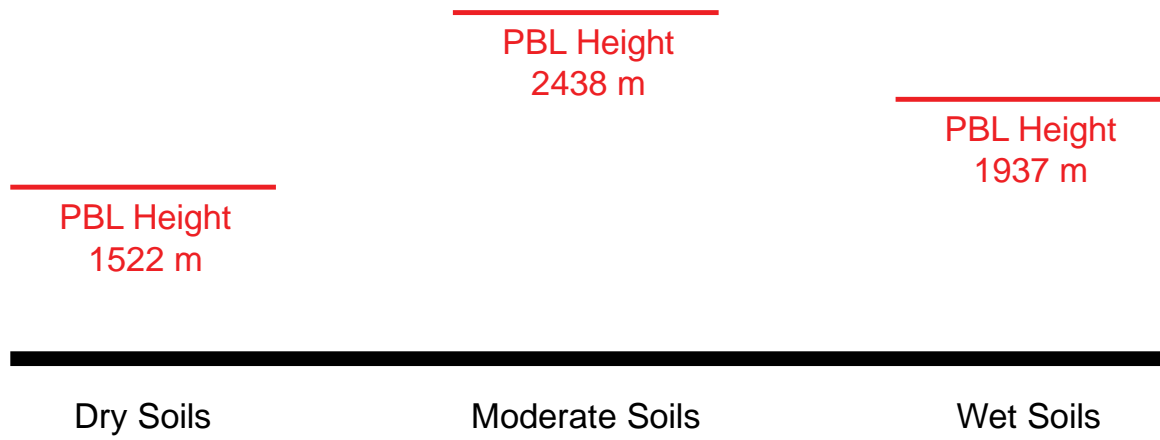


Fig. 2.7: Average PBL growth (m) over Dry, Moderate, and Wet Soils for the period of record.

CHAPTER 3

THE SYNERGISTIC RELATIONSHIP BETWEEN SOIL MOISTURE AND THE LOW LEVEL JET AND ITS ROLE ON THE PRE-STORM ENVIRONMENT IN THE SOUTHERN GREAT PLAINS (1998-2004)²

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ABSTRACT

Changes in low-level moisture alter the convective parameters (e.g., convective available potential energy (CAPE), lifted index (LI), and convective inhibition (CIN)) due to alterations in the latent and sensible heat energy exchange. Two sources for low-level moisture exist in the southern Great Plains: (1) moisture advection by the low-level jet (LLJ) from the Gulf of Mexico and (2) evaporation and transpiration from the soils and vegetation in the region. The primary focus of this study is to examine the spatial distribution of soil moisture on a daily basis and determine the effect it has on the convective parameters. The secondary objective is to investigate how the changes in soil moisture are altered in the region by the presence of a LLJ. The soil moisture data were obtained through newly developed procedures and advances in technology aboard the Tropical Rainfall Measuring Mission's (TRMM) Microwave Imager (TMI). The convective parameter data were obtained through the North American Regional Reanalysis (NARR) dataset. The study examined seven warm seasons (April-September) from 1998-2004 and found that the convective environment is more unstable ($CAPE > 900 \text{ J kg}^{-1}$, $LI < -2^\circ \text{ C}$) but more strongly capped ($CIN > 70 \text{ J kg}^{-1}$) on days with a LLJ present. Spearman's Rank Correlation Analysis showed only a small amount of variance in the convective parameters caused by soil moisture changes. Additional analysis determined that on all synoptic-type days, the probability of reaching various thresholds of convective intensity increased as soil moisture values increase. The probabilities were even greater on days with a LLJ present compared to the days without a LLJ present. Finally, an examination of four days representing each synoptic-type day indicates that

on the daily scale, the intensity of the convective environment is closely related to the high soil moisture and LLJ locations.

3.1. Introduction

The effects of heterogeneities in soil moisture on the heat and moisture fluxes have been investigated using coupled atmospheric and land-surface models. The models generally indicate that the heterogeneities lead to the development of mesoscale circulation patterns (Ookouchi et al. 1984, Pielke and Segal 1986, Avissar and Pielke 1989, Fast and McCorcle 1991, Chang and Wetzel 1991, Emori 1998, Liu et al. 1999, Pielke 2001, Carleton et al. 2001, Berbery et al. 2003, Trier et al. 2004, Holt et al. 2006). Specifically, Fast and McCorcle (1991) found the mesoscale circulation patterns develop along soil moisture boundaries.

These mesoscale circulations have been recognized as a focus region for convective initiation even in the absence of forcing at larger scales (Maddox et al. 1980, Pielke 2001, Xiu and Pleim 2001). The circulation patterns are formed by alterations in latent heat flux over sharp gradients of soil moisture values, causing an area of upward motion, lower surface pressure, and an area of convergence near the ground over the drier soils (Ookouchi et al. 1984, Segal et al. 1988, Segal et al. 1989). The mesoscale circulation patterns create changes in the temperature and moisture fields and also influence the low-level wind fields near the soil moisture boundaries.

Over dry soils the sensible heat flux is larger causing an increase in temperature. Sensible heat flux is smaller over wet soils due to the fact that a portion of the energy received is first used to evaporate water at the surface (latent heat flux). This reduces temperatures but increases dew point temperatures at the surface. These changes in the temperature and dew point temperature control the thermodynamic indices used in convective storm forecasting. Three common measures that are used, and could be

affected by changes in the surface temperature and moisture fields, are lifted index (LI), convective available potential energy (CAPE), and convective inhibition (CIN). (See Storm Prediction Center's Mesoscale Analysis Page at <http://www.spc.noaa.gov/exper/mesoanalysis/s7/index2.html>.)

Lifted Index is a measure of stability and is defined as,

$$LI = 500T_E - 500T_P, \quad (3.1)$$

where $500T_E$ is the environmental temperature at 500 hPa and $500T_P$ is the temperature of a parcel which is lifted from the surface to the lifting condensation level (LCL) dry adiabatically (or along a constant potential temperature line) and then lifted to the 500 hPa moist adiabatically (or along a constant equivalent potential temperature line) (Galway 1956).

While LI is a measure of stability at a single level, CAPE and CIN are measures of buoyancy (or stability) throughout a layer of the atmosphere (Djuric 1994). Weisman and Klemp (1982) define buoyancy (B) as,

$$B = g \int \frac{\theta - \theta_a}{\theta_a} dz, \quad (3.2)$$

where g is the acceleration of gravity, θ is the parcel potential temperature, θ_a is the environmental potential temperature, and dz is the change in height. Convective inhibition is the integration of areas where $\theta < \theta_a$ or negative areas of buoyancy and CAPE is the integration of areas where $\theta > \theta_a$ or positive areas of buoyancy.

Increases in dew point temperatures at the surface have been shown to alter the amount of CAPE (Pielke and Zeng 1989, Pielke 2001). Increases in CAPE values are also shown to be more sensitive to increases in dew point temperature than to increases in

temperature (Pielke 2001 and citations within). Other convective parameters have also shown alterations due to changes in soil moisture values. Pielke and Zeng (1989) found, using idealized experiments from Segal et al. (1988), LI values increased from -6.8°C over irrigated lands to 3.0°C over dry grasslands in Northeastern Colorado. Thus, areas where there is an increase in soil moisture will experience lower LI values which indicate a more unstable atmosphere. This is analogous to the results reviewed in Pielke (2001) using CAPE as the measure of stability.

High values of CIN have been shown to suppress convective development and are usually referred to as the “cap” or “lid.” In order for convection to form, the energy created within the planetary boundary layer must be able to break through the cap. The strength of the cap can also influence the pattern of thunderstorm development. In cases when there is a weak cap, the negative buoyant energy is easily eroded away by the mass and energy built up in the planetary boundary layer. This allows for a widespread pattern of convection to form. If there is a strong cap present, the energy will tend to break in one location causing explosive convective development.

The primary objective of this research is to determine the nature of the relationship between soil moisture and various metrics describing the convective potential (e.g., CAPE, CIN, and LI) in the southern Great Plains (Fig. 3.1) during the warm season. Within this region, the presence of the low-level jet (LLJ) has been shown to alter atmospheric patterns created by small-scale surface heterogeneities (i.e., changes in soil moisture) that could influence the convective environment. Thus, a secondary objective of the research is to determine if a synergistic relationship exists between soil moisture and the presence of a LLJ and how that relationship affects the metrics of

convective potential for a long-term (i.e., seven seasons) observational study. The results of this empirical study can be used to assess the wide range of modeling and short-term field studies that have been conducted on the influence soil moisture and the LLJ have on convective environments. The data and methods which are used to achieve these research objectives are outlined in Section 3.2. Section 3.3 provides the results of the relationship between soil moisture changes and the convective metrics under various synoptic-type days at the climatological scale. Section 3.3 also examines four days which represent each of the four synoptic-type days to illustrate the relationship of the soil moisture-convective metric couplet on a daily scale. A discussion of the results and conclusions are then found in section 3.4.

3.2. Data and Methods

a. Soil Moisture

A daily soil moisture product developed from Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) and ancillary data were utilized. The daily data were created by the Land Surface Hydrology Group at Princeton University (data available at [http://hydrology.princeton.edu /data.sm_tmi.php](http://hydrology.princeton.edu/data.sm_tmi.php); also see Gao et al. 2006). Satellite platforms using microwave energy (e.g., TMI) have allowed for significant improvements in the spatial and temporal coverage of soil properties, including soil moisture. These improvements are especially true when comparing the coverage provided by remotely sensed data and traditional measuring techniques (Engman and Chauhan 1995, Robock et al. 2000).

Gao et al. (2006) utilized a land surface microwave emission model to create a soil moisture product for each pass of TRMM over the southern portions of the U.S. (Level 1 data). The model inputs were TMI X-band (10.65 GHz) as well as ancillary data including surface roughness, vegetation structure, albedo, water fractional coverage, soil texture, vegetation fractional coverage, vegetation water content, and surface temperature. To create a daily soil moisture product, each Level 1 satellite pass from a 24-hour period was combined to create a single set of data for each day from January 1, 1998 to December 31, 2004 (Level 2 data). An additional level of data (Level 3 data) were created to mask out areas where there are known problems in microwave satellite retrievals of soil moisture. These areas of possible contamination included areas with heavy vegetation coverage, snow or frozen ground, and water.

Level 3 data were utilized to create a daily soil moisture map for each day in the warm season (April – September) from 1998-2004 in the study region shown in Fig. 1. The daily soil moisture data, latitude, and longitude were then used to create average soil moisture maps and combined with other data to find correlations between the soil moisture values and convective metrics.

b. Synoptic Conditions

The synoptic conditions were also analyzed to account for large scale conditions that may have influenced the convective parameters. Morning (12 UTC) soundings were utilized from Amarillo, TX (AMA), Dodge City, KS (DDC), Fort Worth, TX (FWD), Midland, TX (MAF), and Norman, OK (OUN) (see Fig. 3.1 for location of stations) to determine the Convective Triggering Potential (CTP) (Findell and Eltahir 2003a, Findell

and Eltahir 2003b). The CTP is determined by integrating the area between the temperature profile and a moist adiabat from 100 hPa above the surface to 300 hPa above the surface. If the integrated area was positive (negative) the day would be considered synoptically primed (benign) for convective activity (for more details please see Findell and Eltahir 2003a, Findell and Eltahir 2003b). The present study used a modified version of the CTP by calculating the lapse rate between 850-hPa level and 700-hPa level for each station during the study period.

The modified-CTP was calculated for each station throughout the study period and each station was classified synoptically benign (primed) if the lapse rate was less than (greater than or equal to) $6.0^{\circ}\text{C}/\text{km}$. A day was then classified as synoptically primed if two or more of the stations were classified as synoptically primed for that particular day.

In addition to determining if the atmosphere was synoptically primed or benign to convective activity, the morning (12 UTC) data from the 32-km North American Regional Reanalysis (NARR) (Mesinger et al. 2006, Ruiz-Barradas and Nigam 2006) upper-air data were analyzed to determine the presence of a low-level jet (Bonner 1968). In the Southern Great Plains the convective parameters can also be strongly influenced by the presence of moist, low-level jet originating in the Gulf of Mexico (Ek and Mahrt 1994, Findell and Eltahir 2003a, Findell and Eltahir 2003b). The day was classified as having a LLJ present if a large portion of the study region was under the influence of winds at the 850-hPa level of greater than 25 knots (12 m s^{-1}) emanating from the Gulf of Mexico region within the study region for that day.

Using the modified-CTP, days within the study period were classified as into four different synoptic-type days; NoLLJ/SB days had no LLJ present and were synoptically benign, NoLLJ/SP days had no LLJ and were synoptically primed, LLJ/SB days had a LLJ present and were synoptically benign, and LLJ/SP days had a LLJ and were synoptically primed (Table 3.1). Table 3.1 shows the number of days classified NoLLJ/SB-LLJ/SP for each month. Most days throughout the study period were synoptically primed for convective activity (NoLLJ/SP and LLJ/SP), with NoLLJ/SP occurring more frequently (34% of all days). NoLLJ/SB was the least occurring classification with 174 days (14% of all days) for the entire period of record.

c. Convective Parameters

Evening (00 UTC) NARR data were analyzed to determine the magnitude of CAPE, CIN, and LI within the study region. NARR was created as a long-term, high-frequency, atmospheric and land hydrology data set for North America (Mesinger et al. 2006). The NARR dataset includes multiple surface and upper-air parameters every three hours at 32-km resolution. The NARR dataset, according to Mesinger et al. (2006), has a much improved land-atmosphere interaction component improving on the National Center for Environmental Prediction (NCEP)-National Center of Atmospheric Research (NCAR) Global Reanalysis dataset. Mesinger et al. (2006) also found that NARR temperature and wind data are more accurate than the reanalysis data from NCEP-DOE GR2 data.

The CAPE, CIN, and LI values were regridded using GEMPAK to match the output grid of the soil moisture data. To determine the relationships on a climatological

scale the gridded convective parameter data were matched with the soil moisture data for each day of the study period. Statistical analysis included a *t*-test to determine if the convective parameters are significantly different between the various synoptic-type days. Since a linear relationship between soil moisture and convective parameters could not be assumed, Spearman's Rank Correlation Coefficient (Rogerson 2001) was also conducted to determine how much variance in the convective parameters is associated with changes in soil moisture.

Additionally, the relationship between soil moisture and the convective parameters were analyzed using convective thresholds commonly used for forecasting the severity of thunderstorm activity. This method was used to determine if there were any changes in the proportion of occurrences of the convective thresholds with changes in soil moisture. Each convective parameter was classified into three categories of Moderate, Strong, and Extreme based on criteria from Table 3.2.

In order to increase the understanding of the relationships established by examining the soil moisture-convective parameter couplet at the climatological scale, a case study from each of the four synoptic-type days was chosen to demonstrate the impact on a smaller time scale. The days chosen were: 17 April 2001 to represent NoLLJ/SB days, 19 August 2001 to represent NoLLJ/SP days, 11 May 2002 to represent LLJ/SB days, and 3 April 2003 to represent LLJ/SP days. These days were chosen because they represent extreme cases of the modified-CTP and LLJ presence. The synoptically benign (primed) days were days in which the lapse rates at the five stations were well below (above) the 6.0°C/km criteria utilized in this study. The LLJ days were chosen based on the existence of a strong 850-hPA LLJ throughout a large portion of the

study region; the non-LLJ days were selected because the 850-hPA wind field had no or very weak southerly flow.

3.3. Results

a. Climatological Analysis

The mean soil moisture distribution for each of the synoptic-type days is shown in Fig. 3.2. The mean values of volumetric soil moisture change slightly across space but the general spatial pattern of wet and dry soils is very similar between the four different classification types. The southeastern portion of the study region has a large area of very low soil moisture excluding the area directly around the Houston, TX region. Higher values (15-25% volumetric soil moisture) are found in the southwestern and northeastern portions of the study region with lower soil moisture values (0-5%) in between.

The spatial distribution of the three convective parameters (CAPE, CIN, and LI) examined have a significant amount of variation between the synoptic-type days (Figs. 3.3-3.5). Fig. 3.3a shows the mean spatial distribution of CAPE under NoLLJ/SB days. The lowest amounts of CAPE ($\sim 200 \text{ J kg}^{-1}$) occur over the northwestern portion of the study region and increase toward the southeast. Under the other three synoptic-type days (NoLLJ/SP, LLJ/SP, LLJ/SB) the spatial pattern of CAPE has a strong east-to-west gradient with lower values of CAPE ($\sim 200 \text{ J kg}^{-1}$) in the western portion of the domain and higher values ($>1000 \text{ J kg}^{-1}$) in the east. Thus, the potential for more severe convection would be higher in the eastern portions of the study region, where CAPE values are high, compared to the west.

Lifted Index maps show days with no LLJ present (NoLLJ/SB and NoLLJ/SP) have higher values ($>0^{\circ}\text{C}$) present throughout much of the domain (Figs. 3.4a and 3.4b). This would lead to more stable conditions under NoLLJ/SB and NoLLJ/SP days. During days with a LLJ present (LLJ/SB and LLJ/SP) the LI values are lower ($<0^{\circ}\text{C}$) and have weaker (as compared to CAPE) east-to-west gradient (Figs. 3.4c and 3.4d). The LI and CAPE values both show increases in instability on the days with a LLJ present, the values being greatest on LLJ/SP days where the environment is also synoptically primed. The increases in instability on these synoptic-type days indicate the presence of moisture from the LLJ may be amplifying the instability in the atmosphere.

Convective suppression, as measured by CIN, is also maximized during LLJ/SB and LLJ/SP days (Figs. 3.5c and 3.5d, respectively). As a result, on days with a low-level jet present the convective environment is maximized for severe potential but is also strongly capped. If the cap is broken then the potential for severe convection is present. The CIN, and thus capping ability, is diminished with NoLLJ/SB and NoLLJ/SP days (Figs. 3.5a and 3.5b, respectively). The potential for severe convection is reduced under NoLLJ/SB and NoLLJ/SP due to the smaller CAPE, higher LI, and smaller CIN to cap the environment.

Independent samples Student's *t*-tests (Rogerson 2001) were run to determine if these differences in CAPE, CIN, and LI were statistically significant between the various synoptic-type days. Table 3.3 shows the mean and standard deviation of the convective parameters under each synoptic-type day. The instability is minimized during NoLLJ/SB days with 460 J kg^{-1} of CAPE and an LI of 1°C and maximized during LLJ/SP days at 1032 J kg^{-1} of CAPE and an LI of -3°C . The LLJ/SP days are also more strongly capped

than the NoLLJ/SB days, -53 J kg^{-1} and -38 J kg^{-1} , respectively. The differences between each synoptic-type day (NoLLJ/SB vs. NoLLJ/SP, NoLLJ/SP vs. LLJ/SB, etc.) were all found to be statistically significant at the $p=0.01$ level (Table 3.4).

The convective parameters were also tested to determine if there was any correlation with the soil moisture values using Spearman's Rank Correlation analysis (Table 3.5). On all synoptic-type days CAPE is inversely correlated with soil moisture values using Spearman's correlation analysis. Thus, as soil moisture increases, CAPE decreases, which increases stability. The same type of relationship, excluding LLJ/SB days, is seen with the Spearman's analysis of soil moisture and LI values. A direct relationship exists between soil moisture and LI values thus increasing stability. On LLJ/SB days there is an inverse relationship between the two parameters. These results are counter to the findings presented in Pielke (2001) (and citations within) and Pielke and Zeng (1989) that increases in low-level moisture, a source of which can be soil moisture, cause increases in CAPE values and LI values, respectively. Spearman's correlation analysis between soil moisture and CIN also show an inverse relationship between the variables on all synoptic-type days. All of the correlation values are statistically significant (at $p=0.01$) but very little variation of the convective parameters is explained by changes in the soil moisture.

To further investigate the relationship between soil moisture and the convective parameters at the climatological scale the soil moisture values were then classified as Dry Soils (lowest quartile), Wet Soils (highest quartile), and Moderate Soils (the middle two quartiles) for each synoptic-type day. Figs. 3.6-3.8 show box and whisker plots for each convective parameter by synoptic-type days and Dry, Wet, and Moderate soil moisture

categories. For NoLLJ/SP, LLJ/SB, and LLJ/SP days the mean and range of CAPE values are maximized over the Dry Soils and minimized over the Moderate Soils (Fig. 3.6). A similar pattern is observed in Fig. 3.7 which shows the means and ranges of LI values over the Dry, Moderate, and Wet soils for each synoptic-type day. LI values are minimized (i.e., maximizing instability) over Dry Soils and maximized over Wet Soils. The suppression of convection, as measured by CIN, is maximized over the Moderate Soils and minimized over Dry Soils under all synoptic-type days (Fig. 3.8). These results show on average the convection over the dry soils should be more intense, due to high CAPE and low LI, and have a weaker cap to break through as indicated by the low CIN values.

b. Convective Thresholds

The possible severity of convection can be determined by examining various threshold levels of convective parameters. For the present study, this was accomplished by calculating the proportion of data points that reached or exceeded three levels of severity (Moderate, Strong, and Extreme) of the convective parameters over the range of soil moisture values (See Table 3.2 for the threshold criteria). Fig. 3.9 shows that as the soil moisture increases, the proportion of points that meet the convective thresholds increased for CAPE, remained fairly constant for LI, and CIN values peaked around 10% volumetric soil moisture before decreasing for NoLLJ/SB days. On the remaining synoptic-type days (Figs. 3.10-3.12) the proportion of each threshold level increases. On NoLLJ/SP, LLJ/SB, and LLJ/SP days the CAPE and LI values all experience a large decrease in proportion from 0-5% volumetric soil moisture and then a steady increase to

50%. This indicates that as soil moisture increases the atmosphere is more likely to become destabilized as indicated by the increase in proportion of data points exceeding the threshold values. The proportion of CIN values on those three synoptic-type days increases from 0-10% volumetric soil moisture values and then decreases as the soil moisture increases to 50% volumetric soil moisture. These results indicate the likelihood of an intense cap to convection is diminished as soil moisture increases. Thus, on NoLLJ/SP, LLJ/SB, and LLJ/SP days, the atmosphere is more likely to become less stable and have a weaker cap in areas where the soil moisture values are larger. This corresponds to the results presented by Pielke and Zeng (1989) and Pielke (2001).

c. Case Studies

1) NoLLJ/SB – 17 April 2001

This day is characterized by a large area of high pressure which dominated much of the Great Plains region. On the morning (12 UTC) of 17 April 2001, the high pressure was dominated by cold temperatures as it moved into place after the passage of a cold front during the previous 24 hours. The temperatures in the Great Plains ranged from the upper teens in the northern part to around 50°F in the southern portions. At 850-hPa the wind flow was from the north throughout most of the study region, which helped account for the synoptically benign conditions and colder temperatures at the surface. A ridge of high pressure at 500-hPa was positioned to the west of the study region in the morning and progressed slowly to the east over the next few days. The soil moisture conditions for the day show very low volumetric soil moisture values for the northwestern portion of

the study region and increases in the southwest and eastern half portions (Fig. 3.13a). While these conditions did not favor any convective activity on this day, the evening LI values (Fig. 13.3b) show the entire study region experiencing values of greater than 0°C . CAPE and CIN patterns showed minimal change throughout the study region ($<100 \text{ J kg}^{-1}$ and $>-50 \text{ J kg}^{-1}$, respectively). The high LI values (i.e., stable conditions) are maximized in the middle portion of the region. This same area is the location where the lowest volumetric soil moisture values are found (Fig. 3.13a). As the soil moisture increases to the east the LI values decrease as well following a similar pattern, especially in the southern portion of the study region. The results on this day correspond to the results of Pielke and Zeng (1989), who found a decrease in LI over irrigated regions in northeast Colorado.

2) NoLLJ/SP – 19 August 2001

At 12 UTC 19 August 2001 a surface cold front was positioned through the middle portion of the study region from the panhandle of Oklahoma through Oklahoma City and northeastward to a low pressure system located over eastern Ohio. A developing low pressure area was located in southern Montana and an associated stationary front extended south to just west of the study region. An 850-hPa level shortwave axis, which was positively tilted, was present as was associated with the developing surface low just to the west of the study region. The winds at 850-hPa level were light (<25 knots) and had a westerly component throughout most of the study region. At 500-hPa level, a shortwave was present which was influencing the study

region; however, this wave was located in the southern portion of the study region and had a positive tilt and ran from southwestern Texas to the Ark-La-Tex region.

The soil moisture field for 19 August 2001 is shown in Fig. 3.14a and shows an axis of higher soil moisture values from the southwest to northeast. The area with the highest soil moisture values is located in the southwest portion of Texas. Using previous results from Pielke and Zeng (1989) and Pielke (2001) these areas would be areas to focus on for increases in instability, measured by LI and CAPE in the present study, based on increases in low-level moisture (Figs. 3.14b and 3.14c). However, the locations of the axes of CAPE and LI are located over the driest soils in the eastern portion of the study region. This shift in the patterns could either be caused by advection of low-level moisture creating higher CAPE values downwind of the maximum soil moisture values or by the development of mesoscale circulation patterns which have been shown to enhance convective patterns along transition zones of surface properties, including soil moisture (Ookouchi et al. 1984, Pielke and Segal 1986, Avissar and Pielke 1989, Fast and McCorcle 1991, Chang and Wetzel 1991, Emori 1998, Liu et al. 1999, Pielke 2001, Carleton et al. 2001). The lowest CIN values, indicating a stronger cap, are located in the northeastern portion of the study region where there are low to moderate soil moisture values (Fig. 3.14d).

3) LLJ/SB – 11 May 2002

On the morning of 11 May 2002 a surface low pressure center was located in east central Colorado and throughout the day moved northeasterly through the upper Great Plains region into southeastern Iowa by the next morning. A negatively tilted trough was

located in the northwest U.S. and slowly progressed towards the Rocky Mountains through the day. Ahead of the trough a strong LLJ developed throughout most of the study region. The soil moisture pattern throughout the study region showed high soil moisture values in the Oklahoma and Texas panhandles region, in the northeast portion of the study region, and in the southwestern portion of the study region (Fig. 3.15a).

Examining Figs. 3.15b-d it appears that there is a relationship between the soil moisture and the LLJ and they both influence the convective parameters on this day.

As with the cases presented for both NoLLJ/SB and NoLLJ/SP days, the CAPE and LI values tend to increase in the transition zones between high and low soil moisture values. However, on this day, which is classified LLJ/SB, the convective parameters indicate more instability and the instability is more widespread than with the NoLLJ days. The strongest portion of the LLJ extends from the eastern border of the Texas panhandle to the Oklahoma-Arkansas border. This region corresponds well with the smaller LI values (Fig. 3.15b) and larger CAPE values (Fig. 3.15c). The CIN values (Fig. 3.15d) appear to be higher, more capped region, over the regions with lower soil moisture values in the southeastern portion of the study area.

4) LLJ/SP – 3 April 2003

Similar to the LLJ/SB day, the LLJ on 3 April 2003 covers a significant portion of the study region. However, this day is classified as synoptically primed due to the presence of a low pressure system traversing the area throughout the day. At 1200 UTC the surface low pressure system is centered in the southeast corner of Nebraska and extends into the Texas panhandle region. At both 850-hPa and 500-hPa there is a

significant trough located to the west of the study region. Within the trough there are multiple shortwaves passing through and within the vicinity of the study region. The soil moisture pattern on this day shows a majority of the southwest portion of the study region with high values and an axis of increased soil moisture located in the eastern portion of the study region (Fig. 3.16a). As with the LLJ/SB day, this day shows a strong relationship between soil moisture and LI and CAPE (Figs. 3.16b and 3.16c). The axes of LI and CAPE correspond well to the location where soil moisture values are the highest. The extent of the maximum instability (i.e., high CAPE and low LI values) is also closely tied to the location of the maximum winds in the LLJ. This indicates that a relationship exists between the soil moisture and LLJ and that this couplet assists in the control of the convective parameters examined. The CIN on this day was small for a majority of the study region (Fig. 3.16d). There is some increase in the cap strength in the southeastern portion of the study region (Fig. 3.16d).

3.4. Conclusion

Modeling studies and short-term field campaigns have shown relationships between soil moisture and various convective parameters. The present study showed that convective parameters over a seven-year period in the southern Great Plains may not only be partially related to the changes in soil moisture but also may be controlled by a synergistic relationship between soil moisture and the presence of a LLJ at 850-hPa level. This research was made possible by new advances in soil moisture measurements from TMI and the development of the NARR dataset.

The climatological relationship between convective parameters and soil moisture measurements was strongly dependent on the synoptic-scale patterns influencing the study region. When the moist LLJ initiating in the Gulf of Mexico was present (LLJ/SB and LLJ/SP) in the region CAPE (approximately 400 J kg^{-1}) and LI (approximately 2°C) values indicated a more severe thunderstorm environment was present. However, these days were also shown to have stronger caps or lids, as indicated by larger CIN values (approximately 12 J kg^{-1}). On days where there was no LLJ present the thunderstorm environment was less severe and if any convection did initiate, it would have a weaker cap to break through.

The relationship, as measured by Spearman's Rank correlation coefficients, between soil moisture and convective parameters was statistically significant but very small (i.e., 0.2% to 11.6% variation in convective parameters is caused by variations in soil moisture depending on the correlation analysis test and synoptic-type day). Despite the small explanation in variance some modeling studies have shown that detailed changes in soil moisture are critical for assimilation into regional models (Capehart et al. 2004, Holt et al. 2006, Niyogi et al. 2006). The results from Capehart et al. (2004) showed little, but significant, change in the pre-storm environments for two modeled case studies in the Northern Great Plains. On all synoptic-type days, Spearman's Correlation Analysis showed an inverse relationship (except LLJ/SB, LI values) between soil moisture and stability, as measured by CAPE and LI. The CIN values on all synoptic-type days also show an inverse relationship indicating a stronger cap is present over wetter soils. Additional analysis after classifying soil moisture values showed that more unstable atmospheres occur over the Dry Soils and more stable conditions over Moderate

Soils (Fig. 3.17). However, in all soil moisture classes the days with a LLJ present showed an increase in the destabilization of the atmosphere. The same conclusion can be drawn from the analysis on Moderate, Strong, and Extreme convective thresholds values. On days with the LLJ present the proportion of data points which meet the convective thresholds was much greater and also showed an increase as soil moisture increased.

In addition to these results being shown on the climatological scale, four days representing the different synoptic-type days were chosen to illustrate the impact of the soil moisture-LLJ couplet on a daily scale. The results of the case studies confirmed the results of the long-term study. Decreases in stability were shown to be located within proximity of the higher soil moisture values. Also on days with a LLJ jet present, the CAPE and LI values were higher and tended to be not only associated with the soil moisture but also co-located with the area of the maximum winds in the LLJ.

The results at the climatological and daily scale suggest that development of thunderstorms over wet soils would be more intense when there is a LLJ present but these thunderstorms would also have a stronger cap to break through. On days with no LLJ present, the relationship is the opposite; increases in soil moisture cause a decrease in the severity of CAPE and LI values. The increases in unstable conditions while a LLJ is present could be due to the heat and moisture transported into the southern Great Plains causing a destabilization of the atmosphere. The increase in instability as soil moisture increases has also been shown by Pielke and Zeng (1989) and Pielke (2001) and the presence of the LLJ causing destabilization has also been identified in modeling studies by McCorcle (1988) and Chang and Wetzel (1991).

In chapter 2, it was shown that the growth of the boundary layer is greatest over the wettest soils as compared to the driest soils under the various synoptic-type days. Thus, convection would be expected over the wettest soils due to the greater likelihood that the turbulent thermals within the boundary layer would be able to reach their level of free convection. However, the results from that chapter also showed that the boundary layer growth is even greater over the Moderate Soils. The results within this chapter indicate that convection would have a higher probability of becoming more severe, based on the convective parameters examined, on days with a LLJ present than on days with no LLJ. When examining thunderstorm development over the various soil moisture classifications, the severity is maximized over the dry soils and minimized in the transition zones between wettest and driest soils.

The results from chapters 2 and 3 show that although convection may be more likely to form over the middle classification of soils this convection would have the least probability of becoming severe, based on the convective parameters examined. The convection would have the highest probability of becoming severe over the driest soils but formation would be more complicated due to the small boundary layer growth suppressing convective thermals from reaching the level of free convection. In order to better understand these conflicting results from Chapter 2 and Chapter 3, the third phase of this study will examine the initiation of convection in relationship to changes in soil moisture. This will be completed by examining cases of convective initiation using radar data from one station within the study region over the entire period of record. The results from this portion of the study should add more clarity to the effects of soil moisture on convection patterns.

3.5. References

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Table 3.1. The number and percentage of days per month for the four synoptic-type days. Fifteen days were eliminated from the study due to the lack of soil moisture or PBL height data (25 April 1998, 8 Aug 1999, 6 July 2000, 17 September 2000, 18 September 2000, 19 September 2000, 6 April 2001, 13 August 2001, 14 August 2001, 15 August 2001, 17 August 2001, 6 April 2003, and 30 April 2003). NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ/SP are days with no LLJ and synoptically primed, LLJ/SB are synoptically benign days with a LLJ present, and LLJ/SP are synoptically primed days with a LLJ present.

| | April | May | June | July | August | September | Total |
|-----------------|--------------|------------|-------------|-------------|---------------|------------------|--------------|
| NoLLJ/SB | 35 (17) | 30 (14) | 27 (13) | 16 (7) | 13 (6) | 53 (26) | 174 (14) |
| NoLLJ/SP | 57 (28) | 50 (23) | 40 (19) | 103 (48) | 113 (54) | 69 (33) | 432 (34) |
| LLJ/SB | 41 (20) | 56 (26) | 70 (33) | 24 (11) | 12 (6) | 35 (17) | 238 (19) |
| LLJ/SP | 72 (35) | 81 (37) | 73 (35) | 73 (34) | 73 (35) | 50 (24) | 422 (33) |
| Total | 205 (16) | 217 (17) | 210 (17) | 216 (17) | 211 (17) | 207 (16) | 266 (100) |

Table 3.2. Threshold values for Moderate, Strong, and Extreme classification of the convective parameters (Vasquez 2006).

| | CAPE (J kg^{-1}) | LI ($^{\circ}\text{C}$) | CIN (J kg^{-1}) |
|----------|-----------------------------|---------------------------|----------------------------|
| Moderate | 1000 | -3 | -21 |
| Strong | 2500 | -6 | -51 |
| Extreme | 3500 | -10 | -101 |

Table 3.3. The mean and standard deviation for CAPE (in J kg^{-1}), LI ($^{\circ}\text{C}$), and CIN (J kg^{-1}) for each synoptic-type day. NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ/SP are days with no LLJ and synoptically primed, LLJ/SB are synoptically benign days with a LLJ present, and LLJ/SP are synoptically primed days with a LLJ present.

| | NoLLJ/SB | NoLLJ/SP | LLJ/SB | LLJ/SP |
|---------------------|-----------------|-----------------|---------------|---------------|
| Mean CAPE | 460 | 726 | 923 | 1032 |
| S.D. of CAPE | 714 | 805 | 961 | 1034 |
| Mean LI | 1 | -2 | -2 | -3 |
| S.D. of LI | 5 | 3 | 4 | 4 |
| Mean CIN | -38 | -41 | -51 | -53 |
| S.D. of CIN | 66 | 58 | 74 | 70 |

Table 3.4. The t -critical ($p=0.01$), t -observed, and degrees of freedom (DF) for the independent samples difference of means Student's t -test conducted on each convective parameter (i.e., CAPE, LI, CIN) between the different synoptic-type days. NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ/SP are days with no LLJ and synoptically primed, LLJ/SB are synoptically benign days with a LLJ present, and LLJ/SP are synoptically primed days with a LLJ present.

| | NoLLJ/SB vs. NoLLJ/SP | NoLLJ/SB vs. LLJ/SB | NoLLJ/SB vs. LLJ/SP | NoLLJ/SP vs. LLJ/SB | NoLLJ/SP vs. LLJ/SP | LLJ/SB vs. LLJ/SP |
|--|-----------------------------|---------------------------|---------------------------|---------------------------|---------------------------|-------------------------|
| t-critical | +/- 2.576 | +/- 2.576 | +/- 2.576 | +/- 2.576 | +/- 2.576 | +/- 2.576 |
| DF | 4352648 | 2854140 | 4227755 | 4889624 | 6263239 | 4764731 |
| t- observed for CAPE | -313.3 | -442.0 | -548.5 | -240.7 | -414.8 | -113.1 |
| t- observed for LI | 550.2 | 480.7 | 732.6 | 86.20 | 333.3 | 173.3 |
| t- observed for CIN | 44.30 | 147.4 | 191.0 | 159.8 | 223.6 | 25.34 |

Table 3.5. Spearman’s correlation coefficients for each convective parameter and soil moisture for each synoptic-type days. (* indicates significance at the $p=0.01$ level). NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ/SP are days with no LLJ and synoptically primed, LLJ/SB are synoptically benign days with a LLJ present, and LLJ/SP are synoptically primed days with a LLJ present.

| | Spearman’s Correlation Coefficients for CAPE | Spearman’s Correlation Coefficients for LI | Spearman’s Correlation Coefficients for CIN |
|-----------------|---|---|--|
| NoLLJ/SB | -0.027* | 0.011* | -0.041* |
| NoLLJ/SP | -0.116* | 0.084* | -0.002* |
| LLJ/SB | -0.008* | -0.011* | -0.081* |
| LLJ/SP | -0.063* | 0.030* | -0.037* |

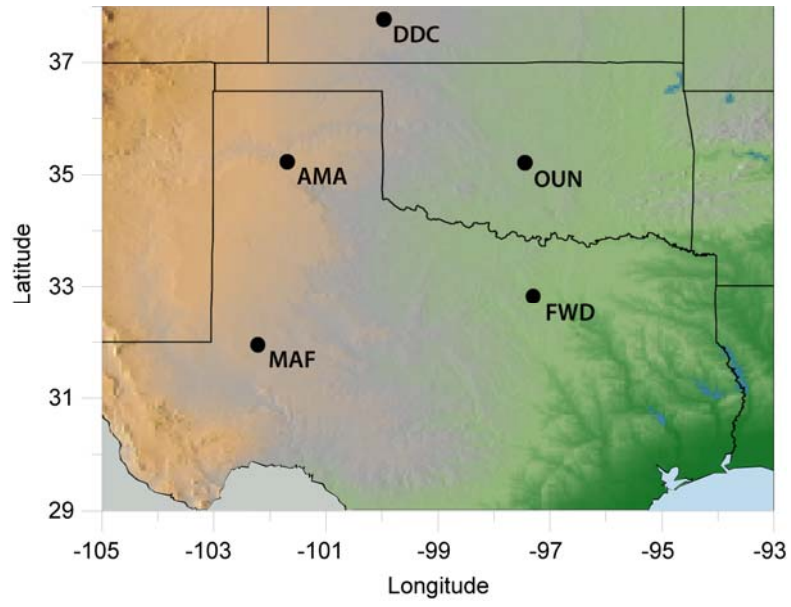


Fig. 3.1. Study region with the locations of radiosonde sites used to determine synoptic-type day. The radiosonde sites include Amarillo, TX (AMA), Dodge City, KS (DDC), Fort Worth, TX (FWD), Midland, TX (MAF), and Norman, OK (OUN). Shaded relief from USGS (2003).

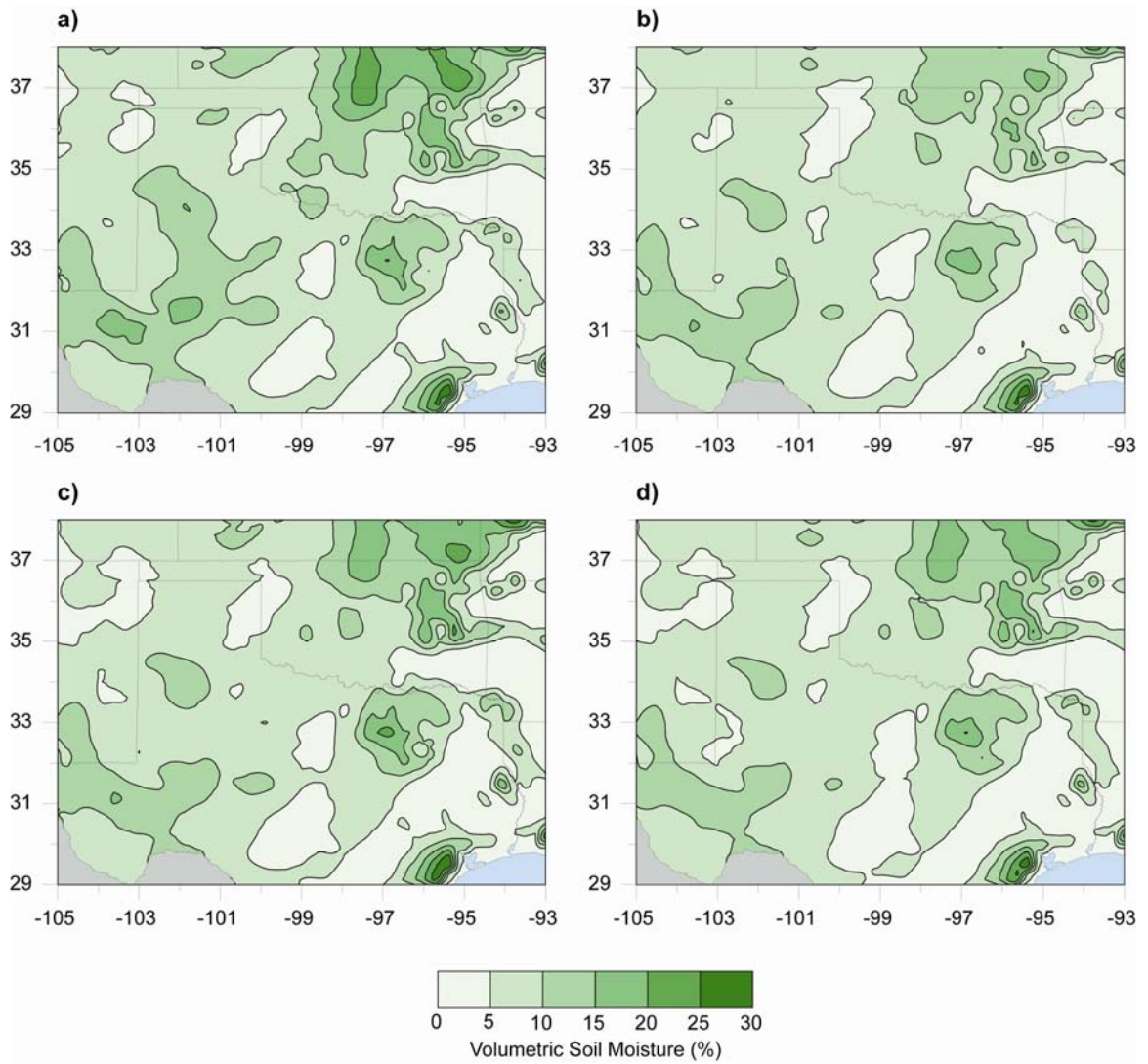


Fig. 3.2. Average soil moisture conditions under each synoptic-type day: a) NOLLJ/SB, b) NOLLJ/SP, c) LLJ/SB, and d) LLJ/SP.

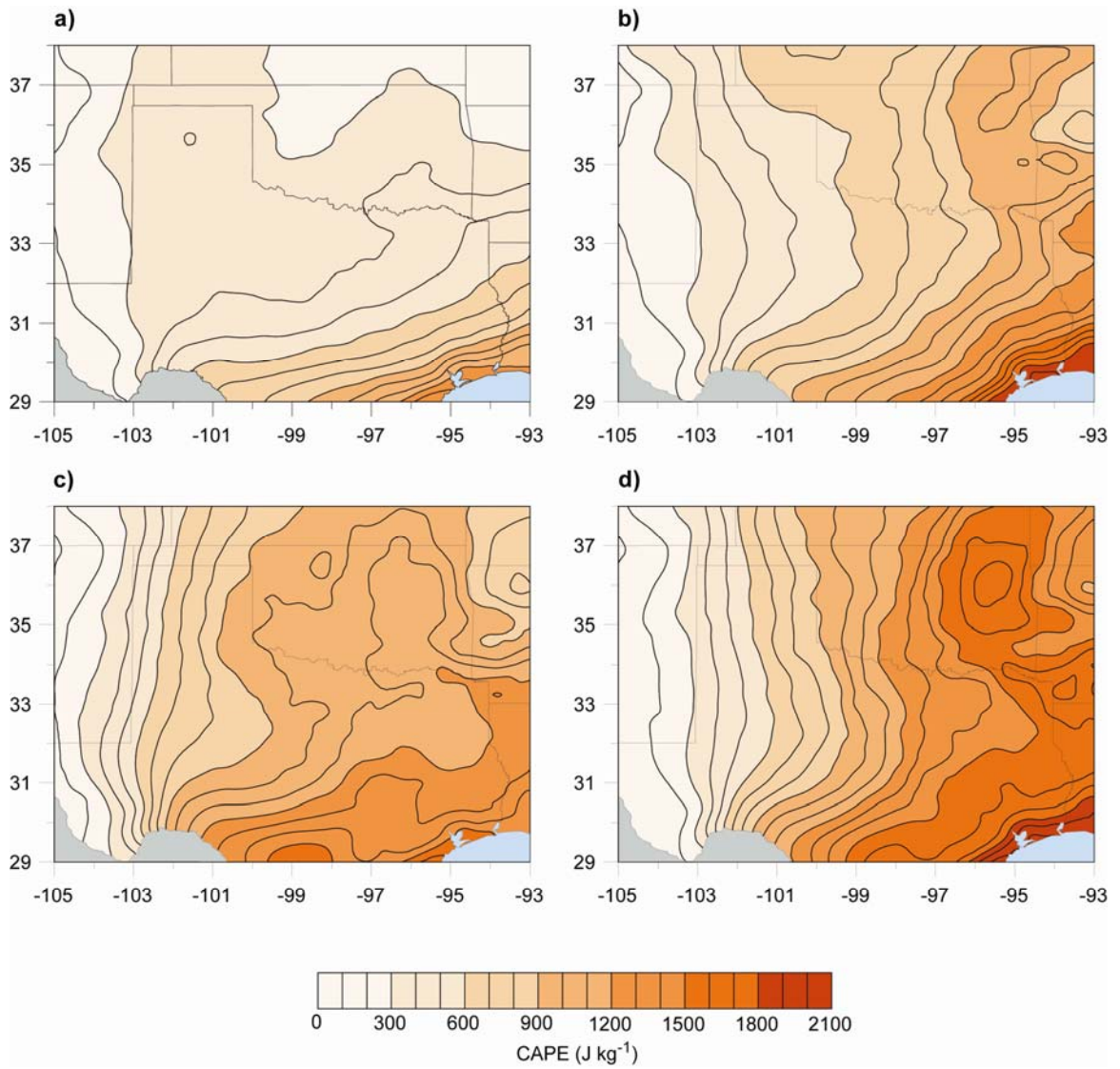


Fig. 3.3. Same as Fig. 3.2 except for CAPE (J kg^{-1}).

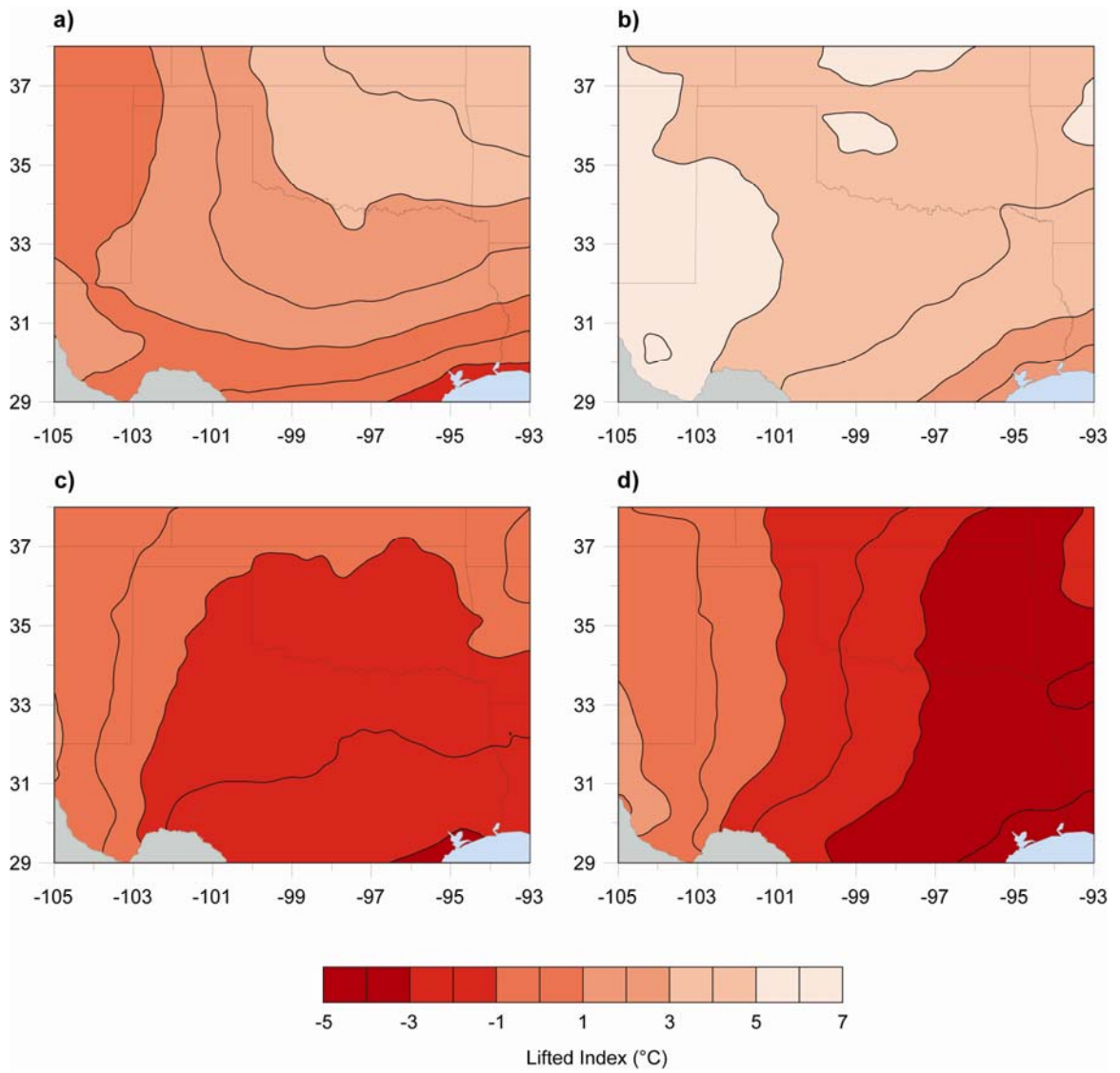


Fig. 3.4. Same as Fig. 3.2 except for LI (°C).

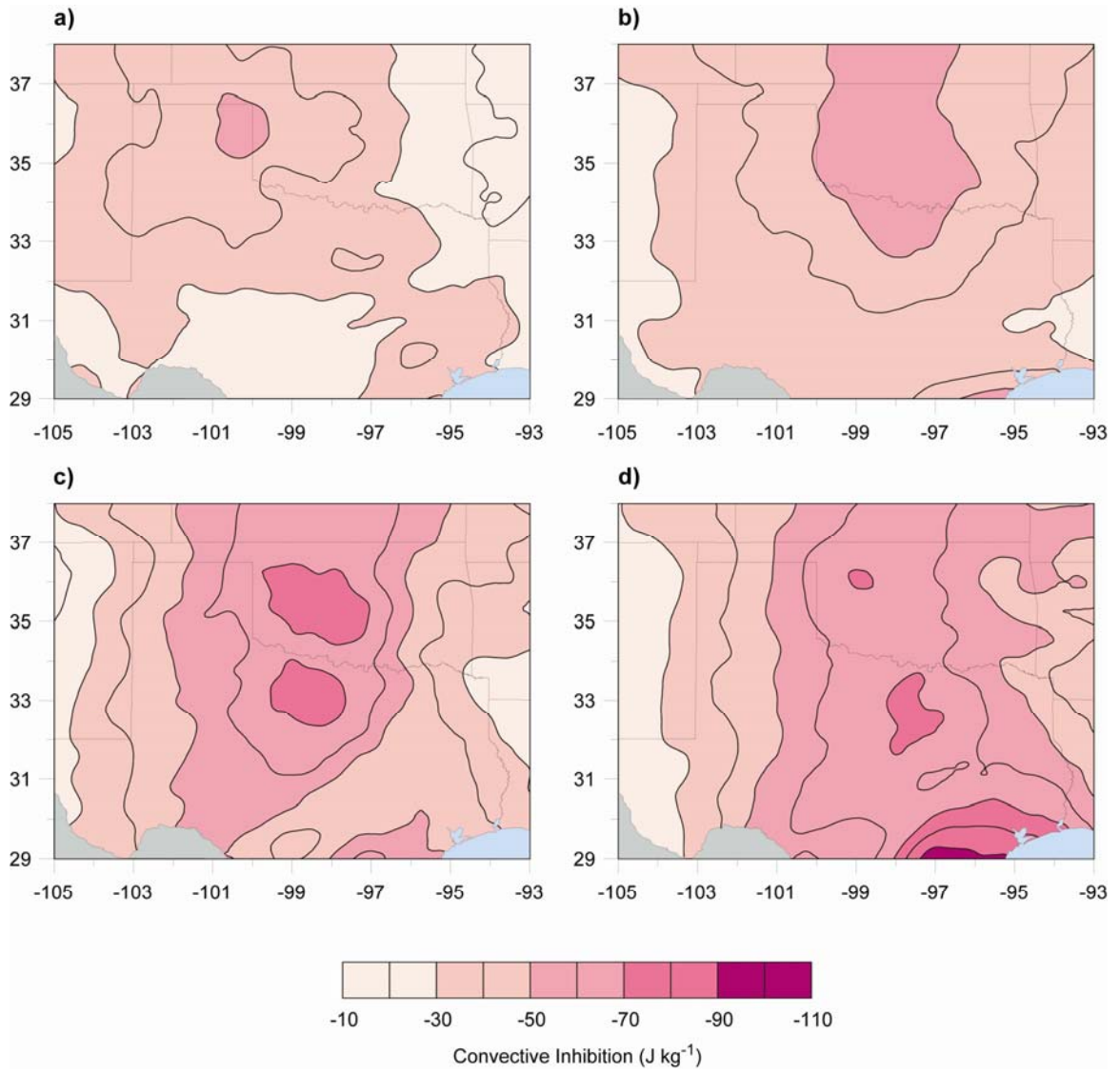


Fig. 3.5. Same as Fig. 3.2 except for CIN (J kg^{-1}).

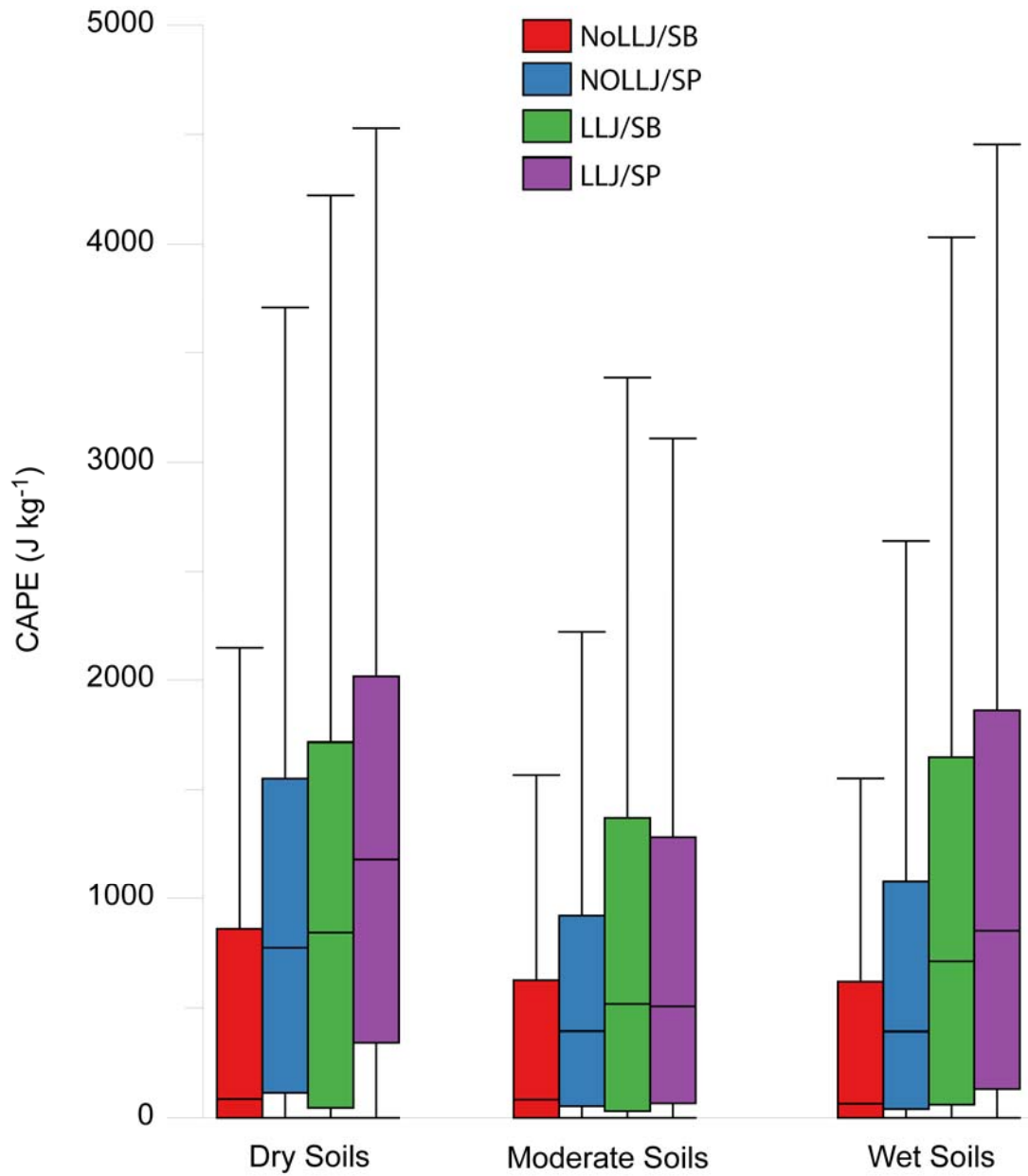


Fig. 3.6. Average and standard deviations of CAPE (J kg^{-1}) by soil moisture category. Mean is indicated by horizontal line in the shaded box, ± 1 standard deviations (shaded boxes), and ± 2 standard deviations (whiskers). Dry Soils (lowest quartile), Wet Soils (highest quartile) and Moderate Soils (middle two quartiles) for each synoptic-type day.

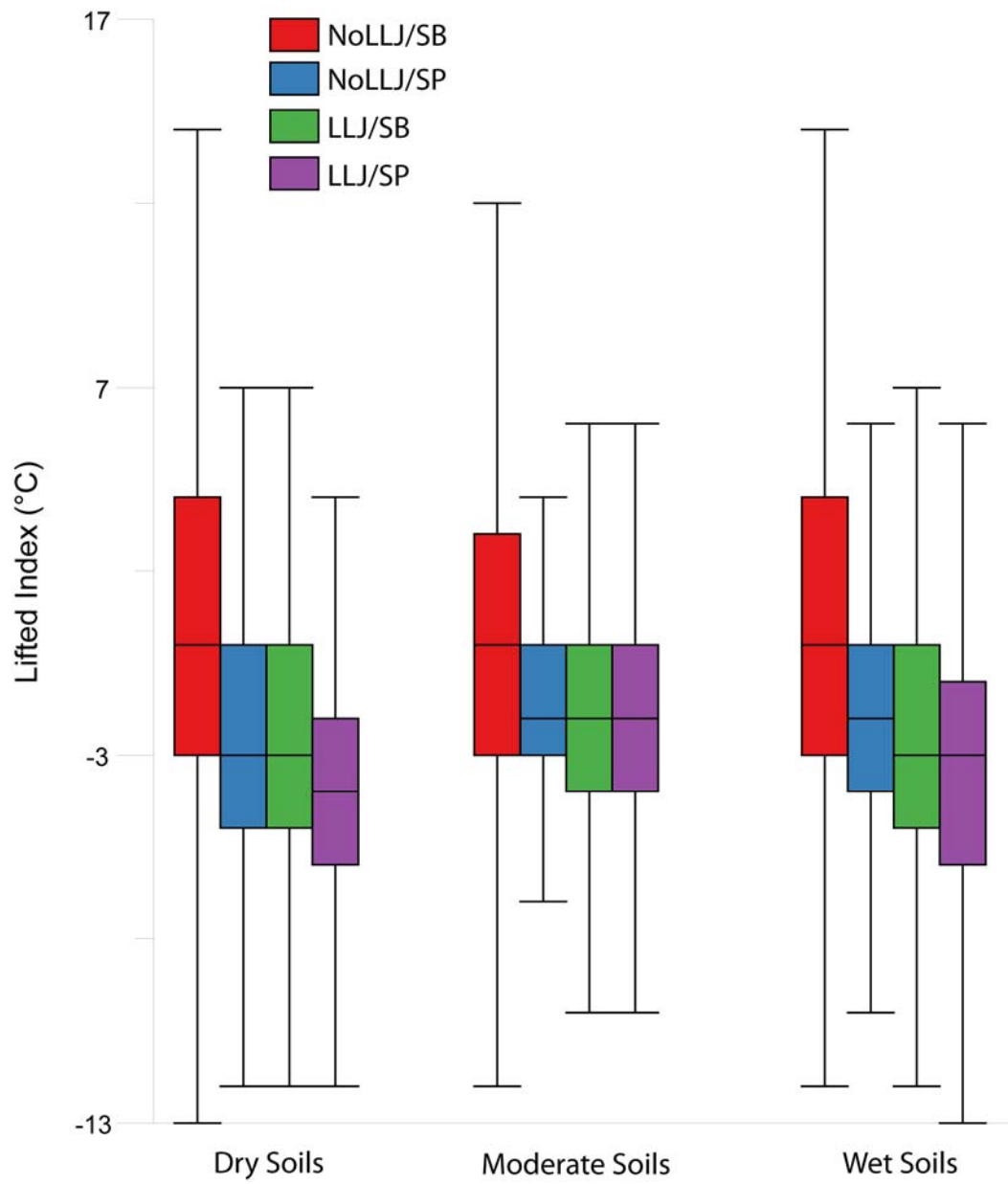


Fig. 3.7. Same as Fig. 3.6 except for LI (°C).

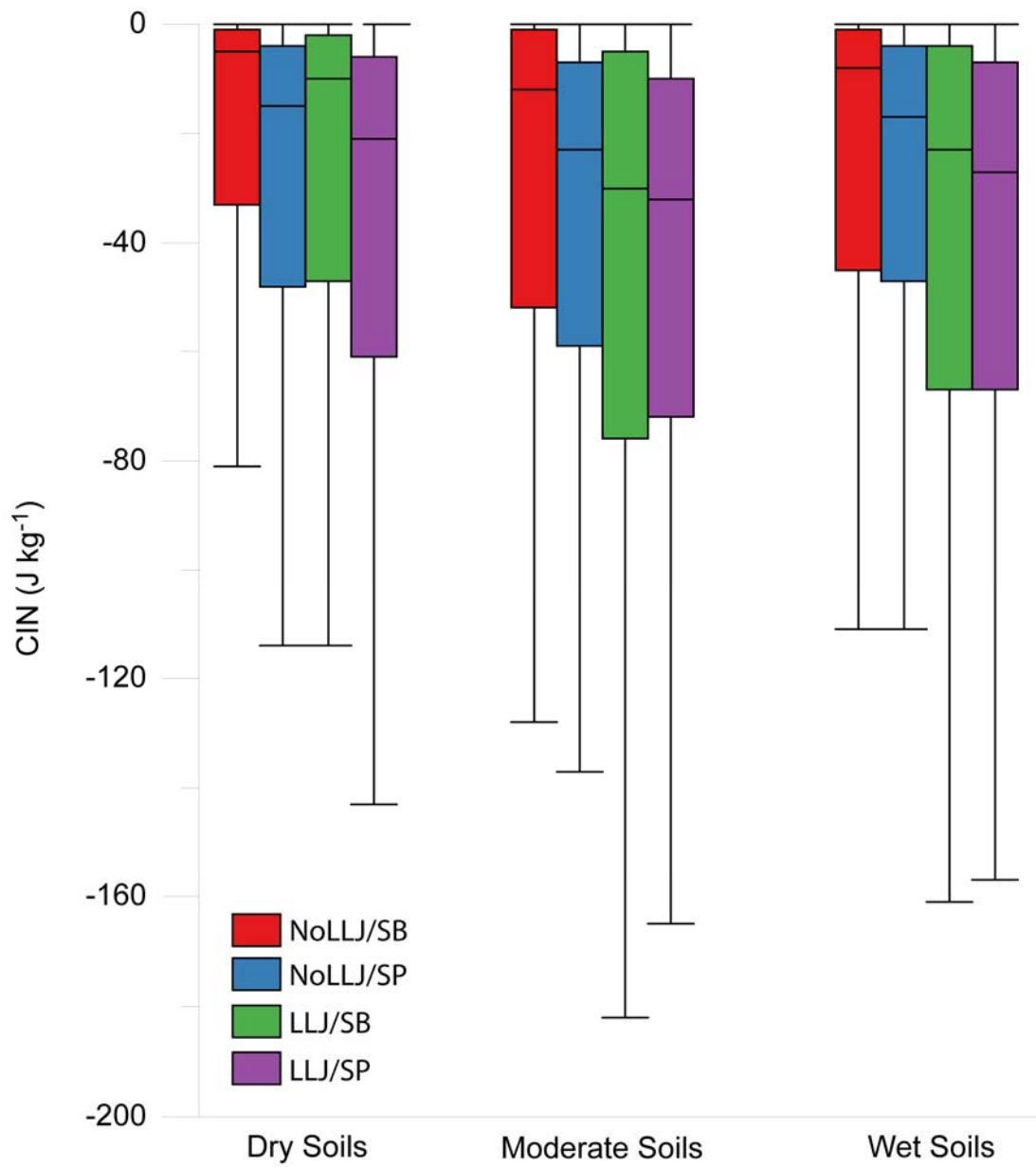


Fig. 3.8. Same as Fig. 3.6 except for CIN (J kg⁻¹).

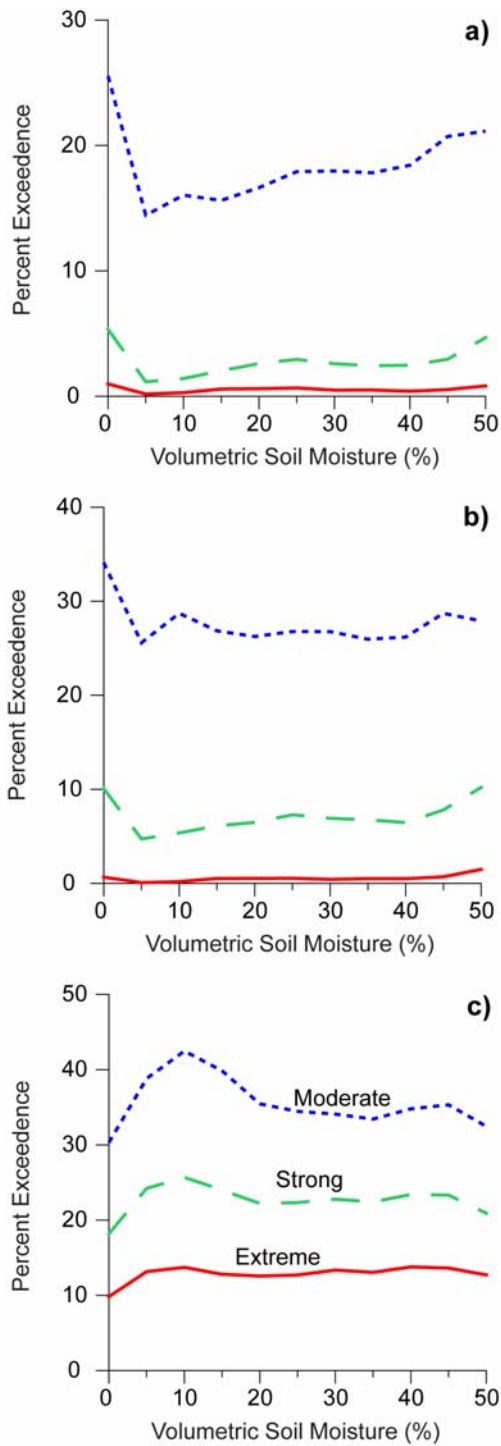


Fig. 3.9. Proportion of data points which meet threshold criteria on NoLLJ/SB days: a) CAPE, b) LI, and c) CIN. Small dashed blue line represents moderate threshold level, long dashed green line represents strong threshold level, and solid red line represents extreme threshold level.

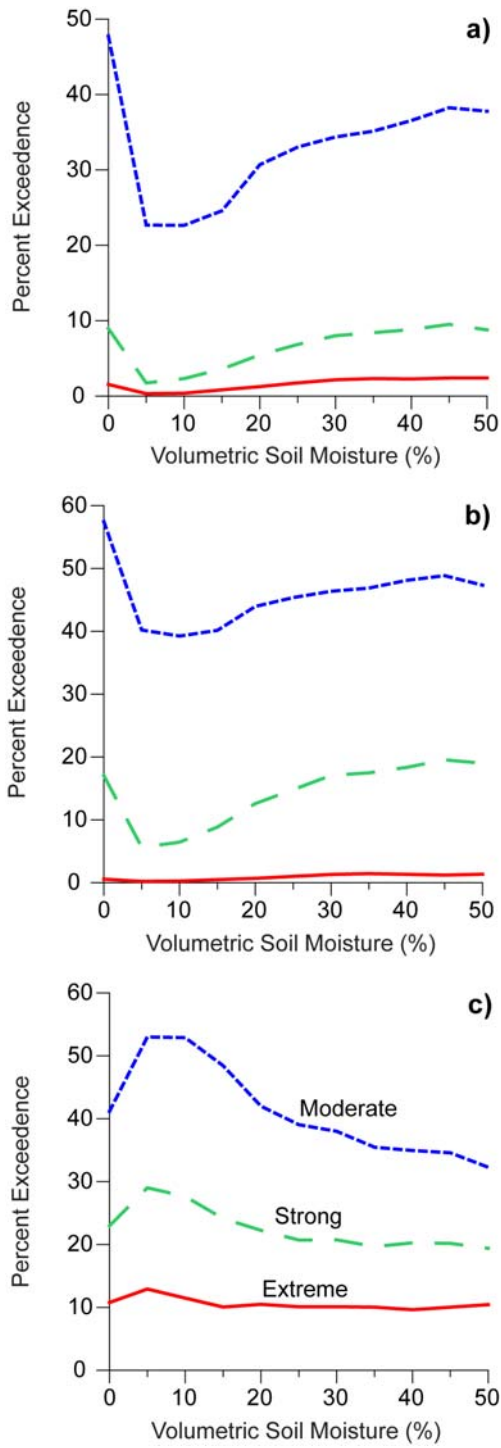


Fig. 3.10. Same as Fig. 3.9 except for NoLLJ/SP days.

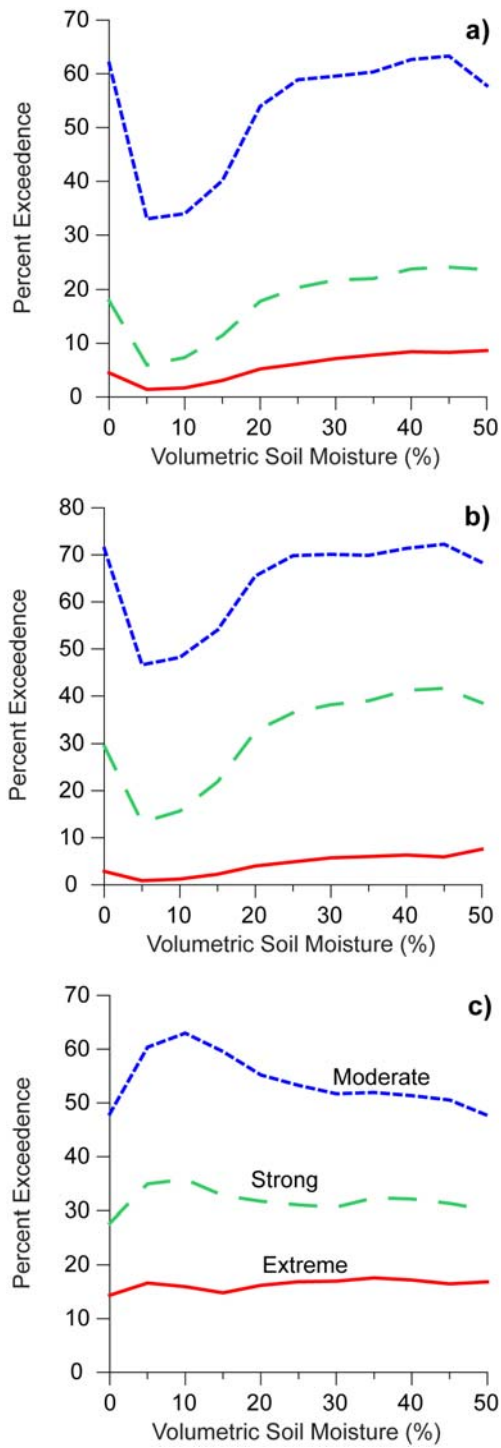


Fig. 3.11. Same as Fig. 3.9 except for LLJ/SB days.

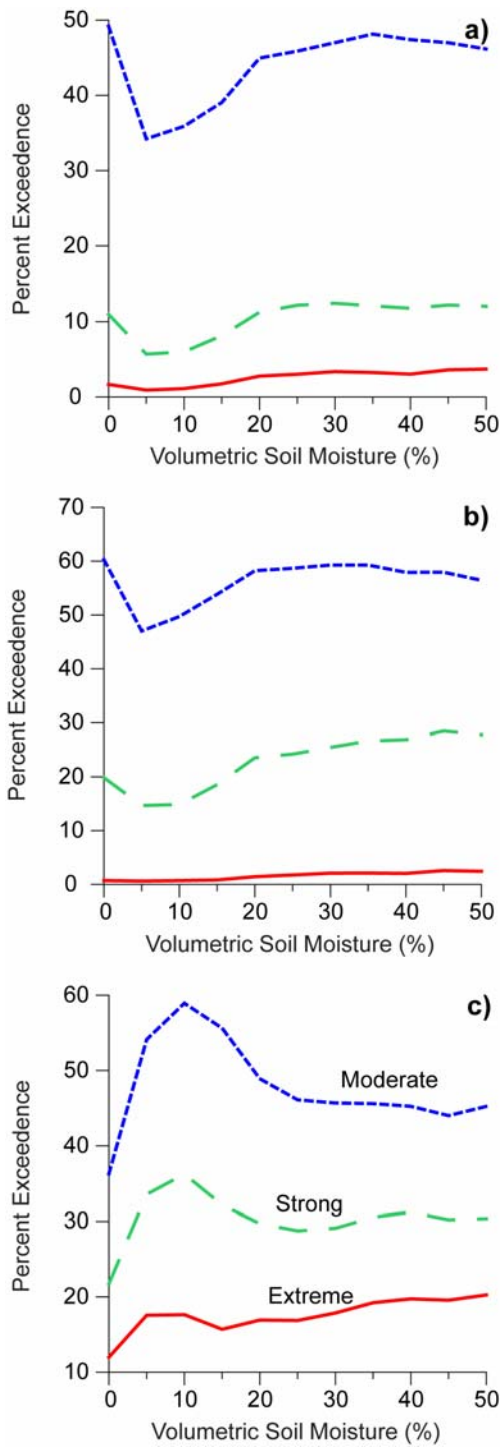


Fig. 3.12. Same as Fig. 3.9 except for LLJ/SP days.

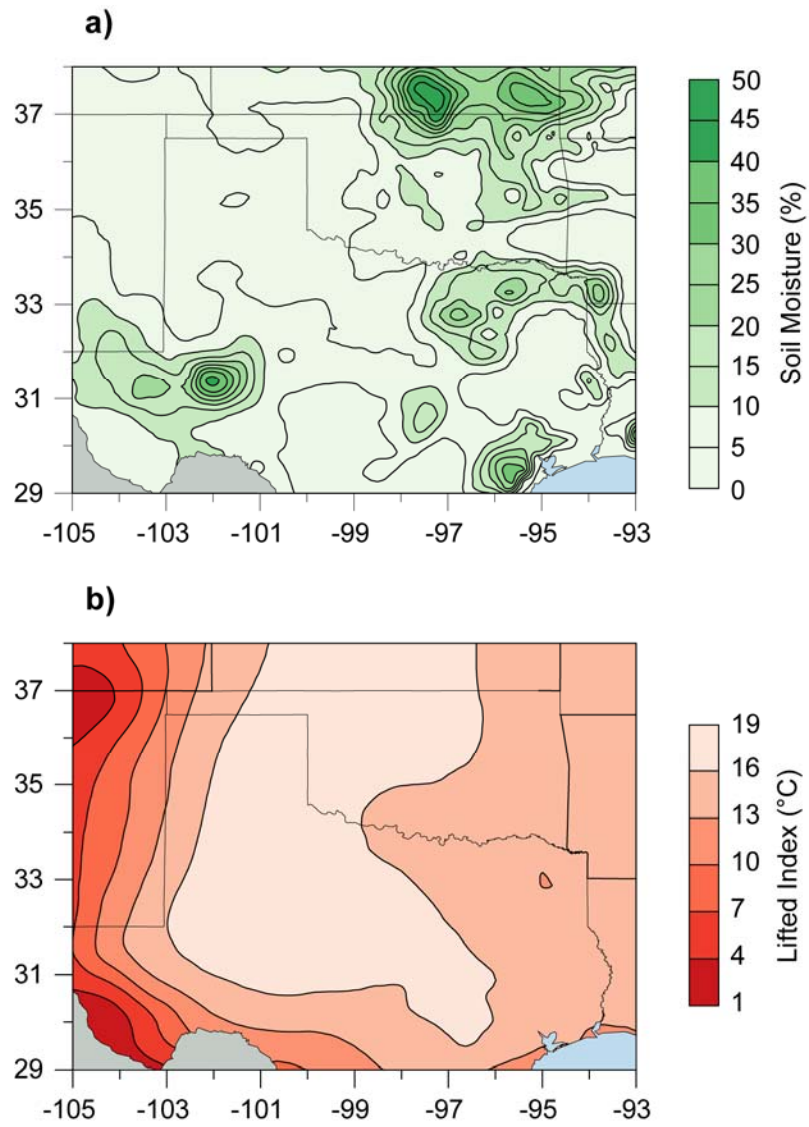


Fig. 3.13. 17 April 2001 illustrating an example of a NoLLJ/SB day: a) volumetric soil moisture (%) and b) LI (°C).

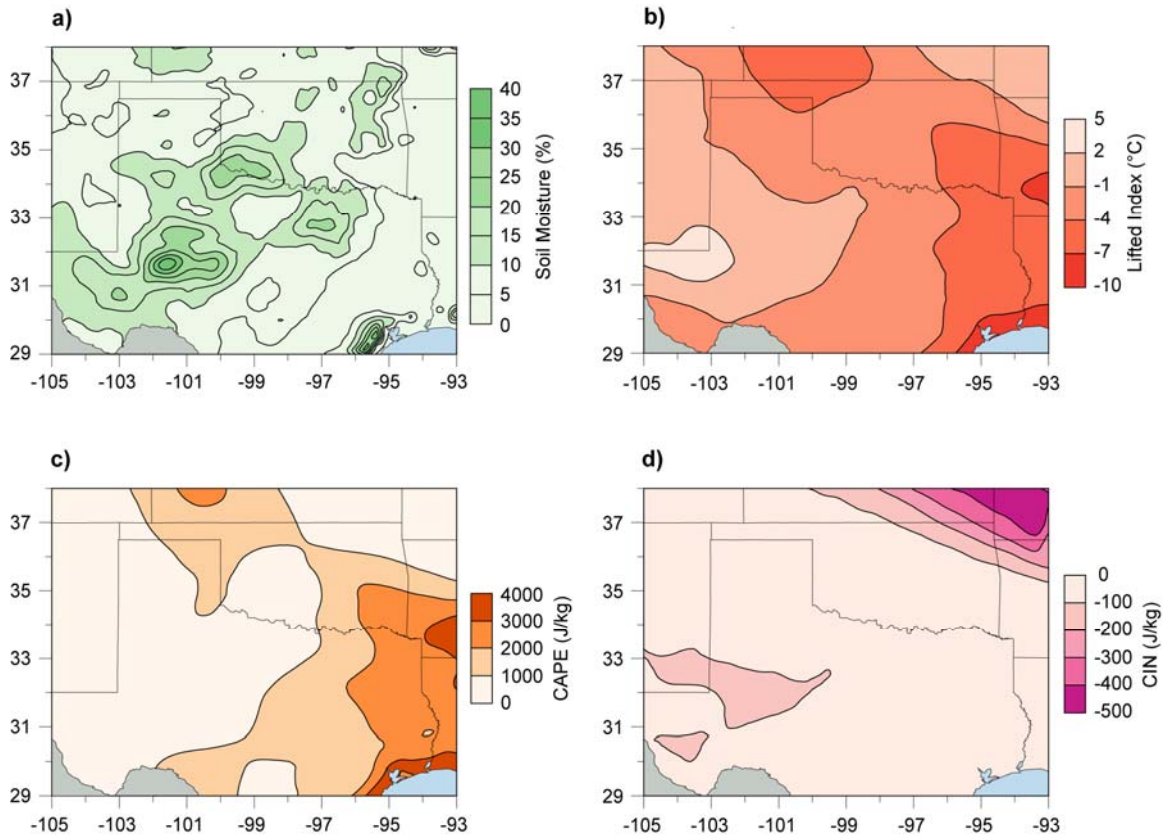


Fig. 3.14. 19 August 2001 illustrating an example of a NoLLJ/SP day: a) volumetric soil moisture (%), b) LI (°C), c) CAPE (J kg^{-1}), and d) CIN (J kg^{-1}).

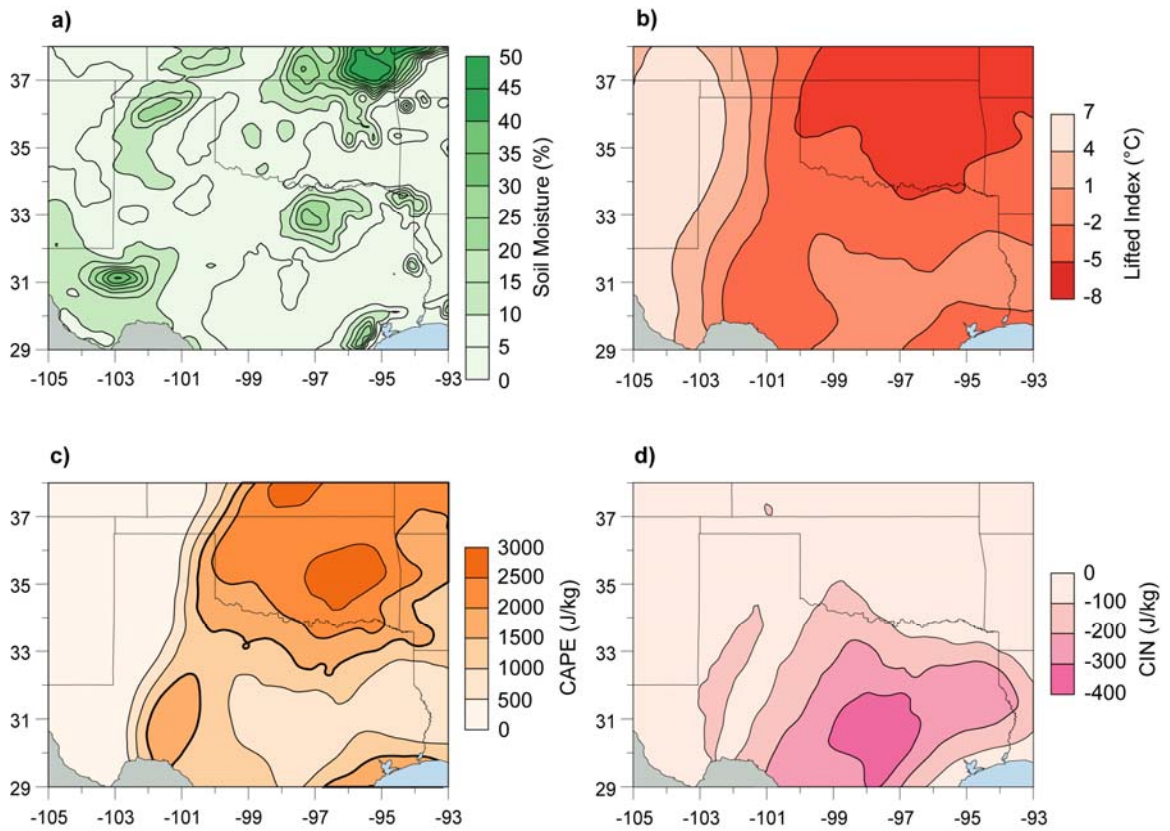


Fig. 3.15. 11 May 2002 illustrating an example of a LLJ/SB day: a) volumetric soil moisture (%), b) LI (°C), c) CAPE (J kg^{-1}), and d) CIN (J kg^{-1}).

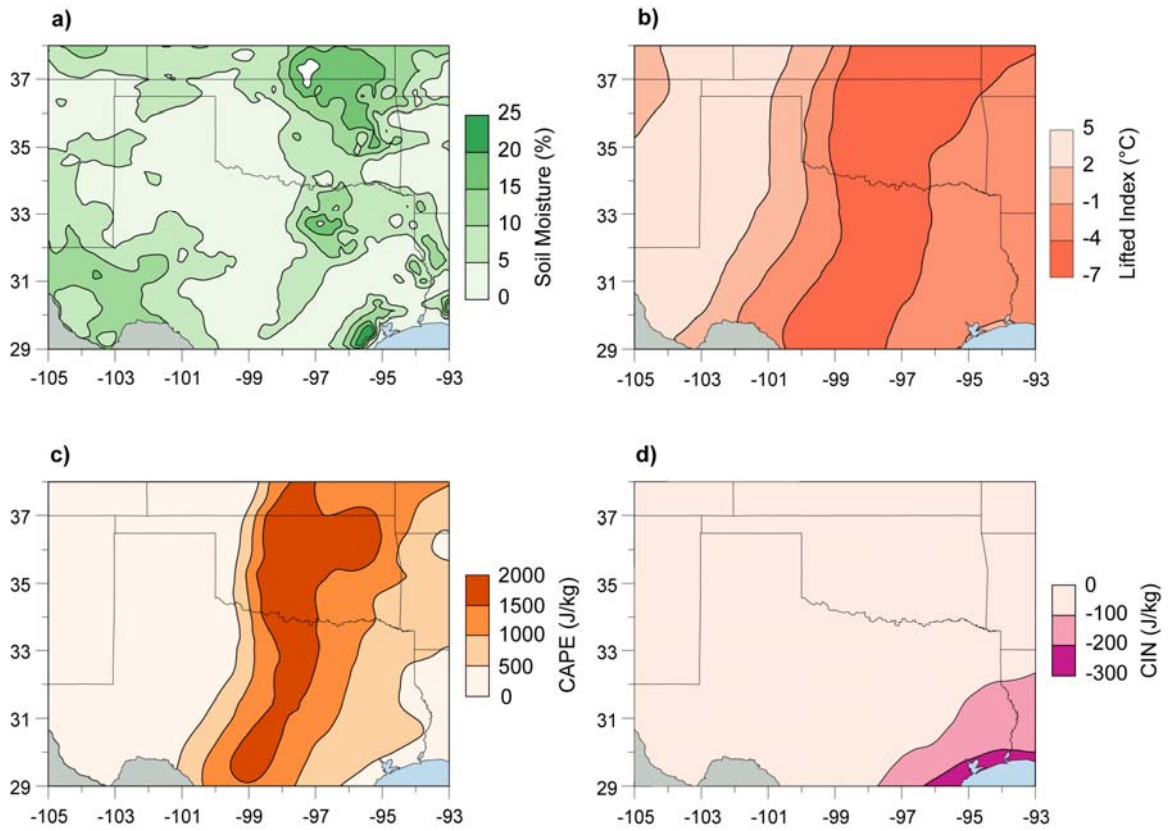


Fig. 3.16. 3 April 2003 illustrating an example of a LLJ/SP day: a) volumetric soil moisture (%), b) LI (°C), c) CAPE (J kg^{-1}), and d) CIN (J kg^{-1}).

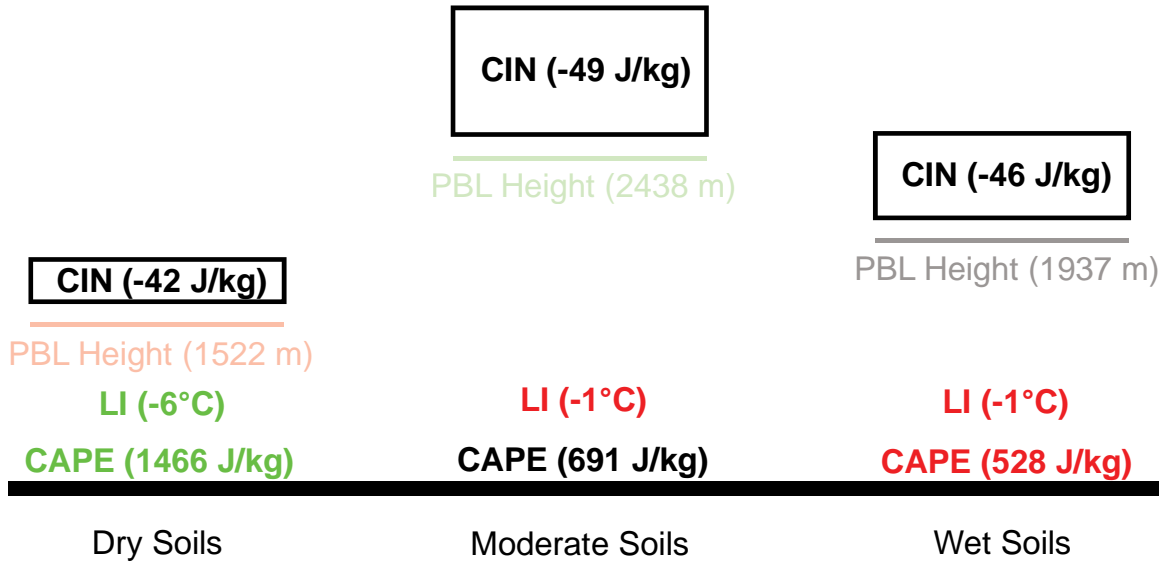


Fig. 3.17: Average values of CIN (J kg^{-1}), CAPE (J kg^{-1}), and LI ($^{\circ}\text{C}$) over Dry, Moderate, and Wet soils for the period of record.

CHAPTER 4

CONVECTIVE INITIATION ALONG SOIL MOISTURE BOUNDARIES IN THE SOUTHERN GREAT PLAINS³

³ J. D. Frye and T. L. Mote. To be submitted to *Monthly Weather Review*.

ABSTRACT

Boundaries between two dissimilar air masses have been shown to be the focus region for convective initiation. One feature that has been shown to create these boundaries, as well as mesoscale circulation patterns conducive for convective, IS soil moisture heterogeneities. These relationships have been validated in modeling studies, short-term field campaigns [e.g., International H₂O Project 2002 (IHOP02)], and reanalysis of severe weather events. The present study examines the role of soil moisture on convective initiation by using observational data over a long-term period (7 years, 1998-2004) in the southern Great Plains. A key component to this research is the recently developed daily soil moisture data from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). The locations of convective initiation were compared to both volumetric soil moisture values and volumetric soil moisture gradient values. The locations of convective initiation were also examined based on synoptic-type day, which accounted for the larger scale weather patterns present. It was found that on synoptically benign days, the probability of convective initiation decreased while soil moisture and soil moisture gradient values increased up to values between 15-25%, respectively. After that point the probability of the development of convection increased as soil moisture and soil moisture gradient increased. On synoptically primed days, an opposite pattern was apparent (i.e., increasing probabilities at lower soil moisture and soil moisture gradient values and decreasing at larger values). These results indicate that a critical value, around 15%-30%, may be present which alters the mesoscale effect of changes in soil moisture on convective initiation on various synoptic-type days.

4.1. Introduction

Forecasting of convective initiation still poses a challenge to forecasters. Thus, a substantial amount of research has focused on the particular subject in the recent years (Fabry 2006). These studies have furthered our understanding of timing and location of convective initiation using advancements in modeling capabilities and observational extensive yet short-term field campaigns [e.g., International H₂O Project 2002 (IHOP02)], and reanalysis of severe weather outbreak events (Mahouf et al. 1987, Rabin et al. 1990, Ek and Mahrt 1994, Clark and Arritt 1995, Taylor et al. 1997, Taylor and Lebel 1998, Weckworth 2000, Findell and Eltahir 2003a, Findell and Eltahir 2003b, Taylor et al. 2003, Weckworth et al. 2004, Holt et al. 2006, Niyogi et al. 2006, Taylor and Ellis 2006, Weckworth and Parsons 2006, Wilson and Roberts 2006, Juang et al. 2007). One finding that has been a focus of multiple studies has been the role of small-scale atmospheric boundaries and the role they have on convective development (e.g., Maddox et al. 1980).

A long-recognized theory on the development of these atmospheric boundaries is related to changes in the land surface properties (McCumber and Pielke 1981, Zhang and Anthes 1982, Anthes 1984, Ookouchi et al. 1984, Lanicci et al. 1987, Mahfouf et al. 1987, Fast and McCorcle 1991, Brown and Arnold 1998, Liu et al. 1999, Berbery et al. 2003, Trier et al. 2004, Holt et al. 2006). When there are distinct surface heterogeneities, present modeling studies have shown that mesoscale circulation patterns developed similar to the mesoscale circulation patterns developed during a land-sea breeze (Pielke 2001, Chaboureau et al. 2004). One such surface characteristic that has been shown to create these patterns and is the focus of the present study is soil moisture. The circulation

patterns develop due to alterations in the latent and sensible heat fluxes caused by changes in soil moisture content.

In regions where dry soils are present, there is a large amount of sensible heat compared to regions with wetter soils where some of the incident energy is first used to evaporate water from the soil (i.e., latent heat energy). The increase in sensible heat creates warmer temperatures over the dry soils, causing the more buoyant warm air to rise, lowering the surface pressure and creating an area of convergence (Ookouchi et al. 1984, Segal et al. 1988, Segal et al. 1989a, Segal et al. 1989b). Over the wetter soils, the temperature is cooler creating an area of subsidence and divergence. When these two areas are in proximity to each other (i.e., a sharp gradient of soil moisture) the two contrasting atmospheric patterns couple and create the mesoscale circulation patterns. Maddox et al. (1980), Pielke (2001) and Xiu and Pleim (2001) all found that these circulation patterns can be strong enough to force convection to develop even in the absence of large scale forcing mechanisms.

These results indicate that a feedback between soil moisture and precipitation exists. Multiple studies have shown that there is a feedback between soil moisture and precipitation (Fast and McCorcle 1991, Chen and Avissar 1994, Pielke 2001, Findell and Eltahir 2003a, Findell and Eltahir 2003b, Taylor and Ellis 2006). However, the sign of the feedback has been shown to be dependent on multiple factors including, but not limited to: (1) study region, (2) atmospheric model utilized, and (3) existing synoptic-scale processes (Rabin et al. 1990, Ek and Mahrt 1994, Taylor et al. 1997, Taylor and Lebel 1998, Taylor et al. 2003, Findell and Eltahir 2003a, Findell and Eltahir 2003b, Taylor and Ellis 2006). Ek and Mahrt (1994) examined the relationship between synoptic

scale conditions and surface sensible and latent heat fluxes. They found that when the free atmosphere (i.e., above the boundary layer) was dry and had strong stratification, convection initiated over regions with a large sensible heat flux. Additionally, when the free atmosphere was moist and weakly stratified the convection initiated over surface regions with large latent heat fluxes. Conversely, Taylor et al. (2003) found that the development of convection was linked to a decrease in the lifting condensation level (LCL) and level of free convection (LFC). They found that the LCL and LFC were lowest over regions with wetter soils.

The main objective of this study is to show the relationship between convective initiation and soil moisture for the warm season (April-September) over a seven-year period (1998-2004) in a 3° latitude by 3° longitude region covered by the Twin Lakes/Oklahoma City, OK (TLX) Weather Surveillance Radar 88 Doppler (WSR-88D) site (Fig. 4.1). This location was chosen due to its location in the southern Great Plains which is within the soil moisture-precipitation feedback “hot spot” identified by Koster et al. (2004).

During the warm season, this region experiences various synoptic-scale conditions which can influence the development of convection. Due to these changing large-scale patterns, the days in the study period are classified into four different synoptic patterns to also determine if the synoptic regime has an influence on the relationship between convective development and soil moisture.

This study helps fill a void in the research community using observational data over a long-term period to investigate the role of soil moisture on convection. The results stemming from this investigation can be utilized to assess the results of previous

modeling studies, case studies, and short-term/observational-intense studies on the relationship between convective initiation and soil moisture fields.

4.2. Data and Methods

a. Synoptic-Scale Environment

To account for the large-scale atmospheric patterns that play a role in convection in the study region, atmospheric soundings and 850-hPa charts were analyzed. The sounding data were used to calculate a modified version of the convective trigger potential (CTP) developed by Findell and Eltahir (2003a, 2003b). The CTP measures the area created by the sounding temperature profile and a moist adiabat from 100 hPa above the surface to 300 hPa above the surface. The modified version used in the present study calculates a lapse rate between 850-hPa and 700-hPa levels and compares that value to a lapse rate of $6.0^{\circ}\text{C}/\text{km}$, a commonly used value for the division between stable and unstable atmosphere (Vasquez 2002). The lapse rates were calculated using the morning soundings (12 UTC) for each day at the following stations: Amarillo, TX (AMA), Dodge City, KS (DDC), Fort Worth, TX (FWD), Midland, TX (MAF), and Norman, OK (OUN) (Fig. 4.1). The assessment was made on an area larger than the study region due to the large scale that these forcing mechanisms operate. A station was classified as synoptically benign (primed) if the measured lapse rate was less than (greater than or equal to) $6.0^{\circ}\text{C}/\text{km}$. The days in which two or more stations were classified as synoptically primed were classified as synoptically primed as well.

A second large-scale feature that influences the weather patterns in the southern Great Plains is a moist low-level jet (LLJ) originating from the Gulf of Mexico. To determine the presence of a LLJ, the morning (12 UTC) 850-hPa level data from the North American Regional Reanalysis (NARR) (Mesinger et al. 2006) data set was used to plot the wind speed and vectors. The present study used the definition introduced by Bonner (1968) of wind speeds greater than 25 knots (12 m s^{-1}) to identify the LLJ. The winds also had to originate from the Gulf of Mexico and encompass a majority of the southern Great Plains region.

Combining the two synoptic scale conditions analyzed, the days in the study period were divided into four different types of days: 1) NoLLJ/SB are days with no LLJ present and synoptically benign, 2) NoLLJ/SP are days with no LLJ present and synoptically primed, 3) LLJ/SB are days with a LLJ present and synoptically benign, and 4) are days with a LLJ present and synoptically primed.

b. Soil Moisture Data

Recent developments in remote sensing techniques have led to improved temporal resolution in soil moisture data which makes the present study possible. Past techniques have included, but not limited to, the use of neutron probes or heat dissipation sensors to acquire soil moisture data. However, these measurements had large spatial and temporal resolution limited their utility (Robock et al. 2000). Recently, multiple studies have shown success of using passive microwave remote sensing to acquire soil moisture estimates (Bindlish et al. 2003, de Jeu and Owe 2003, Njoku et al. 2003, Bindlish et al. 2006, Gao et al. 2006).

This study utilizes soil moisture data from the data obtained by the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). The soil moisture product is a daily product developed by using the X-band (10.65 GHz) channel and additional ancillary data (Gao et al. 2006). The data were created and three levels of data are archived at the Land Surface Hydrology Group at Princeton University (data available at http://hydrology.princeton.edu/data.sm_tmi.php). Level 3 data is used for the current study because it has been quality controlled and masks out any areas where contamination can occur (e.g., heavily vegetated areas, water, and snow or frozen ground). Gao et al. (2006) also showed that the soil moisture data from TMI has a strong correlation to the soil moisture obtained from the Oklahoma Mesonet sites. The daily soil moisture data, along with latitude and longitude, were extracted for the study region (Fig. 4.1) for each day throughout the study period that convective initiation occurred. From this data, soil moisture gradients were calculated for each grid point as well using a centered difference method (Chapra and Canale 2002). The soil moisture and soil moisture gradient data were then linked to convective initiation points to determine the role that changes in soil moisture has on the development of convection.

c. Convective Initiation Data

The locations of convective initiation were obtained from the National Climatic Data Center (NCDC) archive of WSR-88D Next Generation Radar (NEXRAD) Level III data for station TLX (Fig. 4.1). The WSR-88D uses active microwave remote sensing techniques to detect and measure rainfall using an S-band (10 cm wavelength) frequency (Burgess and Ray 1986, NOAA 2005, NOAA 2006a, NOAA 2006b). The radar sends a

pulse of energy away from the antenna, encounters precipitation sized droplets in the atmosphere, and reflects a portion of the energy back to the antenna. The power of the energy returned is a reflectance of the amount of precipitation within the atmosphere (Burgess and Ray 1986, Bader et al. 1995, NOAA 2005). Thus, as the reflectivity, measured in dBZ, increases the intensity of precipitation increases.

Past studies have used various levels of reflectivity to indicate the point where convection initiates. Wilson and Schreiber (1986) and Wilson and Muller (1993) both used 30 dBZ as the convective initiation point. More recently, Mecikalski and Bedka (2006) utilized a higher threshold of ≥ 35 dBZ. It is the latter threshold that is employed in the present study to help eliminate any contamination from ground clutter near the radar site (Fulton et al. 1998).

All available Level III data for TLX during the warm season (April-September) for the period of record (1998-2004) were first examined to eliminate the images that did not contain reflectivity values ≥ 35 dBZ. All the remaining files were then analyzed to determine points of convective initiation within the study region. Points of convective initiation were identified with latitude and longitude coordinates under the following stipulations: (1) initiation occurred solely within the study region, (2) initiation must have occurred within three sequential radar time periods (15-18 minutes dependent on coverage mode), and (3) the convective cell was isolated. Stipulation 1 and 2 were used to eliminate the intensification of convection instead of points of convective initiation. The third stipulation was used in cases where clusters of thunderstorm cells were moving through the coverage area of the radar. Only cells that were isolated from the large

cluster were identified, again this partially helped eliminate convective intensification (Fig. 4.2).

The convective initiation points were divided into the four different synoptic-type days. Then, based on the daily soil moisture data each initiation point was assigned to the soil moisture data grid cells by using a nearest neighbor technique. Thus, each initiation point was assigned a soil moisture and soil moisture gradient value based on the grid cell point that it fell closest to in that domain. To eliminate noise within the data, the values were binned into 5 % interval groups, with 0% being a separate group due to the large occurrence of these values.

4.3. Results

a. Convective Initiation

For each synoptic-type day, the convective initiation points are plotted (Figs. 4.3a-d). Fig. 4.3a shows the initiation points for NoLLJ/SB days. On these days, there appears to be a random spatial pattern associated with the initiation points (i.e., there appears to be limited clustering and points are spread throughout the entire study area). This also remains true for the rest of the synoptic-type days: NoLLJ/SP (Fig. 4.3b), LLJ/SB (Fig. 4.3c), and LLJ/SP (Fig. 4.3d). On all synoptic-type days, the initiation points are scattered throughout the entire study area and there appears to be minimal clustering.

a. Convective Initiation-Soil Moisture Relationship

To determine if there was a significant difference between the volumetric soil moisture values where convective initiation occurred between each synoptic-type day, an independent sample difference of means Student's *t*-test was conducted. All difference of means test were significant ($p=0.05$) for all comparisons except NoLLJ/SB days versus LLJ/SP days and LLJ/SB days versus LLJ/SP days.

For each synoptic-type day, all soil moisture values were grouped into equal interval classes (excluding a class for just 0% volumetric soil moisture due to its large amount of incidence) to establish the total occurrence in each class for the entire period of record. The soil moisture points associated with convective initiation were also grouped in the same manner (Table 4.2). In Table 4.2 there is a large number of total incidences of volumetric soil moisture values on the lower end of the spectrum, thus the probability of convective initiation occurring over lower soil moisture values is already increased. Thus, to determine the role soil moisture has on convective initiation, the percentage of the total soil moisture values where convection occurred was calculated for each synoptic-type day (Table 4.3).

Fig. 4.4 shows a plot of the values in Table 4.3. Each of the synoptic-type days (Figs. 4.4a-d) also have the percentage of convective initiation points for all days combined plotted; this line is used as a baseline to compare the individual days. On NoLLJ/SB days (Fig. 4.4a), the probability for occurrence of convection is between 0.03% and 0.62% less than the baseline for much of the range of volumetric soil moisture values. The percentage of occurrence on NoLLJ/SP days (Fig. 4.4b) shows a shifting pattern from greater than to less than the baseline.

The patterns of convective initiation on LLJ/SB (Fig. 4.4c) and LLJ/SP (Fig. 4.4d) appear to transition between low and high volumetric soil moisture values. LLJ/SB days (Fig. 4.4c) have a decreasing percentage of occurrences between 0-15% volumetric soil moisture values but then see a steady increase and then a plateau between 15-45%. As the soil moisture increase to 50% on LLJ/SB days, the percent of convective initiation decreases. The percentages on LLJ/SB days are also between 0.05% and 0.52% below the baseline value for a majority of the soil moisture range. The opposite is true of LLJ/SP days (Fig. 4.4d), where the percentage of convective initiation is 0.03% to 0.28% greater than the baseline for a majority of the soil moisture range. The percentage on the LLJ/SP days increases as soil moisture values increase from 0-30%. There is then a large decrease in the percent of convective initiation in the 31-35% range of soil moisture, which also mirrors a large decrease in the baseline.

c. Convective Initiation-Soil Moisture Gradient Relationship

Similar to the volumetric soil moisture data, an independent sample difference of means Student's *t*-test was conducted on the soil moisture gradient values between each synoptic-type days. Only two tests, NoLLJ/SB days versus No LLJ/SP days and NoLLJ/SP days versus LLJ/SP days, showed a statistically significant ($p=0.05$) difference between the soil moisture gradient values. All other tests (i.e., NoLLJ/SB days versus LLJ/SB days, NoLLJ/SB days versus LLJ/SP days, NoLLJ/SP days versus LLJ/SB days, LLJ/SB days versus LLJ/SP days) were not significantly different.

Table 4.4 shows the occurrence, in classes of equal intervals, of all volumetric soil moisture gradient values and gradient values where convective initiation occurred for

each synoptic-type day. Similar to the volumetric soil moisture values, soil moisture gradient values were skewed toward zero. Therefore, a percent of convective initiation over each soil moisture gradient classes was calculated (Table 4.5).

The percentages in Table 4.4 are also shown in Fig. 4.5. A baseline, which is calculated from the percentages from all days combined, was also included on each synoptic-type day (Fig. 4.5a-d). This baseline provides a means of comparing how the change in synoptic-scale conditions alters the percent of convective initiation over soil moisture gradient values. Fig. 4.5a shows the probability of convective initiation decreases as soil moisture gradient values increase from $0\% \text{ km}^{-1}$ to $2.0\% \text{ km}^{-1}$ on NoLLJ/SB days. However, as soil moisture gradient increases from that point, the probability of convective initiation sharply increases. On NoLLJ/SP days (Fig. 4.5b) the probability of convective initiation is greater than the baseline probability for most of the range in soil moisture gradient values. The opposite is true for LLJ/SB days (Fig. 4.5c). The probability on days which have a LLJ present and are synoptically benign are less than the baseline and decrease from $0\% \text{ km}^{-1}$ to $2.0\% \text{ km}^{-1}$. The probability of convective initiation begins to increase as soil moisture gradient increases, eventually becoming greater than the baseline values. The LLJ/SP days (Fig. 4.5d) show a slightly different relationship between the probabilities on those days and the baseline probabilities. On these days, the probability of convective initiation showed a steadier transition as soil moisture gradient values increase. At the lower soil moisture gradient values the probability of convective initiation increases peaking at $1.5\% \text{ km}^{-1}$ and then a steady decrease occurred.

4.4. Conclusion

Past studies have shown that atmospheric boundaries are ideal locations for convective initiation to occur. This theory has been tested by multiple modeling studies, verified during short-term observation-extensive field study campaigns, and examined extensively with case studies from significant weather events. Soil moisture has been recognized to establish these atmosphere boundaries. Some modeling studies have indicated that if the soil moisture gradient is significant, it can establish mesoscale circulation patterns equal in strength to sea breeze circulation. This study has filled a gap in this research field by conducting a long-term (7 years from 1998-2004), observational study to determine on larger time scales is this relationship still recognizable.

A portion of the coverage area of the Twin Lakes/Oklahoma City (TLX) WSR-88D site was utilized to examine the relationship between soil moisture and convective initiation and soil moisture gradients and convective initiation. The study also used recently developed daily soil moisture product from the TRMM Microwave Imager. This soil moisture product provides a more spatially detailed measure of soil moisture in the southern part of the United States, filling gaps between the sparsely scattered soil moisture probes.

The synoptic-scale patterns have shown to influence the occurrence of convection. Thus, the days in which convection initiated in the TLX range were subdivided into four different synoptic-type days. The days were first classified as being synoptically primed or synoptically benign based on morning (12 UTC) sounding data throughout the southern Great Plains. The days were also classified as having a moist LLJ initiating from the Gulf of Mexico present throughout the region as well. A majority

of the days, 383, were found to be synoptically primed (versus 141 synoptically benign days). Of the 141 days that were synoptically benign 98 had a LLJ present and of the 383 synoptically primed days 197 had a LLJ present.

The convective initiation points under each synoptic-type day showed random spatial patterns (Fig. 4.3). The points were well scattered throughout the study region and there appeared to be no clustering of events. These points were then matched to soil moisture and soil moisture gradient values based on the day the convection occurred and the closest grid point in the soil moisture data field.

The probability of convective initiation based on volumetric soil moisture on synoptically benign days was below the baseline (established by all days) probabilities. On the other hand, the probabilities on synoptically primed days were greater than the baseline probabilities. As would be expected, this shows that convection is less likely to occur on days that are synoptically benign and more likely on synoptically primed days. Another aspect of the relationship between synoptically primed and benign days is the change in probabilities as soil moisture increases. On synoptically benign days, as the soil moisture increases from 0% the probabilities of convective initiation decrease; this occurs until 15% (25%) with (without) a LLJ. After this point, the probabilities begin to increase as the soil moisture values increase. This indicates that there may be a “tipping point” or critical soil moisture value (around 15%-25%) needed for convection to initiate under synoptically benign days.

On synoptically primed days, especially those with a LLJ present, the probabilities increase as soil moisture increase from 0% before decreasing once the soil moisture values reach 30%. The increase at the lower soil moisture gradient levels

indicates that convection is initiating in these areas due to the increase in moisture. The decrease in convective initiation, as soil moisture gradients increase indicate there may be a critical soil moisture value that causes the conditions to switch from conducive for to suppressing convection.

As with the soil moisture values, a similar pattern is seen when examining the probability of convective initiation over soil moisture gradient values on synoptically benign and primed days. The probabilities were greater than the baseline on synoptically primed days and less than the baseline on synoptically benign days. On the synoptically benign days and synoptically primed days with no LLJ present, the probability of convective initiation also decreases as volumetric soil moisture gradient increases from $0\% \text{ km}^{-1}$. However, once the volumetric soil moisture gradient value reaches $1.5\% \text{ km}^{-1}$ or $2.0\% \text{ km}^{-1}$, the probability of the development of convection increases. This indicates when the soil moisture gradient is large, the development of a mesoscale circulation pattern becomes strong enough to force convection despite no support for the development at larger scales (Pielke 2001). With the change in pattern occurring at roughly the same point on days with or without a LLJ indicates that this may also be the critical point at which that circulation pattern becomes strong enough.

On synoptically primed days with a LLJ present, the probability of convection developing increases as soil moisture gradients increase, until reaching the $1.5\% \text{ km}^{-1}$ soil moisture gradient level. This indicates that as the gradient gets larger, the strength of mesoscale circulations that develop are enhancing the synoptic scale patterns and causing a condition more conducive to convective development. However, once the soil moisture gradient is greater than $1.5\% \text{ km}^{-1}$, the probabilities of convective initiation decrease.

The results from Chapters 2 and 3 indicated conflicting results between where convection may occur, based on planetary boundary layer growth and various convective metrics, and volumetric soil moisture values. One finding from these chapters indicated that convection may be more likely over soil moisture in the middle part of the typical range of values. The findings from this chapter indicate that the middle soil moisture values, as well as the middle soil moisture gradient values, may create a tipping point between the suppression of convection and convective development (Fig. 4.6). Fig. 4.6 shows that while convection may occur frequently over lower soil moisture values due to a very unstable environment and weak cap, that convection over the Moderate Soils and moderate soil moisture gradients may be less wide spread but could be more intense through the development of mesoscale circulation patterns which draw convective energy from areas with more unstable conditions. In this middle range, the probabilities changed from increasing to decreasing on synoptically primed days. On synoptically benign days the probability decreased as soil moisture increased in the low range of soil moisture values and increased as soil moisture values increased in the high range of values. Further investigation of the convective patterns and soil moisture values could lead to a better understanding of this critical point within the ranges of soil moisture and soil moisture gradient values.

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Table 4.1. Number of days and convective initiation (CI) points for each synoptic-type day. NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLLJ are days with no LLJ and synoptically primed, LLJ/SB are days with a LLJ present and synoptically benign, and LLJ/SP are synoptically primed days with a LLJ also present.

| | # of Days | # of CI |
|-----------------|------------------|----------------|
| NoLLJ/SB | 43 | 359 |
| NoLLJ/SP | 186 | 1673 |
| LLJ/SB | 98 | 735 |
| LLJ/SP | 197 | 1848 |

Table 4.2. Number of occurrences of all volumetric soil moisture values (ALL) and those points associated with convective initiation (CI). NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLLJ are days with no LLJ and synoptically primed, LLJ/SB are days with a LLJ present and synoptically benign, and LLJ/SP are synoptically primed days with a LLJ also present.

| | ALL NoLLJ /SB | ALL NoLLJ /SP | ALL LLJ /SB | ALL LLJ /SP | CI NoLLJ /SB | CI NoLLJ /SP | CI LLJ /SB | CI LLJ /SP |
|---------------|------------------------------|------------------------------|----------------------------|----------------------------|-----------------------------|-----------------------------|---------------------------|---------------------------|
| 0% | 3580 | 13963 | 8178 | 14545 | 64 | 259 | 109 | 201 |
| 1-5% | 4403 | 34623 | 15313 | 31569 | 46 | 351 | 180 | 414 |
| 6-10% | 7739 | 41471 | 19175 | 39836 | 94 | 542 | 193 | 519 |
| 11-15% | 5244 | 17310 | 10832 | 21044 | 72 | 273 | 96 | 327 |
| 16-20% | 3020 | 8243 | 5481 | 11182 | 35 | 119 | 62 | 169 |
| 21-25% | 1934 | 4208 | 2678 | 5907 | 14 | 53 | 38 | 93 |
| 26-30% | 1136 | 2258 | 1640 | 3357 | 10 | 33 | 23 | 56 |
| 31-35% | 659 | 1293 | 967 | 1846 | 6 | 14 | 13 | 14 |
| 36-40% | 440 | 839 | 587 | 1294 | 6 | 11 | 8 | 18 |
| 41-45% | 314 | 564 | 455 | 832 | 3 | 9 | 6 | 12 |
| 46-50% | 599 | 991 | 942 | 1760 | 8 | 9 | 7 | 25 |

Table 4.3. Percent of convective initiation over volumetric soil moisture classes for each synoptic-type day. NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLLJ are days with no LLJ and synoptically primed, LLJ/SB are days with a LLJ present and synoptically benign, and LLJ/SP are synoptically primed days with a LLJ also present.

| | NoLLJ/SB | NoLLJ/SP | LLJ/SB | LLJ/SP | Total |
|---------------|-----------------|-----------------|---------------|---------------|--------------|
| 0% | 1.79 | 1.85 | 1.33 | 1.38 | 1.57 |
| 1-5% | 1.04 | 1.01 | 1.18 | 1.31 | 1.15 |
| 6-10% | 1.21 | 1.31 | 1.01 | 1.30 | 1.25 |
| 11-15% | 1.37 | 1.58 | 0.89 | 1.55 | 1.41 |
| 16-20% | 1.16 | 1.44 | 1.13 | 1.51 | 1.38 |
| 21-25% | 0.72 | 1.26 | 1.42 | 1.57 | 1.34 |
| 26-30% | 0.88 | 1.46 | 1.40 | 1.67 | 1.45 |
| 31-35% | 0.91 | 1.08 | 1.34 | 0.76 | 0.99 |
| 36-40% | 1.36 | 1.31 | 1.36 | 1.39 | 1.36 |
| 41-45% | 0.96 | 1.60 | 1.32 | 1.44 | 1.39 |
| 46-50% | 1.34 | 0.91 | 0.74 | 1.42 | 1.14 |

Table 4.4. Number of occurrences of all volumetric soil moisture gradient values (% km⁻¹) (ALL) and those points associated with convective initiation (CI). NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLJ are days with no LLJ and synoptically primed, LLJ/SB are days with a LLJ present and synoptically benign, and LLJ/SP are synoptically primed days with a LLJ also present.

| | ALL NoLLJ /SB | ALL NoLLJ /SP | ALL LLJ /SB | ALL LLJ /SP | CI NoLLJ /SB | CI NoLLJ /SP | CI LLJ /SB | CI LLJ /SP |
|--------------------|------------------------------|------------------------------|----------------------------|----------------------------|-----------------------------|-----------------------------|---------------------------|---------------------------|
| 0.000 | 2157 | 8248 | 5390 | 9341 | 36 | 143 | 67 | 117 |
| 0.001-0.500 | 22771 | 106601 | 53062 | 109288 | 280 | 1376 | 586 | 1524 |
| 0.501-1.000 | 3173 | 8969 | 5812 | 11306 | 37 | 131 | 66 | 163 |
| 1.001-1.500 | 692 | 1399 | 1369 | 2299 | 5 | 14 | 14 | 35 |
| 1.501-2.000 | 201 | 373 | 405 | 618 | 0 | 6 | 0 | 7 |
| 2.001-2.500 | 66 | 147 | 182 | 287 | 1 | 3 | 2 | 2 |
| 2.501-3.000 | 8 | 26 | 28 | 33 | 0 | 0 | 0 | 0 |

Table 4.5. Percent of convective initiation over volumetric soil moisture gradient classes ($\% \text{ km}^{-1}$) for each synoptic-type day. NoLLJ/SB represents days with no LLJ present and synoptically benign, NoLLLJ are days with no LLJ and synoptically primed, LLJ/SB are days with a LLJ present and synoptically benign, and LLJ/SP are synoptically primed days with a LLJ also present.

| | NoLLJ/SB | No/LLJ/SP | LLJ/SB | LLJ/SP | Total |
|--------------------|-----------------|------------------|---------------|---------------|--------------|
| 0.000 | 1.67 | 1.73 | 1.24 | 1.25 | 1.44 |
| 0.001-0.500 | 1.23 | 1.29 | 1.10 | 1.39 | 1.29 |
| 0.501-1.000 | 1.17 | 1.46 | 1.14 | 1.44 | 1.36 |
| 1.001-1.500 | 0.72 | 1.00 | 1.02 | 1.52 | 1.18 |
| 1.501-2.000 | 0.00 | 1.61 | 0.00 | 1.13 | 0.81 |
| 2.001-2.500 | 1.52 | 2.04 | 1.10 | 0.70 | 1.17 |

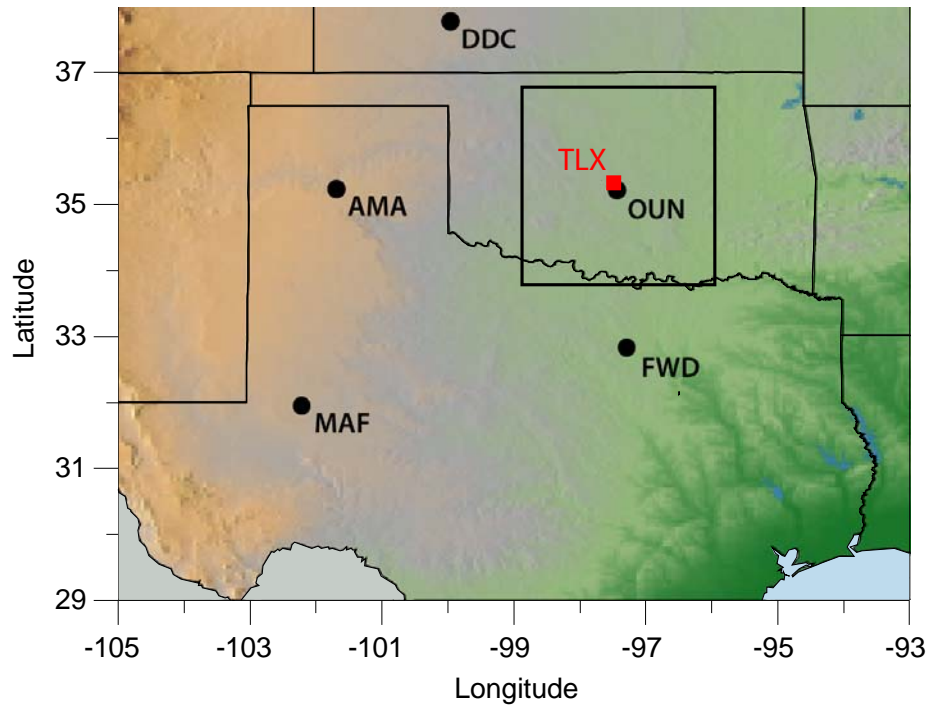


Fig. 4.1. Southern Great Plains region with study region indicated by outlined area. The WSR-88D site used for the study region is Twin Lakes/Oklahoma City site (TLX). The radiosonde sites used to determine synoptic-type days were Amarillo, TX (AMA), Dodge City, KS (DDC), Fort Worth, TX (FWD), Midland, TX (MAF), and Norman, OK (OUN). Shaded relief from USGS (2003).

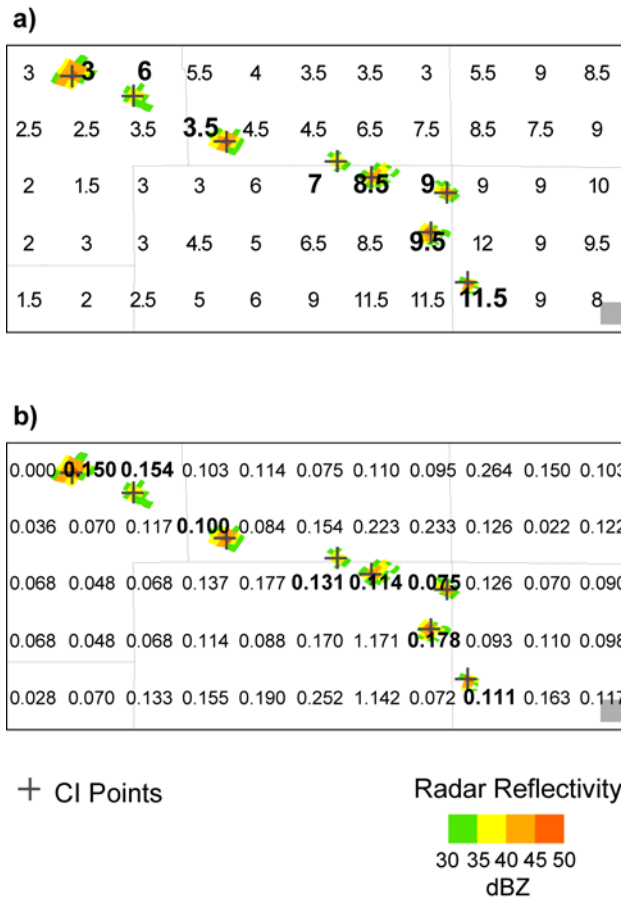


Fig. 4.2. Example of radar reflectivity (dBZ) and convective initiation (CI) points on 5 May 1998 at 0534 UTC. The numbers represent a) volumetric soil moisture (%) and b) volumetric soil moisture gradient ($\% \text{ km}^{-1}$), with bold numbers representing the values associated with CI points. TLX station identified by gray box.

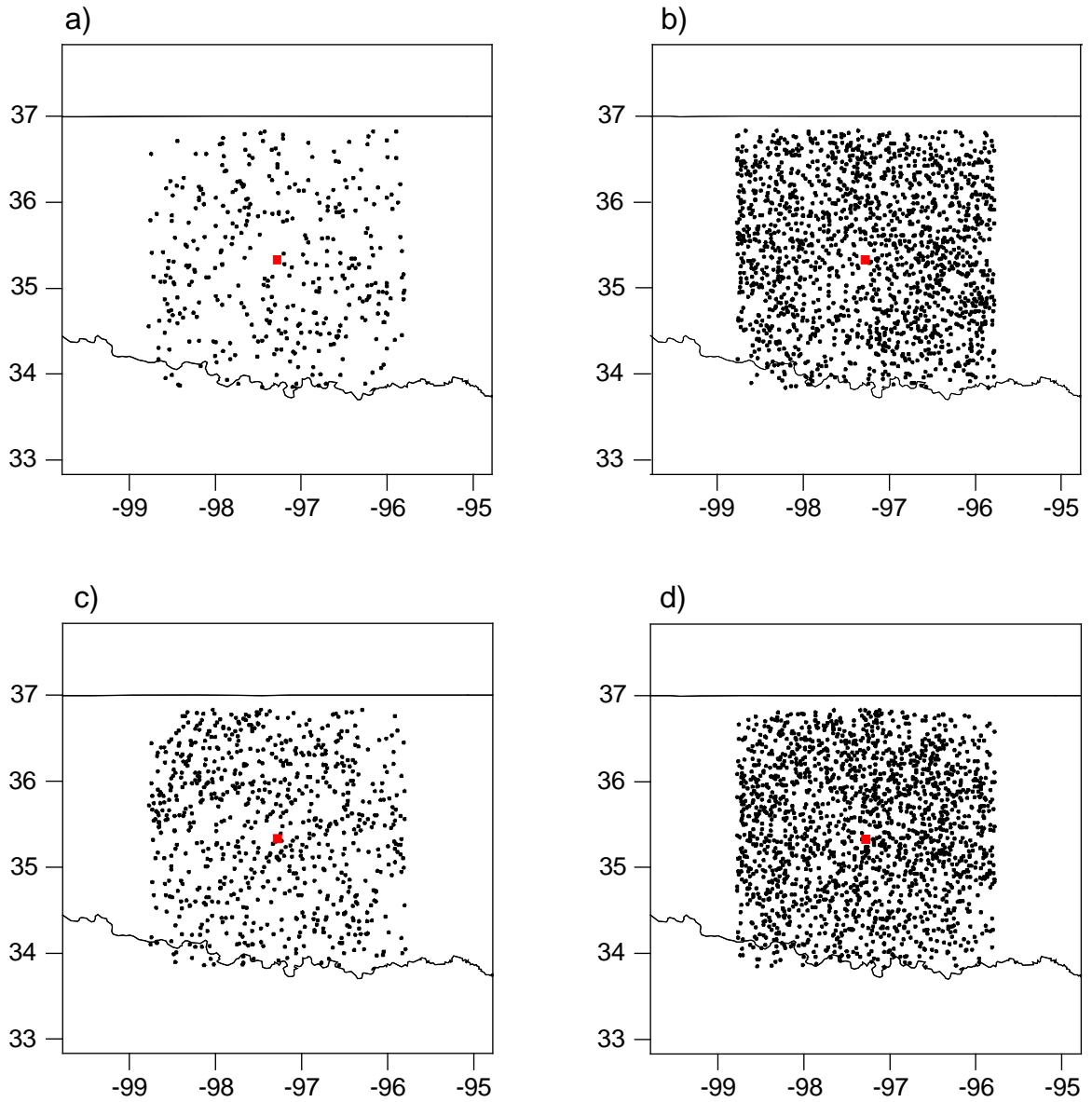


Fig 4.3. Points of convective initiation for each synoptic-type day: a) NoLLJ/SB days, b) NoLLJ/SP days, c) LLJ/SB days, and d) LLJ/SP days. Red dot represents the location of TLX site.

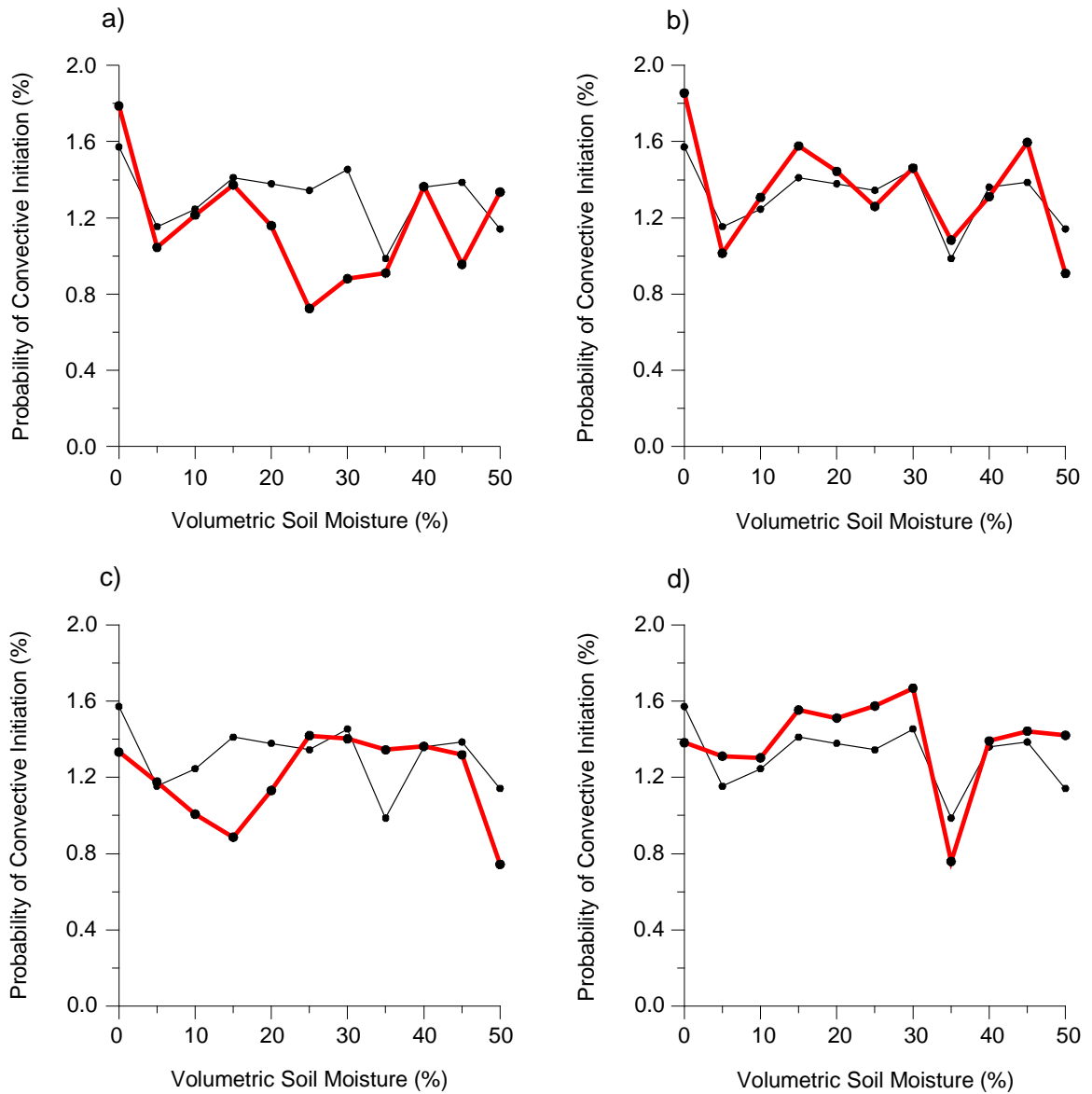


Fig. 4.4. Probability of convective initiation by volumetric soil moisture (%). Black, thin line represents a baseline calculated from all days and the thick, red lines indicating the probabilities for a) NoLLJ/SB days, b) NoLLJ/SP days, c) LLJ/SB days, and d) LLJ/SP days.

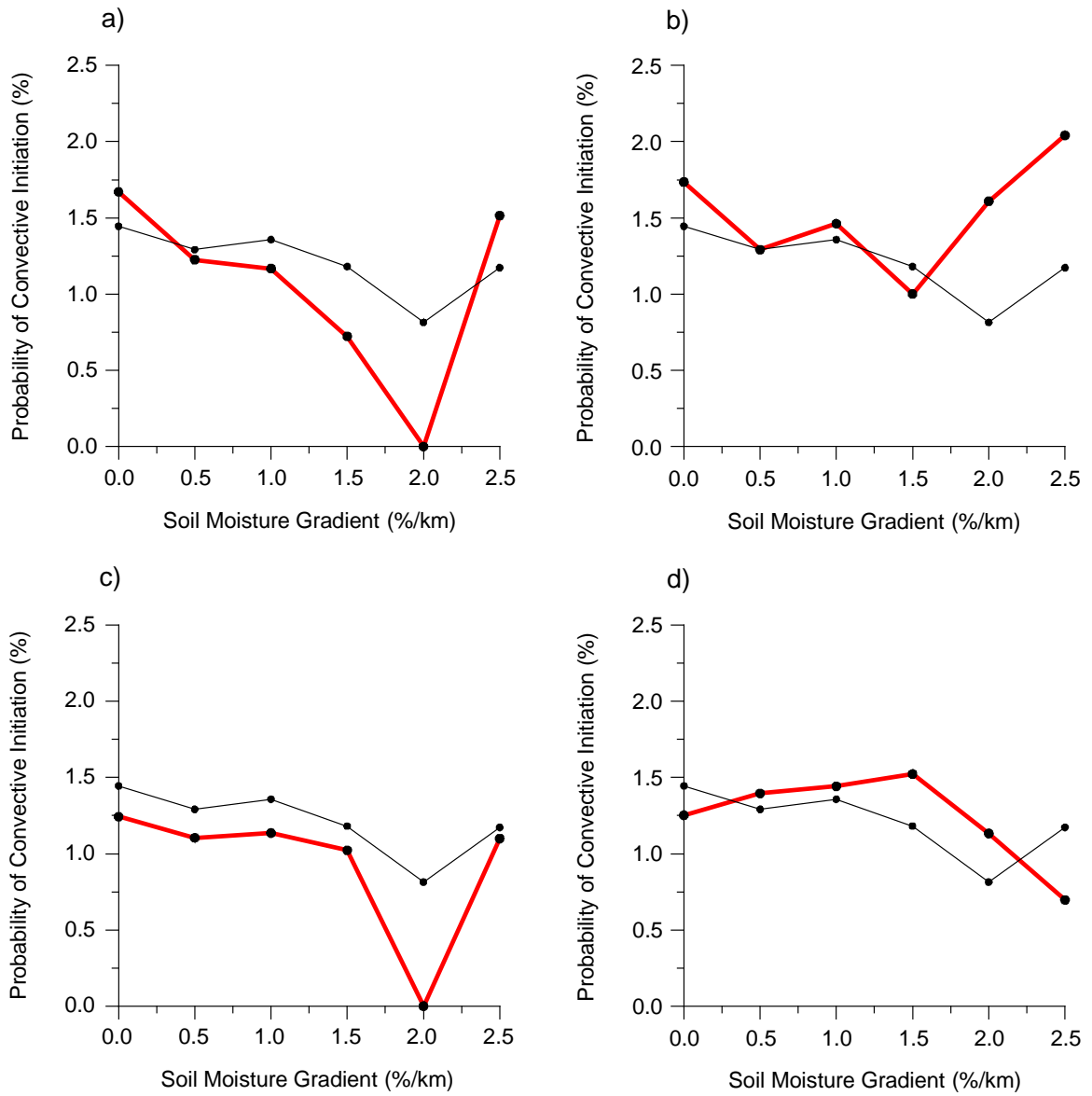


Fig. 4.5. Same as Fig. 4.4 except for volumetric soil moisture gradient ($\% \text{ km}^{-1}$).

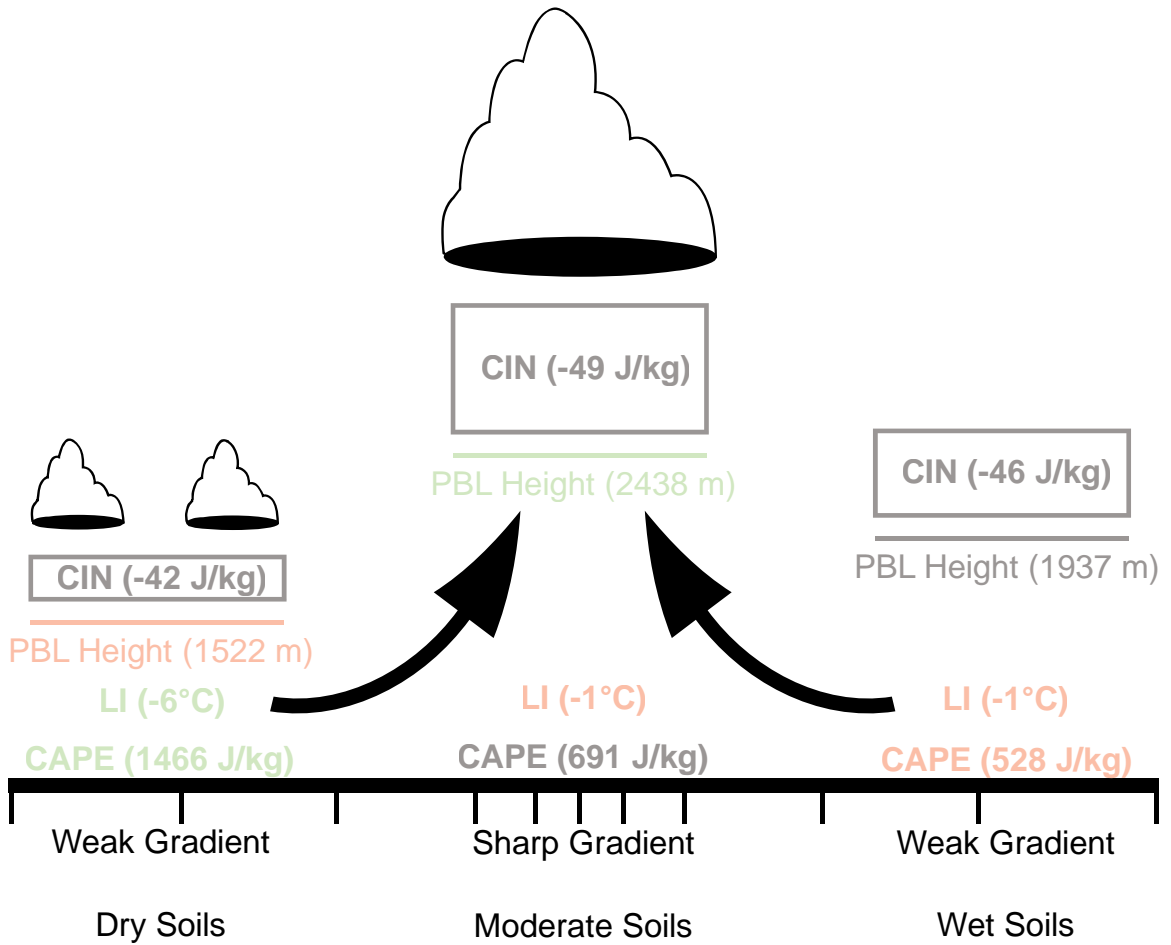


Fig. 4.6: Schematic showing the variability in the type of convective activity over Dry, Moderate, and Wet Soils and over Weak and Sharp soil moisture gradients

CHAPTER 5

CONCLUSION

This dissertation represents one of the first long-term empirical studies to examine the relationship between soil moisture and convection. The southern Great Plains of the United States was examined during the warm seasons of 1998-2004. The southern Plains is among the most active regions in the world for the development of convective thunderstorms and has been shown to have strong feedbacks between soil moisture and convective development in modeling studies and field experiments (Barnston and Schickedanz 1984, Lanicci et al. 1987, Capehart et al. 2004, Koster et al. 2004, Weaver 2004a, Weaver 2004b, Niyogi et al. 2006).

The first manuscript of this dissertation (Chapter 2) examined the influence of soil moisture on the planetary boundary layer (PBL). This lowest layer of the atmosphere is where most of the thermal updrafts that create convective storms originate. Thus, changes in PBL height, created by soil moisture discontinuities, may allow rising air parcels to reach the level of free convection in regions where the boundary layer height is greatest. The second manuscript (Chapter 3) looked at various convective metrics used to forecast the location and intensity of convection in relation to soil moisture. In the final manuscript (Chapter 4), both soil moisture and the gradient of soil moisture were investigated to determine if either had any influence on the location where convective thunderstorms initiated. In all three manuscripts, days in the study period were stratified into multiple synoptic-scale weather patterns to control for the influence of the changes at

the synoptic scale on the convective environment, thereby helping to isolate the role of soil moisture on convective development.

This study helps fill a gap in the existing literature on this topic by including two recently developed data sets. One such data set is a daily soil moisture product developed from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) (data available at http://hydrology.princeton.edu/data.sm_tmi.php; also Gao et al. 2006). This product provides higher spatial and temporal resolution of soil moisture for the southern portion of the United States. The second data set used extensively in the study was the North American Regional Reanalysis (NARR) (Mesinger et al. 2006). The NARR data set also provides higher temporal resolution on a much finer scale (32-km) than other available sources for atmospheric profiles. Most previous studies regarding soil moisture and convection have either been modeling studies, short-term field campaigns, or analysis of single severe weather events. This dissertation is the first study to utilize the TMI soil moisture and NARR data sets to provide a long-term empirical study on the relationship between soil moisture and convection.

5.1. Soil Moisture and PBL Height

The growth of the PBL was examined for four different sets of days, defined by the prevailing synoptic scale patterns, based on the presence or absence of the low-level jet (LLJ) and whether a baroclinic (synoptically primed) or barotropic (synoptically benign) atmosphere was present. The diurnal PBL growth was shown to be significantly different among the four different synoptic-type days. This result shows that the PBL growth throughout the day was significantly influenced by the synoptic-scale weather

patterns. Additional analysis showed that the PBL growth was positively correlated to volumetric soil moisture under each synoptic-type day. Thus, as soil moisture increased, the growth of the diurnal boundary layer also increased, which agrees with the results of previous studies from modeling efforts and field campaigns (McCumber and Pielke 1981, Zhang and Anthes 1982, Ookouchi et al. 1984, Lanicci et al. 1987, Fast and McCorcle 1991, Chen and Avissar 1994, Liu et al. 1999, Berbery et al. 2003, Trier et al. 2004). Because the relationship between soil moisture and PBL growth was non-linear, further analysis was conducted by classifying soil moisture into three categories based on quartiles of soil moisture. Dry Soils were the lowest quartile of soil moisture values, Wet Soils were the highest quartile, and Moderate Soils were the middle two quartiles. On all synoptic-type days, the diurnal PBL growth was greater over the Moderate Soils.

5.2. Soil Moisture and the Pre-Storm Environment

The relationship between soil moisture and the stability in the atmosphere, as measured by convective available potential energy (CAPE) and lifted index (LI), showed a direct relationship over the entire period of record. As soil moisture increased, the atmosphere became more stable. This relationship is opposite to the common notion that low-level moisture would create a more unstable environment. The stabilization of the atmosphere over wet soils may be due to the partitioning of the latent/sensible heat energy. Over the wetter soils, more latent heat energy will be used to evaporate the water from the soil, leaving less sensible heat energy and thus cooler temperatures near the surface and stabilizing the lower troposphere. Additionally, there is a strong synergistic relationship between these stability measures and the presence of a low-level jet (LLJ).

On days when the LLJ was present, the CAPE values increased by approximately 400 J kg^{-1} and LI values decreased by approximately 2°C . Both of these changes indicate an environment more conducive to thunderstorm development.

Similar to the approach used in Chapter 2, the soil moisture was categorized into three soil moisture classes (i.e., Dry, Moderate and Wet Soils). CAPE was highest over Dry Soils and lowest over Moderate Soils. LI was lowest (indicating more unstable conditions) over Dry Soils and highest over Moderate Soils. Analysis of convective inhibition (CIN) showed that the “cap” or “lid” to convection was much weaker over Dry Soils and stronger over Moderate Soils. These findings indicate that while the atmosphere was more unstable over the Dry Soils, the weaker cap likely would not allow the accumulation of convective energy throughout the day and convection would most likely be widespread and disorganized. With the stronger cap over the Moderate Soils, the convective energy would be allowed to accumulate throughout the day until the cap was broken, leading to more explosive convective development in a more organized fashion.

A further analysis of the relationship between soil moisture and stability was conducted by examining changes in the probability of reaching three threshold values of CAPE, LI and CIN. Three categories of intensity of convective potential (Moderate, Strong, and Extreme) were created from the threshold values. Under each category (Moderate, Strong, and Extreme), the probability of reaching the threshold values increased as soil moisture values increased. These findings were also examined in four case studies, each representing a synoptic-type day. In all cases, the atmosphere was less stable over the areas of increased soil moisture. On case days with a LLJ present, there

appeared to be an increase in instability over areas with a sharp transition between wet and dry soils. This finding helped confirm the synergistic relationship between soil moisture and the LLJ that was established during the long-term climatological portion of the study.

5.3. Soil Moisture and Soil Moisture Boundaries' Role in Convective Initiation

Locations of convective initiation were identified in the Twin Lakes/Oklahoma City, Oklahoma (TLX) WSR-88D radar site over the seven-year study period. Not surprisingly, a majority of the convective initiation events occurred on synoptically primed days, with a majority of those days having a LLJ present. An examination of the convective initiation points on each of the four synoptic-type days showed a random spatial pattern across the study area. The points were then matched with soil moisture values and soil moisture gradient values to determine the relationship between the location of convective initiation and soil moisture.

The analysis of the convective initiation points and soil moisture and soil moisture gradient values showed some similarities between the synoptically primed and synoptically benign days. On synoptically benign days, the probability of convective initiation decreased as soil moisture values increased from 0% to between 15% (with LLJ) and 25% (without LLJ). The probabilities based on soil moisture gradient values also decreases as soil moisture gradient values increased from 0% km⁻¹ to 2.0% km⁻¹ on days that are synoptically benign with or without a LLJ. At higher soil moisture (i.e., greater than 15% or 25%, respectively) and soil moisture gradient values (greater than 2.0% km⁻¹) on synoptically benign days, the probability of convective initiation begins to

increase as the soil moisture and soil moisture gradient values increase. On synoptically primed days, the probability of convective initiation increased as soil moisture increased from 0% to 15% (without LLJ) and 0% to 30% (with LLJ), and then decreased after this point. The probabilities of convective initiation followed a similar pattern based on changes in soil moisture gradient. The probabilities increased from 0% to 2.0% km⁻¹ and then decreased with larger soil moisture gradient values. These findings indicate that there may be a “tipping point” in the 15%-30% range in soil moisture and 1.5% km⁻¹ to 2.0% km⁻¹ soil moisture gradient values for all synoptic-type days. This “tipping point” is a change in the atmosphere at the mesoscale, based on soil moisture discontinuities, that produces an environment more conducive or more suppressive for convection.

5.4. Synthesis and Future Research

The findings from each of three individual manuscripts (Chapters 2-4) indicate that the moderate soil moisture values and moderate soil moisture gradient values are of great importance with regard to the convective process at the mesoscale (Figs. 2.7, 3.17, 4.6). In this intermediate range of soil moisture, the diurnal growth of the PBL is at its greatest on all synoptic-type days. This finding indicates that within these regions, turbulent thermals that developed in the PBL had a better chance of reaching their level of free convection and creating convective storms. Within the same values of soil moisture, the stability parameters (CAPE and LI) indicated a more stable atmosphere than regions with drier or wetter soils. However, the CIN values were greatest in this region, indicating the probability that the convective energy below the cap (i.e., within the PBL) would have more time to accumulate throughout the day before the cap was

broken. Once a strong cap is broken, it tends to release the convective energy quickly and in a more isolated and organized fashion (Fig. 4.6). This hypothesis was supported with the examination of the convective initiation points (Chapter 4). On synoptically benign days, the probability of convective initiation increased from low to moderate soil moisture values but then decreased from moderate to high soil moisture values. On synoptically primed days, the probability of convection decreased from low to moderate values but then increased from moderate to high values. In all cases, the “tipping point” was in the moderate range of soil moisture and soil moisture gradient values. All of the findings suggest that the moderate soil moisture values are the most critical in convection and that within this range there may be a tipping point from a more conducive to suppressive environment for convection.

The present study has advanced the understanding of soil moisture on various aspects of convection over a long-term a relatively long study period (1998-2004) in a region known for its convective activity. This is one of the first long-term studies of its nature by using recently developed data products for both soil moisture and high resolution atmospheric data. The results indicate that the moderate range (15-30%) of soil moisture values may be the most critical in the mesoscale impacts for the development of convection. However, further investigation of moderate soil moisture values will be needed to validate the findings of this study. Because this dissertation focuses on the long-term climatological relationships, the manner in which these critical values could be tested is through the use of atmospheric models and re-analysis of significant convective events. This study also only examined certain aspects of the PBL and stability of the atmosphere. Thus, additional directions could include the

investigation of the relationship between soil moisture and the following atmospheric conditions: (1) surface moisture (e.g., dew-point temperature), (2) surface temperature, (3) low-level moisture and temperature (i.e., at 950 or 850-hPa levels), and (4) surface wind fields. If changes in surface and low-level moisture and temperature fields are found, it may have implications on the convective parameters used in the present study. For example, do changes in moisture alter CAPE more than changes in temperature; if so by how much? Analysis of the surface wind fields could lead to a better understanding of the convergence zones, which have been shown to be conducive to convective development, and how the changes in the wind fields could produce more wind shear leading to an environment conducive for more severe convective development.

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