Soil Moisture–Precipitation Coupling: Observations from the Oklahoma Mesonet and Underlying Physical Mechanisms

Trent W. Ford[1], Anita D. Rapp[2], Steven M. Quiring[1], Jennifer Blake[3]

[1] Department of Geography, Texas A&M University, College Station, Texas

[2] Department of Atmospheric Sciences, Texas A&M University, College Station, Texas

[3] Department of Geology and Geophysics, Texas A&M University, College Station, Texas

Correspondence to: T. W. Ford (twford@tamu.edu)

Abstract

Interactions between soil moisture and the atmosphere are driven by the partitioning of sensible and latent heating, through which, soil moisture has been connected to atmospheric modification that could potentially lead to initiation of convective precipitation. The majority of previous studies linking the land surface to subsequent precipitation have used atmospheric reanalysis or model datasets. In this study, we link *in situ* observations of soil moisture from more than 100 stations in Oklahoma to subsequent unorganized afternoon convective precipitation. We use hourly NEXRAD radar-derived precipitation to identify convective events, and then compare the location of precipitation initiation to underlying soil moisture anomalies in the morning. Overall we find a statistically significant preference for convective precipitation initiation over drier than normal soils, with over 70% of events initiating over soil moisture below the long-term median. The significant preference for precipitation initiation over drier than normal soils is in contrast with previous studies using satellite-based precipitation to identify the region of maximum precipitation accumulation. We evaluated 17 convective events occurring near Lamont, Oklahoma, where soundings of the atmospheric profile at 0600 and 1200 LST are also available. For these events, soil moisture has strong negative correlations with the level of free convection, planetary boundary layer height, and surface temperature changes between 0600 to 1200 LST. We also find strong positive correlations between morning soil moisture and morning-to-afternoon changes in convective available potential energy and convective inhibition. In general, the results of this study demonstrate that both positive and negative soil moisture feedbacks to are important in this region of the United States.

1. Introduction

1.1. Background

Soil moisture is vital to the climate system. Root zone soil moisture in vegetated regions has a significant influence on evapotranspiration rates (Teuling *et al.* 2006; McPherson, 2007) and latent and sensible heat exchange (Dirmeyer *et al.* 2000; Basara and Crawford, 2002; Guillod *et al.* 2014). Through the modification of evapotranspiration and moisture transport from the land surface to the atmosphere, soil moisture can impact regional temperature and precipitation. Because of the strong control soil moisture has on sensible and latent heating, studies have focused on the mechanistic modification of atmospheric conditions by the land surface through energy exchange. Findell and Eltahir (2003) derived a convective triggering potential and, combined with a low-level atmospheric humidity index, determined atmospheric potential for convective initiation over relatively wet or relatively dry soils in Illinois. Santanello *et al.* (2009) used observations of soil moisture and atmospheric conditions to describe the modification of atmospheric moisture and energy by the land surface at the hourly time scale. In addition to local-scale interactions, soil moisture-precipitation coupling can be important for meso-scale circulation initiation, particularly over strong meso-scale soil moisture heterogeneity (Taylor *et al.* 2011). Results from these and similar studies suggest that soil moisture anomalies, which drive preferential latent or sensible heating at the surface, can alter low-level atmospheric temperature and humidity such that atmospheric dew point depressions will be generally lower (higher) over wetter (drier) soils.

Through its control of surface evaporative fraction (EF), anomalously wet or dry soils can induce modification of the planetary boundary layer (PBL), including changes in the height of the lifting condensation level (LCL) and the level of free convection (LFC) (Brimelow *et al.* 2011).

Without consideration of free-tropospheric conditions, afternoon LCL and LFC heights generally decrease with sufficient moisture flux from a wet soil surface, which increases energy available for convection (i.e., CAPE). In turn, relatively dry soils enhance sensible heating at the surface and promote increased LCL and LFC heights (Frye and Mote, 2010a), increasing mixed-layer stability. These mechanisms act as a positive soil moisture feedback, in which convective cloud cover and subsequent precipitation is more probable over a moist land surface than a dry land surface (Findell *et al.* 2011). However, studies have documented an increased probability of convective precipitation over a dry soil surface, partially attributable to dry soils (enhanced sensible heating) resulting in sufficient PBL growth and eroding of strong morning convective inhibition (CIN) (Santanello *et al.* 2009).

Ek and Holtslag (2004) demonstrate the interactive roles of soil moisture and free-tropospheric stability on relative humidity tendency and convective cloud development at the PBL-top. Their model simulations show dry (wet) soils combined with weaker (stronger) above-PBL stability enhances the probability of PBL cloud development (Ek and Holtslag, 2004); a finding later corroborated with observations in the Sahel (Westra *et al.* 2012). Gentine *et al.* (2013) integrate the impacts of surface latent and sensible heat flux and free-tropospheric stability into a two-regime framework, specifically a wet-soil advantage regime and dry-soil advantage regime. Under this framework, moist convection occurs earlier over moist surfaces coinciding with strong free-tropospheric stability, and occurs earlier over dry surfaces coinciding with warm, weakly stratified free-tropospheric conditions (Gentine *et al.* 2013). In light of the results of these studies, we could expect unorganized convection to occur over both wet and dry soils, depending on the overlying free-tropospheric conditions.

Because soil moisture has a significant impact on atmospheric conditions and the persistence of strong land-atmosphere interactions, it is important for seasonal climate predictions. Meng and Quiring (2010) show that anomalous spring soil moisture in the North American Great Plains influenced the amount of summer precipitation in the Community Atmosphere Model (CAM3). Roundy *et al.* (2013) demonstrated the importance of soil moisture conditions and land-atmosphere coupling in drought monitoring and forecasting in the Southeast U.S. These and other studies suggest that land-atmosphere interactions, modulated by soil moisture, can significantly influence temperature anomalies and potentially, precipitation, and can aid in climate and extreme event forecasting (Douville and Chauvin, 2000; Koster *et al.* 2011).

1.2. Soil Moisture-Precipitation Coupling in the U.S. Southern Great Plains

Although land-atmosphere interactions have considerable impact on regional climate and climate persistence, debate continues as to the sign and strength of these interactions at various scales. Global climate models have identified the U.S. Southern Great Plains as a “hot spot” of land-atmosphere interactions wherein the probability of precipitation responds strongly to land surface conditions (Koster *et al.* 2004). Studies employing soil moisture observations show less consistent results, with some suggesting a wet soil advantage regime in the region (Frye and Mote, 2010b; Ford *et al.* 2015), and others providing evidence of a dry soil advantage regime (Santanello *et al.* 2013; Guillod *et al.* 2015). Still other studies show no evidence of soil moisture–precipitation coupling in the Southern Great Plains region, based on *in situ* observation (Phillips and Klein, 2014), satellite (Taylor *et al.* 2012), and reanalysis datasets (Findell *et al.* 2011). The lack of a strong, consistent land-atmosphere signal in this region is impeded by the occurrence of both positive and negative soil moisture feedbacks (Findell and Eltahir, 2003b). Additionally, the conflicting results from these and other studies are partially attributable to the breadth of datasets and methodologies employed (e.g., Findell *et al.* 2011; Guillod *et al.* 2014). However, both wet-positive and dry-negative soil moisture feedback on precipitation are potentially relevant in the Southern Great Plains.

The lack of consensus from observation-based studies on the sign and strength of soil moisture–precipitation coupling, combined with the strong positive coupling in global climate models precludes solid conclusions as to the relevance of soil moisture–precipitation coupling in the global climate system. Mesoscale studies are uniquely capable of documenting land-atmosphere interactions while simultaneously accounting for region-specific factors that could confound the results. For example, atmospheric stability in the Southern Great Plains region is significantly impacted by the strength and location of the Great Plains Low-Level Jet (Higgins *et al.* 1997; Frye and Mote, 2010). This is further complicated by the intrusion of squall lines and frontal systems during the warm season (Raddatz and Hanesiak, 2008), corresponding with conditions unfavorable for surface-induced convection (Matyas and Carelton, 2010). To properly account for these factors, we use a dense network of meteorological monitoring stations with *in situ* soil moisture observations, combined with radar-derived precipitation estimates and atmospheric soundings to analyze the soil moisture-precipitation coupling strength in the Southern Great Plains of the United States. Specifically we address whether unorganized convective events *initiate* preferentially over drier or wetter than normal soils in Oklahoma and document how atmospheric conditions prior to convection respond to soil moisture variability.

2. Data and Methods

2.1. Soil Moisture Data

In situ observations of soil moisture are taken from the Oklahoma Mesonet (http://mesonet.org/), comprised of over 100 continuously monitoring stations across the state (Illston *et al.* 2008). Campbell Scientific 229-L heat dissipation sensors are deployed at four depths (5, 25, 60, 75 cm) in the soil column and measure matric potential, from which volumetric water content is derived. Mesonet soil moisture observation error is low (Scott *et al.* 2013), and station density in Oklahoma is among the highest in North America.

Daily (9:00 a.m. LST) measurements are used to characterize soil moisture conditions on the morning of each convective event. Because volumetric water content is a strong function of site-specific characteristics, we convert daily volumetric water content measurements to percentiles. For this conversion, an empirical cumulative distribution function, comprised of all daily soil moisture observations for a given calendar month, is constructed. Daily observations are then fit to the distribution, and percentiles of the overall distribution are calculated. This means that a daily percentile value on (e.g.) July 5th of 100 represents the wettest soil moisture condition experienced during any July day over the entire study period. The percentiles are then gridded at a 0.25° spatial resolution across the study region. The location of convective precipitation initiation is matched to the soil moisture grid and a corresponding soil moisture value. It is worth mentioning that soil moisture percentiles in this study represent only local temporal variability, and therefore cannot be used to examine the impact of soil moisture spatial heterogeneity on convective precipitation initiation. Soil moisture observations from the 5 cm depth are used in all analyses.

2.2. Precipitation Event Identification

The majority of precipitation in the central United States is caused by frontal activity and mesoscale convective systems (Raddatz and Hanesiak, 2008; Carleton *et al.* 2008). In these cases, moisture is advected into the region by mid-latitude cyclones or fronts (Matyas and Carleton, 2010). Therefore, analyzing the influence of soil moisture on those precipitation events will likely result in a weak or nonexistent relationship. For example, Phillips and Klein (2014) found large-scale atmospheric forcings dominated a relatively weak local feedback signal in the Southern Great Plains. Unorganized convection, as defined by Carleton *et al.* (2008), includes isolated convective events that occur in the absence of strong, synoptic-scale atmospheric forcing. Separating these afternoon precipitation events from organized convective events, like MCSs, and those forced by synoptic-scale atmospheric processes will help to remove confounding factors (i.e., noise) and isolate the influence of the land surface (i.e., signal).

Capturing individual convective precipitation events, particularly unorganized convection most pertinent to our study, requires datasets with a high spatial and temporal resolution. Taylor *et al.* (2012) identified convective events using the Climate Prediction Center Morphing Method (CMORPH, Joyce *et al.* 2004), a global precipitation dataset with a 3-hour (temporal) and 0.25° (spatial) resolution. Their precipitation event detection methodology (also implemented by Ford *et al.*, 2015 and Guillod *et al.* 2015) identifies the grid cell that resides within a 1.25° x 1.25° box in which the maximum amount of precipitation occurred. It also identifies the grid cell(s) within the same 1.25° x 1.25° box with the minimum amount of precipitation. Compositing soil moisture associated with these locations of maximum and minimum precipitation provides a means of determining whether there is a preference for convective precipitation to fall over relatively wetter or drier land surfaces. The use of CMORPH precipitation is well-suited for global-scale analyses; however the 3-hour temporal resolution precludes the identification of the point of precipitation *initiation*.

Our study identifies unorganized convective precipitation events using ground-based Doppler radar from the National Weather Surface (NWS) Next-Generation or NEXRAD radar network. NEXRAD includes over 160 S-band Doppler radars in the United States, including 5 in Oklahoma. The NWS produces their Stage IV hourly precipitation product at 4 km spatial resolution using a mosaic of the ground-based radar data that covers nearly all of the contiguous United States (Lin and Mitchell, 2005). The Stage IV product undergoes bias-correction, quality control, and a series of automated algorithms and manual inspection. NEXRAD precipitation products are ideal for characterizing soil moisture-precipitation interactions occurring at sub-daily time scales (Guillod *et al.* 2014).

We examined hourly Stage IV radar images of precipitation accumulation from 3 a.m. to 8 p.m. each day between May and September, 2002–2012, and manually identified unorganized convective events. The manual identification procedure was completed according to a pre-determined decision tree (Fig. 1), which approximates the classification system of Schoen and Ashley (2011). Schoen and Ashley's (2011) system classified storms as cellular unorganized, quasi organized, cellular organized, and linear organized, and was based on previous studies examining radar morphology of convective storms (Parker and Johnson, 2000; Klimowski *et al.* 2003). The decision tree process included 5 assessments or queries: (1) the location of precipitation initiation, (2) minimum event size, (3) precipitation rate, (4) shape and (5) propagation of the event. The classification systems attempts to exclude organized convective events. Specifically, organized convective events in our classification were identified as either (1) conglomerates of convective storms arranged in a linear or quasi-linear fashion or line-echo wave pattern, including bow echoes and squall lines, or (2) as individual cells which initiate and propagate in the same vicinity and direction, arranged in a linear or nonlinear fashion (Gallus *et al.* 2008), and that move/evolve with respect to one another. Organized convection is undesirable because it is typically associated with the synoptic-scale atmospheric processes that we are trying to exclude from this study. The desired unorganized storm type was defined as individual cells which initiated, propagated, and evolved independently of each other and were arranged in a nonlinear fashion (Ashely and Gilson, 2009). These systems are typically shorter lived than organized events, and do not develop into or dissipate from more organized convective modes.

Manual event identification procedures have advantages and disadvantages. The primary advantage of a manual classification procedure is the ability of the researcher to discern isolated, unorganized cells from those which develop/evolve together or bifurcate from larger systems. The primary disadvantage of such a manual classification methodology is the lack of repeatability. Even with a well-rooted decision tree to guide the classification process, the results are researcher-specific. To test the reproducibility of this study, classification of all events was completed independently by two researchers. There was 72% agreement between the two researchers with regards to event identification. Agreement varied from year to year and month to month, ranging from 50% for 2009 events to 87% for 2007 events, and 63% for June events to 80% for events in September. Qualitatively, it seemed that the most frequent disagreements between researchers were for (1) multiple, isolated systems that initiated at the same time, and (2) systems which initiated in Oklahoma, but could have been associated with systems initiating outside the study region. Overall, there was a reasonable amount of consistency when using this methodology to detect unorganized convective events.

Once an unorganized convective event is identified, the location of afternoon precipitation initiation is established as the grid cell in which precipitation is first captured in the radar dataset. This procedure is different from those used by Taylor *et al.* (2012) and Ford *et al.* (in press), as we identify the point of precipitation initiation instead of the region of maximum accumulation. Once the location of precipitation initiation was established for an event, we determined if more than 3 mm of precipitation occurred between 3:00 a.m. and noon (LST) of the preceding morning within 20 km of the location of initiation. Convective events were retained only if precipitation did not occur or less than 3 mm had accumulated near the location of initiation. Through our precipitation classification methodology, 477 unorganized events were identified by both researchers during the warm season (May–September) between 2002 and 2012 in Oklahoma (Fig. 2). These events were then used to determine if unorganized convection initiates more frequently over wetter or drier than normal soils.

2.3. Atmospheric Conditions

In addition to documenting the frequency of convection over wet and dry soils, we also use a subset of convective events to characterize atmospheric modification by the land surface in greater detail. Soundings of the atmospheric profile allow for direct connection with the underlying land-surface conditions, but are limited in spatial coverage. Therefore, we use atmospheric soundings at 1200 UTC (0600 LST) and 1800 UTC (1200 LST) from the Department of Energy Atmospheric Radiation Measurement facility at Lamont, Oklahoma for the diurnal evolution of atmospheric moisture and energy. In addition to the atmospheric soundings, we also use estimates of latent and sensible heat flux (W m^{-2}) from the Atmospheric Radiation Measurement facility Energy Balance Bowen Ratio system at Lamont, Oklahoma. The instantaneous latent and sensible heat flux estimates at 1800 UTC (1200 LST) are used to calculate EF, which is the percent of incoming solar radiation used for evaporation.

Cluster analysis is used with a Ward's linkage and a 4-class maximum to separate events near Lamont. Hierarchical cluster methods, such as the Ward's method have been used frequently for distinguishing precipitation regimes (Gong and Richman, 1995; Ramos, 2001) and other environmental patterns (Allen and Walsh, 1996). The events are clustered based on their morning (0600 LST) convective triggering potential and low-level humidity (e.g. Findell and Eltahir, 2003). Within each cluster of events, we examine changes in atmospheric humidity and temperature, the level of free convection (LFC), and PBL height.

The convective environment and stability of the atmosphere associated with each precipitation event is also characterized using profile-integrated convective available potential energy (CAPE) and convective inhibition (CIN). Taylor and Lebel (1998) suggest that soil moisture anomalies can have a significant influence on CAPE, while Myoung and Nielsen-Gammon (2010) find a strong statistical relationship between soil moisture and CIN values in the Southern Great Plains. We calculate CAPE and CIN using the non-virtual surface parcel in this study. Atmospheric stability measures combined with changes in atmospheric humidity and temperature are linked to underlying soil moisture conditions for the events surrounding Lamont. We examine the physical mechanisms coupling the land surface with the atmosphere, potentially leading to convective precipitation. The organization of the results and discussion are presented as follows: section 3 describes the preference for convection to occur over wet or dry soils, connections between soil moisture and atmospheric conditions are presented in section 4, and section 5 provides a summary and discussion of our results with respect to the broader climate community.

3. Results

3.1. Dry or Wet Soil Moisture Preference

The location of precipitation initiation was identified for each precipitation event and is used to determine the soil moisture conditions in that location (grid cell). The soil moisture percentiles underlying all convective events are presented in Fig. 3. The histogram shows a larger number of convective events occurred over drier than normal soils (< 0.5) than over wetter than normal soils (> 0.5). In fact, the three lowest soil moisture bins (0 – 30th percentile) contain the highest number of convective events.

We evaluate the statistical significance of the preference for precipitation initiation over dry soils using a bootstrapping methodology adopted from Ford *et al.* (in press). The procedure compares the frequency of convective events over dry and wet soils to the frequency of dry and wet soils from of a sample of 477 randomly selected days (both event and non-event). For the sample days, soil moisture is taken from a randomly chosen grid cell. Frequency distributions generated from the 10,000 iterations of randomly-sampled days are used to assess the likelihood of achieving the ratio of convective events over dry soils to those over wet soils. Based on this evaluation, the number of convective events observed to occur over drier than normal soils is associated with the 99th percentile of the bootstrapped distribution. This means that the probability of obtaining these results by chance is less than 1%. Therefore, we conclude that there is a statistically significant preference for unorganized precipitation to initiate over drier than normal soils. These results suggest the presence of a dry soil advantage regime (e.g., Gentine *et al.* 2013) in which convective cloud development is favored over a dry soil surface with a deep PBL and a weakly-stratified, warm/dry free-troposphere (Huang and Margulis, 2011).

The statistically significant preference for precipitation initiation over dry soils is seemingly in direct contrast with the wet preference found in Ford *et al.* (2015). The primary difference between studies is the use of CMORPH for event identification by Ford *et al.* (2015), and NEXRAD radar in the present study. Two important advantages of NEXRAD which may be partly responsible for the contrasting results are: (1) the ability to identify the location of precipitation *initiation* rather than the location of maximum accumulation, and (2) the ability to discern between unorganized and larger-scale organized systems (Guillod *et al.* 2014). For each of the 477 events, we identified both the location of precipitation *initiation* as well as the location of maximum precipitation accumulation. When we substitute the location of maximum accumulation for the location of initiation when compositing soil moisture underlying events, we find an even stronger preference for convection to initiate over dry soils (not shown). This suggests that the lack of agreement between the findings presented here and those in Ford *et al.* (2015) is most likely due to differences in the datasets and methods used to identify events. When the convective events identified in Ford *et al.* (2015) using methods adopted from Taylor *et al.* (2012) were reanalyzed, it was found that large-scale thunderstorms due to frontal activity, low pressure systems, and even tropical storms were grouped together with mesoscale unorganized convective events (Wang *et al.* in review). The ability to detect soil moisture impacts on convective precipitation initiation is hindered when events due to frontal activity and tropical storms are included because these events do not initiate over the study region. The results presented in this study, however, are based on isolating unorganized convective events and identifying the location of precipitation initiation. This gives us confidence in our assessment of the relationships between soil moisture and unorganized convective events.

3.2. Convective Event Spatial Variability

Land cover and land use boundaries have been shown to dramatically impact atmospheric temperature and humidity in Oklahoma (Avissar and Pielke 1989; McPherson *et al.* 2004). Therefore, we investigated whether the unorganized convective events identified in this study show any spatial patterns that are attributable to variations in land cover (Fig. 2). The G-function was used to provide a quantitative measure of spatial randomness (Diggle, 2003; Perry *et al.* 2006). This method examines the cumulative frequency distribution of nearest neighbor distances for all events. The distribution of nearest neighbor distances calculated from the 477 convective events is then compared against the theoretical distribution of distances generated from a sample of randomly generated points that is the same size as the number of events. More specifically, 477 points are randomly placed around Oklahoma, and from these points a theoretical nearest neighbor distribution is generated. This random-point generation procedure is iterated 1,000 times to create a robust theoretical distribution of nearest neighbor distances. The 50^{th}, 97^{th} and 3^{rd} percentiles are identified from this distribution and are used to represent the median and the confidence interval, respectively. The confidence interval is used to determine if the observed location of the convective events are spatially random.

Fig. 4 shows the cumulative distribution functions of nearest neighbor distances for the observed convective events (blue line), the bootstrapped median (red line) and 95% confidence envelopes (black lines). The nearest neighbor distance distribution from the convective events falls within the confidence intervals at nearly all distances and, therefore, we conclude that they are spatially random. We repeated this analysis for only wet and only dry events, and both groups were also spatially random.

Despite our findings of statistically significant spatial randomness, unorganized convective events seem to cluster in the southeast corner of the state. The cluster is coincident with predominantly mixed forest land cover; however, no association can be made between the location of these events and land cover-induced atmospheric modification. Instead the grouping of these events is attributed to increased atmospheric instability in the form of mid-morning CAPE (J kg^{-1}) (Fig. 5). Mid-morning (0900 LST) CAPE composited for the events that occur in the southeast corner of the state (Fig. 5a) is shown separately from 0900 LST CAPE composited for all other events (Fig. 5b). Spatial patterns of the composites are very similar, with the exception of increased CAPE in the southeast corner of the state during the clustered events. Increased potential energy and instability increases the probability of convection, and may explain the apparent grouping of events in the southeast corner of Oklahoma.

3.3. Convective Event Temporal Variability

We examine the monthly and inter-annual variability of wet and dry convective events in Oklahoma. Fig. 6a shows the frequency of dry and wet events during each warm season between 2002 and 2012, as well as total (May–September) precipitation (mm) for each year, averaged over all Oklahoma climate divisions. Precipitation totals are taken from the National Climate Data Center Climate Divisional Dataset (http://www.ncdc.noaa.gov/cag/). The ratio of dry soil events to wet soil events closely follows the total (May–September) precipitation each year. The two years, 2007 and 2008, with more wet soil events than dry soil events experienced the wettest and second wettest seasons over the study period, at 693 and 539 mm, respectively. The years with the highest dry soil to wet soil event ratios (2002, 2006, 2011, 2012) had the four lowest seasonal precipitation totals. The fact that wet soil events tend to occur in wet years and dry soil events tend to occur in dry years is expected because of the direct impact precipitation has on soil moisture, irrespective of any soil moisture feedback. In addition, because our study focuses on the location of convective precipitation initiation, we cannot account for the potential influence of atmospheric persistence and the impact of large-scale atmospheric conditions (e.g., Taylor *et al.* 2011). Therefore, it is important to note that the patterns shown in Fig. 6 might simply depict the impact of precipitation on soil moisture, rather than a wet or dry soil feedback.

Interestingly, the total number of events per year does not seem to be connected to the seasonal precipitation totals. A similar number of events occurred in 2011 (28), a very dry year, as in 2008 (29), which was a wet year. However, the lack of correspondence between total seasonal precipitation and the number of convective events could be due to our preferential selection of unorganized convective events. Fig. 6b shows the monthly variability of all unorganized convective events, both dry and wet. Dry events occur more frequently in May and June than July and August, when the number of wet events increases. To better describe the patterns of temporal variability shown in Fig. 6, we combine monthly and annual frequency into one grid (Fig. 7). The top panel in Fig. 7 shows the frequency of all events, while the middle and bottom panels show frequencies of wet and dry events, respectively. The primary conclusion that can be drawn from Fig. 7a is that the unorganized convective events tend to occur most frequently between June and August, coinciding with the peak convective season in the Southern Great Plains (Fritsch *et al.* 1986). While Fig. 7a is divided somewhat horizontally between the middle and beginning/end of the warm season, Figs. 7b and 7c are split vertically. The frequency of wet events (Fig. 7b) is relatively consistent from year to year between 2002 and 2006, with August exhibiting the most frequent wet events. This pattern changes in 2007 and 2008, with a considerable increase in wet event frequency for nearly all months, except September and May. These two very wet years are followed by a pattern that is similar to that observed during 2002 to 2006. The increase in wet events in 2007 and 2008 corresponds with a simultaneous decrease in dry events during the same time period. The warm season in 2007 was the 2nd wettest on record in Oklahoma, with total precipitation more than 237 mm above the 30-year mean. Although the same time period in 2008 was less anomalous (25th wettest on record), precipitation was still more than 75 mm above the mean. The abundant precipitation during these two warm seasons led to near-saturated soils for the majority of the time and helps to explain why convection initiated preferentially over wetter than normal soils (i.e., atmospheric persistence, Taylor *et al.* 2011).

Over the 11-year study there is, on average, a statistically significant preference for precipitation to initiate over drier than normal soils. However, the total number of events and ratio of dry to wet soil events varies considerably on inter-annual and monthly timescales. Wet soil events occurred most frequently in August during years with less-than-normal to normal precipitation. Not surprisingly, seasons with dry and near-normal rainfall conditions coincided with a higher dry to wet event ratio, while convection over wet soils was most frequent during seasons with above normal precipitation totals.

3.4. Atmospheric Pre-Conditioning to Convection

This study has produced a climatology of unorganized convection in Oklahoma and connected the location of initiation with soil moisture conditions. This analysis is useful for improving our understanding of the relationship between soil moisture and the location and timing of convection. In this section we investigate the physical mechanisms that link the land surface and atmosphere. We composited convective events occurring within 50 km of Lamont, Oklahoma, where atmospheric soundings are taken daily at 0600 and 1200 LST. These events were used to quantify the relationship between the land surface and the atmosphere. The 50 km threshold was selected based on the expected representativeness of the atmospheric profile (Potvin *et al.* 2010) over Lamont as well as the spatial autocorrelation of soil moisture in Oklahoma. Convective events were only retained if: (1) they occurred within 50 km of Lamont, (2) afternoon precipitation was also recorded in Lamont, and (3) soil moisture percentiles in the grid cell where convection occurred had the same anomaly (wet or dry) as Lamont. Based on these criteria, 17 events were selected for analysis.

The goal of this analysis is to document the differences in atmospheric conditions between 0600 and 1200 LST preceding convection and to account for atmospheric preconditioning to convection occurring over wet soils and that occurring over dry soils. We used convective triggering potential (CTP, J kg^{-1}) and low-level humidity (HI_{low}, °C), adopted from Findell and Eltahir (2003a), to identify events with a morning atmosphere preconditioned for convection over wet soils, dry soils, or convection regardless of the land surface. CTP is the integrated area between the environmental temperature profile and a moist adiabat from 900 to 700 mb. The HI_{low} is the summation of the dewpoint depression at 950 and 850 mb. The atmospheric levels used for these calculations are taken directly from Findell and Eltahir (2003a) and are assumed to be relevant for Oklahoma.

This comparison is important, as morning atmospheric conditions from which dry soils could potentially force convection should be very different than those favoring wet soil-forced convection. Namely, a dry soil surface modifies atmospheric conditions by forcing PBL growth and free-tropospheric air entrainment, while wet soils effect specific humidity within the PBL (Gentine et al. 2013). Preference for afternoon convective cloud development over wet or dry soils will depend on morning PBL depth and the stability, temperature, and moisture of free-tropospheric air (Findell and Eltahir, 2003a; Huang and Margulis, 2011). Therefore morning (0600 LST) atmospheric profiles and CTP- HI_{low} conditions over dry and wet soils are expected to be noticeably different. Fig. 8a shows all 17 events composited around Lamont, plotted in dual CTP-

HI_{low} space. The scatter plot shows clear separation of the dry and wet soil events, particularly in the vertical (HI_{low}) and to a lesser extent in the horizontal (CTP). Atmospheric conditions prior to convection over wet soils are characterized by an environmental temperature profile relatively close to the moist adiabatic lapse rate, with an average CTP of 139 J kg^{-1} and high humidity at low levels (mean HI_{low} of 10°C). These conditions are similar to the findings of Findell and Eltahir (2003a) for deep convection initiating over wet soils, and are consistent with a wet soil advantage regime (Gentine *et al.* 2013) in which the wet soils impact PBL specific humidity and therefore PBL depth (i.e., dynamic factor). Atmospheric conditions prior to convection over dry soils have much higher CTP values (mean of 313 J kg^{-1}) and higher HI_{low} (mean of 25°C), representing less stability of the free troposphere (Huang and Margulis, 2011). Delineation of morning atmospheric conditions between wet and dry soil convective events (Fig. 8a) is remarkably consistent with wet and dry soil advantage regimes reported by Gentine *et al.* (2013), representing the importance of both surface soil moisture conditions and pre-convective atmospheric thermal stability in determining a wet or dry soil preference (Huang and Margulis, 2011).

In addition to the separation of dry and wet events in CTP-HI_{low} space, there appears to be a distinction within dry and wet events (Fig. 8a). We clustered the 17 events using the 0600 LST CTP and HI_{low} and a hierarchical clustering algorithm with the Ward's linkage and a 4-class maximum. Clustering has been shown to be a useful method for distinguishing disparate conditions leading to the different scatter points (Khong *et al.* 2015), and is therefore deemed appropriate here. The result of the clustering is shown in Fig. 8b, which displays a similar scatter plot as Fig. 8a, only with points separated into distinct clusters. The 4 clusters span the entire CTP-HI_{low} range and increase in both CTP and HI_{low}, generally from cluster 1 to cluster 4. Interestingly, despite not including soil moisture as a variable for the clustering analysis, the algorithm divided wet events (clusters 1 and 2) from dry events (clusters 3 and 4). The clusters are used to demonstrate the 0600 LST to 1200 LST atmospheric modification in terms of underlying soil moisture and the preconditioning of the morning atmosphere to convection over wet or dry soils.

3.5. Physical Connections between Soil Moisture and Atmospheric Conditions

Atmospheric profiles from soundings at 0600 and 1200 LST are used to characterize conditions and modification from the morning to afternoon before convection occurs. At both 0600 and 1200 LST, we calculate the LFC (mb), PBL height (m) and surface temperature (°C). Additionally for the 0600 LST sounding, we calculate convective temperature (°C), the temperature the near-surface must reach for convection to occur in the absence of synoptic forcing mechanisms, to represent the potential for convection given adequate surface heating. We also calculate CAPE and CIN ($J\ kg^{-1}$) to characterize atmospheric stability at both sounding times. Large differences are observed between the clusters for all atmospheric measures. Table 1 shows the average LFC height, CAPE, CIN, convective temperature and PBL height from 0600 and 1200 LST as well as the average 0900 LST soil moisture percentile for events in each cluster. CAPE (CIN) values are much higher (lower) at both 0600 and 1200 LST for clusters 1 and 2 events, corresponding with relatively wet soils. Additionally, these clusters have relatively lower LFC and PBL heights and much lower 0600 LST convective temperatures. In direct contrast, dry soil events in clusters 3 and 4 are characterized by relatively low (high) CAPE (CIN) values, deeper PBLs and higher LFC heights. However, more interesting than atmospheric conditions at any one point during the day, are the modifications of atmospheric conditions between 0600 and 1200 LST.

Fig. 9 shows scatter plots of the soil moisture percentiles and the 1200 LST – 0600 LST difference in (a) LFC height (mb), (b) PBL height (m) and (c) surface temperature (°C), delineated by cluster. Additionally, Fig. 9d shows the same scatter plot, only with 0600 LST convective temperature on the y-axis. The drier soils of clusters 3 and 4 correspond to increased LFC height, stronger PBL growth and increased surface air temperature and morning convective temperature. The change in these atmospheric conditions is an ideal example of the thermodynamic effect for a deep boundary layer over strong surface sensible heating, with decreased LCL and LFC height compared to PBL growth (Santanello *et al.* 2011; Gentine *et al.* 2013). In contrast, events from wet soils events of clusters 1 and 2 show limited PBL growth, decreased LFC heights, lower convective temperature, and smaller changes in surface temperature from 0600 to 1200 LST. This is characteristic of a stable PBL moistened by increased latent heating from a relatively wet surface (i.e., dynamic effect, Gentine *et al.* 2013). Despite the small sample size, all of the relationships depicted in Fig. 9 are statistically significant. The coefficients of determination for soil moisture and changes in LFC height, PBL height, surface temperature and convective temperature are 0.26, 0.49, 0.60, and 0.53 respectively. Obviously the relationship between soil moisture and near-surface atmospheric temperature is strongest; however, even with varying atmospheric conditions from 17 events, soil moisture percentiles at 0900 LST still explain more than 25% of the variance in LFC height change from 0600 to 1200 LST.

Along with changes in the atmospheric temperature and LFC/PBL heights, we also relate soil moisture percentiles from the 17 events to atmospheric stability. Fig. 10a shows scatter plots of soil moisture percentile and the change (difference) in CAPE (ΔCAPE, J kg^{-1}) between 1200 and 0600 LST. Fig. 10b shows the same scatter plot, only showing the 1200 LST – 0600 LST difference in CIN (ΔCIN, J kg^{-1}) delineated by cluster. For clarity, negative ΔCIN values represent a decrease in CIN (decrease in stability) between 0600 and 1200 LST. The general relationship between soil moisture and the changes in both CAPE and CIN are positive, with (wet soil) events in clusters 1 and 2 corresponding with larger (smaller) changes in CAPE (CIN). Mechanistically, drier than normal soils enhance sensible heating at the surface, which results in increased near-surface air temperature and heating of the air parcel near the surface (Fig. 9c). The enhanced warming of the surface allows the surface temperature to approach (or to reach) the convective temperature, essentially decreasing CIN values. Wet soils diminish surface heating, which results in a negligible change in CIN between 0600 and 1200 LST. Concurrently, wetter than normal soils provide enhanced moisture flux to the atmosphere through increased latent heating (Ek and Holtslag, 2004; Gentine *et al.*, 2013). This decreases the level of the LFC (Fig. 9a) and increases CAPE throughout the profile. Through the modification of CAPE and CIN, both wet and dry soils have the potential to initiate convection, and in the case of our 17 events, are physically linked to modifications of the atmosphere. The coupling between soil moisture and CAPE/CIN is also statistically significant, with coefficient of determination values of 0.42 and 0.77, respectively. This means that an overwhelming amount of variance in the evolution of CIN between 0600 and 1200 LST (77%) is captured by 0900 LST soil moisture percentiles.

Gentine *et al.* (2013) delineate positive and negative regions of relative humidity sensitivity to EF, through which convection is induced. We examine our 17 convective events in (1200 LST) potential temperature slope (γ_θ, K km^{-1}) – EF space to determine if we can similarly separate the events into regions of positive and negative relative humidity sensitivity (Fig. 11). Although not as distinct as the separation demonstrated by Gentine *et al.* (2013), the 17 convective events show a delineation along γ_θ – EF space. Mixed layer relative humidity is most sensitive to changes in surface energy flux when evaporation is constrained under a less stable boundary layer and when evaporation is enhanced under a more stratified boundary layer. The convective events are colored in Fig. 11 based on the 5 cm soil moisture percentile underlying the initiation point. Event separation is further demonstrated as wet and dry soil advantage regimes (e.g., Gentine *et al.* 2013), corresponding with positive and negative regions of relative humidity sensitivity, respectively. Overall, the pattern shown in Fig. 11 supports the dual wet soil-dry soil advantage regimes proposed by Gentine *et al.* (2013), and suggest that convective initiation can occur under both regimes in the Southern Great Plains.

Through the manual event identification procedure, we were able to quantify individual event duration (hours), average size (pixels), and total precipitation accumulation (mm) (Table 1). We relate these event characteristics to precedent land surface and atmospheric conditions using correlation analysis. All three event characteristics (duration, size, total precipitation) are significantly, negatively related to the change in PBL height (m) between 0600 and 1200 LST. Larger PBL growth (over predominantly drier soils) corresponds with decreased atmospheric relative humidity, which results in events with shorter duration, smaller size, and less overall precipitation. The coefficient of determination between the change in PBL height and duration, size, and total precipitation are 0.22, 0.31 and 0.40, respectively. Two of the three characteristics, duration and total precipitation, are significantly, positively related to CAPE at 0600 LST. Events exhibiting larger CAPE values correspond to longer event duration and more total precipitation, with coefficient of determination values of 0.41 and 0.85, respectively. The soil moisture percentile does not have a statistically significant relationship with any of the event characteristics.

4. Summary and Conclusions

Soil moisture-precipitation interactions have been a major avenue of hydroclimatic research for decades. Previous studies have found evidence of a wet-positive soil moisture feedback in which increased latent heating from a wet soil surface moistens a stable PBL, decreasing surface temperatures, the lifting condensation level, and the level of free convection, and increasing CAPE (Pielke, 2001; Pal and Eltahir, 2003; Ek and Holtslag, 2004; Ferguson and Wood, 2011; Huang and Margulis, 2011). In contrast, other studies have found that anomalously dry soils can impact convective initiation more strongly than wet soils through increased sensible heat flux, a decrease in CIN and increase in PBL height (Santanello *et al.* 2009; Taylor *et al.* 2012). The preference for convective development over relatively dry soils is particularly evident when PBL growth entrains relatively warm, dry air from a weakly stratified free-troposphere (Westra *et al.* 2012; Gentine *et al.* 2013).

Our results show a statistically significant preference for unorganized convection to occur over drier than normal soils, although there are a non-negligible number of events that occur over wet soils. Importantly, the ability of our analysis to discern between unorganized convection and organized systems associated with frontal passage and low-pressure systems is dependent on our precipitation event identification. Automated event identification algorithms using other datasets, such as CMORPH, tend to lump together unorganized convective events (e.g., those initiating from local-scale processes), with large-scale frontal systems and tropical storms that do not initiate over the region of interest (Wang *et al.* in review). We compare maximum hourly precipitation accumulation between the 477 events identified here using NEXRAD and the 353 events identified in Ford *et al.* (in press) using CMORPH (Fig. 12). The CMORPH events have a significant larger median maximum hourly accumulation rate, as determined using the Kruskill-Wallis test, than the NEXRAD events. However, the largest differences between the datasets are in the right tail of the distribution, with many CMORPH event accumulation rates exceeding 100 mm/hr. The occurrence of extremely large precipitation rates in the CMORPH dataset suggests that events associated with large-scale systems are being included in the 353 events. Therefore, the lack of agreement between the results of this study and previous studies (Taylor *et al.* 2012; Ford *et al.* in press) can be partly attributed to the different data products and methods used for event identification. With these results in mind, we argue that our manual event identification procedure works best for (1) identifying the point of precipitation *initiation* and (2) separating unorganized from organized convective events. Therefore, we have confidence in our assessment of the relationships between soil moisture and unorganized convective events.

After compositing 17 events near Lamont, OK where atmospheric soundings observations were available, we found strong connections between soil moisture and atmospheric modification between 0600 LST and 1200 LST. The strongest modification was to CIN and surface air temperature during this time period, as soil moisture explained 77% and 60% of the variance, respectively. Soil moisture has been previously connected to changes in near-surface air temperature in Oklahoma, albeit at much longer time scales (Ford and Quiring, 2014b). Basara and Crawford (2002) also found that the daily evolution of the PBL, including 2 m air temperature, was connected to soil moisture anomalies on clear sky days. The strong connection between soil moisture and CIN is mechanistically consistent with enhanced (diminished) surface heating over dry (wet) soils. Myoung and Nielsen-Gammon (2010) showed that on monthly time scales, CIN was a better determinant to the occurrence of precipitation during the warm season in Texas. However, their results also showed a strong, negative relationship between soil moisture and CIN such that drier than normal soils resulted in stronger CIN values and therefore stronger atmospheric stability (Myoung and Nielsen-Gammon, 2010). The results from our analysis are not necessarily in disagreement because we evaluated the relationship between soil moisture and the 0600 to 1200 LST change in CIN. In fact, as Table 1 shows, 0600 LST and 1200 LST CIN values were strongest over dry soils; however, the enhanced surface heating attributable to moisture-limited land surface conditions in these cases allowed for more rapid surface heating and therefore a larger overall decrease in CIN over dry soils. It should be noted that although stronger CIN over drier than normal soils (e.g. Myoung and Nielsen-Gammon, 2010) can be considered a general deterrent for convection, dry soils can also erode strong CIN much more quickly than wetter soils due to increased sensible heating.

The results of this study show strong statistical relationships between soil moisture and several atmospheric conditions and stability indices. These relationships are mechanistically consistent with wet-positive and dry-negative feedbacks to precipitation, suggesting that both positive and negative soil moisture feedbacks are relevant in this region of the United States.

Acknowledgements

We gratefully acknowledge the National Science Foundation (Award numbers: AGS-1056796, BCS-1433881) for funding this work. We would also like to thank the Oklahoma Mesonet for providing soil moisture observations used in this work. Data files from the Mesonet can be obtained online at: http://www.mesonet.org/index.php/weather/category/past_data_files. Finally we would like to thank Dr. Pierre Gentine and two anonymous reviewers for their helpful comments and suggestions.

References

Allen, T. R., and Walsh, S. J.: Spatial and compositional pattern of alpine treeline, Glacier National Park, Montana. *Photogram. Engin. Rem. Sens.*, 62, 1261-1268, 1996.

Ashley, W. S., and Gilson, C. W.: A reassessment of U.S. lightning mortality, *Bull. Amer. Meteor. Soc.*, 90, 1501-1518, doi: 10.1175/2009BAMS2765.1, 2009.

Basara, J. B. and Crawford, K. C.: Linear relationships between root-zone soil moisture and atmospheric processes in the PBL. *J. Geophys. Res.*, 107, doi: 10.1029/2001JD000633, 2002.

Berg, A., Findell, K., Lintner, B. R., Gentine, P., and Kerr, C.: Precipitation sensitivity to surface heat fluxes over North America in reanalysis and model data, *J. Hydrometeor.*, 14, 722-743, doi:10.1175/JHM-D-12-0111.1, 2013.

Brimelow, J. C., Hanesiak, J. M., and Burrows, W. R.: Impacts of land-atmosphere feedbacks on deep, moist convection on the Canadian Prairies. *Earth Interact.*, 15, 1-29, doi:10.1175/2011EI407.1, 2011.

Carleton, A. M., Arnold, D. L., Travis, D. J., Curran, S., and Adegoke, J. O., 2008: Synoptic circulation and land surface influences on convection in the Midwest US “Corn Belt” during the summers of 1999 and 2000. Part I: Composite synoptic environments. *J. Clim.*, 21, 3389-3415, doi: 10.1175/2007JCLI1578.1, 2008.

Diggle, P. J., Ribeiro, P. J., and Christensen, O.: An introduction to model-based geostatistics. In *Spatial statistics and computational methods. Lecture Notes in Statistics 173 (*ed. J. Møller), 43-86. Springer, New York, 2003.

Dirmeyer, P. A., Zeng, F. J., Ducharne, A., Morrill, J. C., and Koster, R. D.: The sensitivity of surface fluxes to soil water content in three land surface schemes. *J. Hydrometeorol.*, 1, 121-134, doi:10.1175/1525-7541, 2000.

Dirmeyer, P. A., Schlosser, C. A., and Brubaker, K. A.: Precipitation, recycling, and land memory: An integrated analysis. *J. Hydrometeorol.*, 10, 278-288, doi:10.1175/2008JHM1016.1, 2009.

Douville, H., and Chauvin, F.: Relevance of soil moisture for seasonal climate predictions: a preliminary study. *Clim. Dynam., 16*, 719-736, doi: 10.1007/s003820000080, 2000.

Ferguson, C. R., and Wood, E. F.: Observed land-atmosphere coupling from satellite remote sensing and reanalysis. *J. Hydrometeorol.*, 12, 1221-1254, doi: 10.1175/2011JHM1380.1, 2011.

Findell, K. L. and Eltahir, E. A. B.: Atmospheric controls on soil moisture-boundary layer interactions. Part I: Framework development. *J. Hydrometeorol.*, 4, 552-569, doi:10.1175/1525-7541, 2003.

Findell, K. L., Gentine, P., Lintner, B. R., and Kerr, C.: Probability of afternoon precipitation in eastern United States and Mexico enhanced by high evaporation. *Nature*, 4, 434-439, doi:10.1038/ngeo1174.

Ford, T. W., Rapp, A. D., and Quiring, S. M.: Does afternoon precipitation occur preferentially over dry or wet soils in Oklahoma?, *J. Hydrometeorol.*, doi: 10.1175,JHM-D-14-0005.1, 2015.

Ford, T. W., and Quiring, S. M.: Comparison and application of multiple methods for temporal interpolation of daily soil moisture. *Int. J. Clim.*, 34, 2604-2621, doi: 10.1002/joc.3862, 2014a.

Ford, T. W., and Quiring, S. M.: In situ soil moisture coupled with extreme temperatures: A study based on the Oklahoma Mesonet. *Geophys. Res. Lett.*, 41, 4727-4734, doi:10.1002/2014GL060949, 2014b.

Fritsch, J. M., Kane, R. J., and Chelius, C. R.: The contribution of mesoscale convective weather systems to the warm-season precipitation in the United States. *J. Appl. Clim. Meteor.*, 25, 1333-1345, doi:10.1175/1520-0450, 1986.

Frye, J. D. and Mote, T. L.: Convection initiation along soil moisture boundaries in the southern Great Plains. *Mon. Weather Rev.*, 138, 1140-1151, doi:10.1175/2009MWR2865.1, 2010a.

Frye, J. D., and Mote, T. L.: The synergistic relationship between soil moisture and the low-level jet and its role on the prestorm environment in the Southern Great Plaisn. *J. Appl. Meteor. Climat.*, 49, 775-791, doi:10.1175/2009JAMC2146.1, 2010b.

Gallus, W. A. Jr., Snook, N. A., and Johnson, E. V.: Spring and summer severe weather reports over the Midwest as a function of convective mode: A preliminary study, *Wea. Forecasting*, 23, 101-113, doi: 10.1175/2007WAF2006120.1, 2008.

Gentine, P., Holtslag, A.A.M., D'Andrea, F., and Ek, M.: Surface and atmospheric controls on the onset of moist convection over land. *J. Hydrometeorol.*, 14, 1443-1462, doi: 10.1175/JHM-D-12-0137.1, 2013.

Gong, X., and Richman, M. B.: On the application of cluster analysis to growing season precipitation data in North America East of the Rockies. *J. Clim.*, 8, 897-931, doi:10.1175/1520-0442, 1995.

Guillod, B. P., Orlowsky, B., Miralles, D., Teuling, A. J., Blanken, P. D., Buchmann, N., Ciais, P., Ek, M., Findell, K. L., Gentine, P., Lintner, B. R., Scott, R. L., Van den Hurk, B., and Seneviratne, S. I.: Land-surface controls on afternoon precipitation diagnosed from observational data: uncertainties and confounding factors. *Atmos. Chem. Phys.*, 14, 8343-8367, doi:10.5194/acp-14-8343-2014, 2014.

Illston, B. G., Basara, J. B., Fiebrich, C. A., Crawford, K. C., Hunt, E., Fisher, D. K., Elliott, R., and Humes, K.: Mesoscale monitoring of soil moisture across a statewide network. *J. Atmos. Ocean. Technol.*, 25, 167-182, doi: 10.1175/2007JTECHA993.1, 2008.

Joyce, R. J., Janowiak, J. E., Arkin, P. A., and Xie, P.: CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *J. Hydrometeorol.*, 5, 487-503, doi:10.1175/1525-7541, 2004.

Khong, A., Wang, J. K., Quiring, S. M., and Ford, T. W.: Soil moisture variability in Iowa, *Int. J. Clim.*, doi:10.1002/joc.4176, 2015.

Klimowski, B. A., Bunkers, M. J., Hjelmfelt, M. R., and Covert, J. N.: Severe convective windstorms over the Northern High Plains of the United States, *Wea. Forecasting*, 18, 502-519, doi: 10.1175/1520-0434, 2003.

Koster, R. D., Dirmeyer, P. A., Guo, Z., Bonan, G., Chan, E., Cox, P., Gordon, C. T., Kanae, S., Kowlczyk, E., Lawrence, D., Liu, P., Lu, C., Malyshev, S., McAvaney, B., Mitchell, K., Mocko, D., Oki, T., Oleson, K., Pitman, A., Sud, Y. C., Taylor, C. M., Verseghy, D., Vasic, R., Xue, Y. and Yamada, T.: Regions of strong coupling between soil moisture and precipitation, *Science*, 305, 1138-1140, doi:10.1126/science.1100217, 2004.

Koster, R. D., Mahanama, S. P. P., Yamada, T. J., Balsamo, G., Berg, A. A., Boisserie, M., Dirmeyer, P. A., Doblas-Reyes, F. J., Drewitt, G., Gordon, C. T., Guo, Z., Jeong, J. H., Lee, W. S., Li, Z., Luo, L., Malyshev, S., Merrfield, W. J., Senevirantne, S. I., Stanelle, T., van den Hurk, B. J. J. M., Vitart, F., and Wood, E. F.: The second phase of the Global Land-Atmosphere Coupling Experiment: soil moisture contributions to subseasonal forecast skill. *J. Hydrometeor.*, 12, 805-822, doi: 10.1175/2011JHM1365.1, 2011.

Lin, Y., and Mitchell, K.E.: The NCEP Stage II/IV hourly precipitation analyses: development and applications. *19th Conf. on Hydrology, American Meteorological Society*, San Diego, CA, 9 – 13 January 2005, Paper 1.2.

Matyas, C. J. and Carleton, A. M.: Surface radar-derived convective rainfall associations with Midwest US land surface conditions in summer seasons 1999 and 2000. *Theor. Appl. Clim.*, 99, 315-330, doi: 10.1007/s00704-009-0144-7, 2010.

McPherson, R. A.: A review of vegetation—atmosphere interactions and their influences on mesoscale phenomena. *Prog. Phys. Geogr.*, 31, 261-285, doi:10.1177/0309133307079055, 2007.

Meng, L. and Quiring, S. M.: Examining the influence of spring soil moisture anomalies on summer precipitation in the US Great Plains using the Community Atmosphere Model version 3. *J. Geophys. Res.*, 115, doi: 10.1029/2010JD014449, 2010.

Myoung, B. and Nielsen-Gammon, J. W.: The convective instability pathway to warm season drought in Texas. Part I: The role of convective inhibition and its modulation by soil moisture. *J. Clim.*, 23, 4461-4473, doi:10.1175/2010JCLI2946.1, 2010.

Pal, J. S. and Eltahir, E. A. B.: Pathways relating soil moisture conditions to future summer rainfall within a model of the land-atmosphere system. *J. Clim.*, 14, 1227-1242, doi:10.1175/1520-0442, 2001.

Parker, M. D., and Johnson, R. H.: Organizational models of midlatitude mesoscale convective systems, *Mon. Wea. Rev.*, 128, 3413-3436, doi: 10.1175/1520-0493, 2001.

Perry, G. L. W., Miller, B. P., and Enright, N. J.: A comparison of methods for the statistical analysis of spatial point patterns in plant ecology, *Plant. Ecol.*, 187, 59-82, doi:10.1007/s11258-006-9133-4, 2006.

Pielke, R. A.: Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Rev. Geophys.*, 39, 151–177, doi:10.1029/1999RG000072, 2001.

Potvin, C. K., Elmore, K. L., and Weiss, S. J.: Assessing the impacts of proximity sounding criteria on the climatology of significant tornado environments. *Wea. Forecast.*, 25, 921-930, doi:10.1175/2010WAF2222368.1, 2010.

Raddatz, R. L., and Hanesiak, J. M.: Significant summer rainfall in the Canadian Prairie Provinces: modes and mechanisms 2000 – 2004. *Int. J. Clim.*, 28, 1607-1613, doi: 10.1002/joc.1670, 2008.

Ramos, M. C.: Divisive and hierarchical clustering techniques to analyse variability of rainfall distribution patterns in a Mediterranean region. *Atmos. Res.*, 57, 123-138, doi:10.1016/SO169-8095, 2001.

Roundy, J. K., Ferguson, C. R., Wood, E.F.: Temporal variability of land–atmosphere coupling and its implications for drought over the Southeast United States. *J. Hydrometeorol.*, 14, 622-635, doi:10.1175/JHM-D-12-090.1, 2013.

Santanello, J. A., Peters-Lidard, C. D., Kumar, S. V., Alonge, C., and Tao, W.: A modeling and observational framework for diagnosing local land-atmosphere coupling on diurnal time scales. *J. Hydrometeor.*, 10, 577-599, doi:10.1175/2009JHM1066.1, 2009.

Santanello, J. A., Peters-Lidard, C. D., and Kumar, S. V.: Diagnosing the sensitivity of local land-atmosphere coupling via the soil moisture-boundary layer interaction. *J. Hydrometeorol.*, 12, 766-786, doi: 10.1175/JHM-D-10-05014.1, 2011.

Santanello, J. A., and Peters-Lidard, C. D.: Diagnosing the nature of land-atmosphere coupling: A case study of dry/wet extremes in the U.S. Southern Great Plains. *J. Hydrometeorol.*, 14, 3-24, doi:10.1175/JHM-D-12-023.1, 2013.

Schoen, J. M., and Ashley, W. S.: A climatology of fatal convective wind events by storm type. *Wea. Forecasting*, 26, 109-121, doi:10.1175/2010WAF2222428.1, 2011.

Scott, B. L., Ochsner, T. E., Illston, B. G., Fiebrich, C. A., Basara, J. B., and Sutherland, A. J.: New soil property database improves Oklahoma Mesonet soil moisture estimates. *J. Atmo. Ocean. Tech.*, 30, 2585-2595, doi: 10.1175/TECH-D-13-00084.1, 2013.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Sci. Rev.*, 99, 125-161, doi:10.1016/j.earscirev.2010.02.004, 2010.

Taylor, C. M., de Jeu, R. A., Guichard, F., Harris, P. P., and Dorigo, W. A.: Afternoon rain more likely over drier soils, *Nature*, 489, 423-426, doi:10.1038/nature11377, 2012.

Taylor, C. M. and Lebel, T.: Observational evidence of persistent convective-scale rainfall patterns, *Mon. Weather Rev.*, 126, 1597-1607, doi: 10.1175/1520-0493.

Teuling, A. J., Seneviratne, S. I., Williams, C., and Troch, P. A.: Observed timescales of evapotranspiration response to soil moisture. *Hydrol. Land Surf. Stud.*, 33, doi:10.1029/2006GL028178, 2006.

Wu, W. and Dickinson, R. E.: Time scales of layered soil moisture memory in the context of land-atmosphere interaction. *J. Clim.*, 17, 2752-2764, doi:10.1175/1520-0442, 2004.

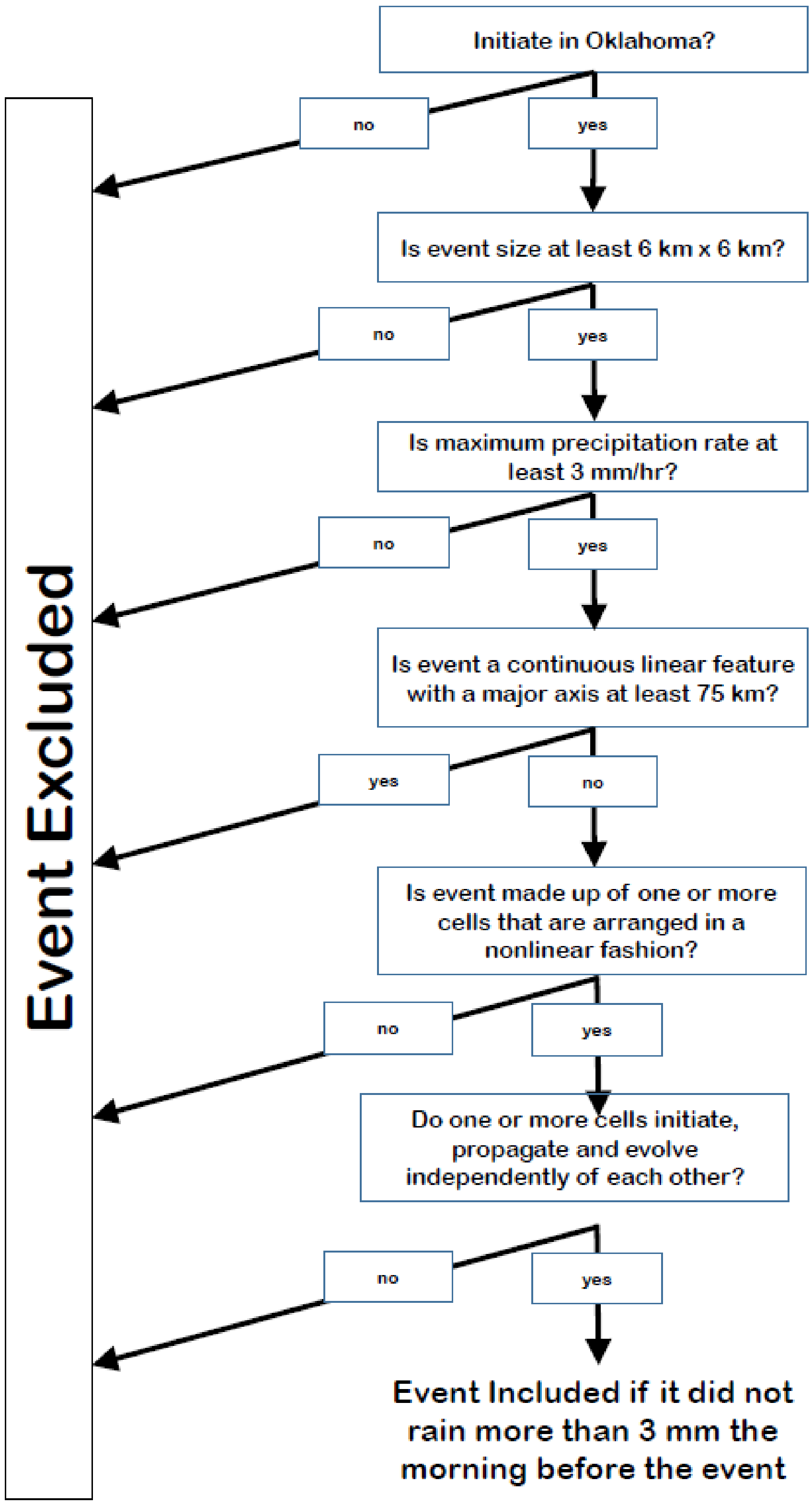


Figure 1. Schematic of the decision tree that was used for manual identification of unorganized convective events.

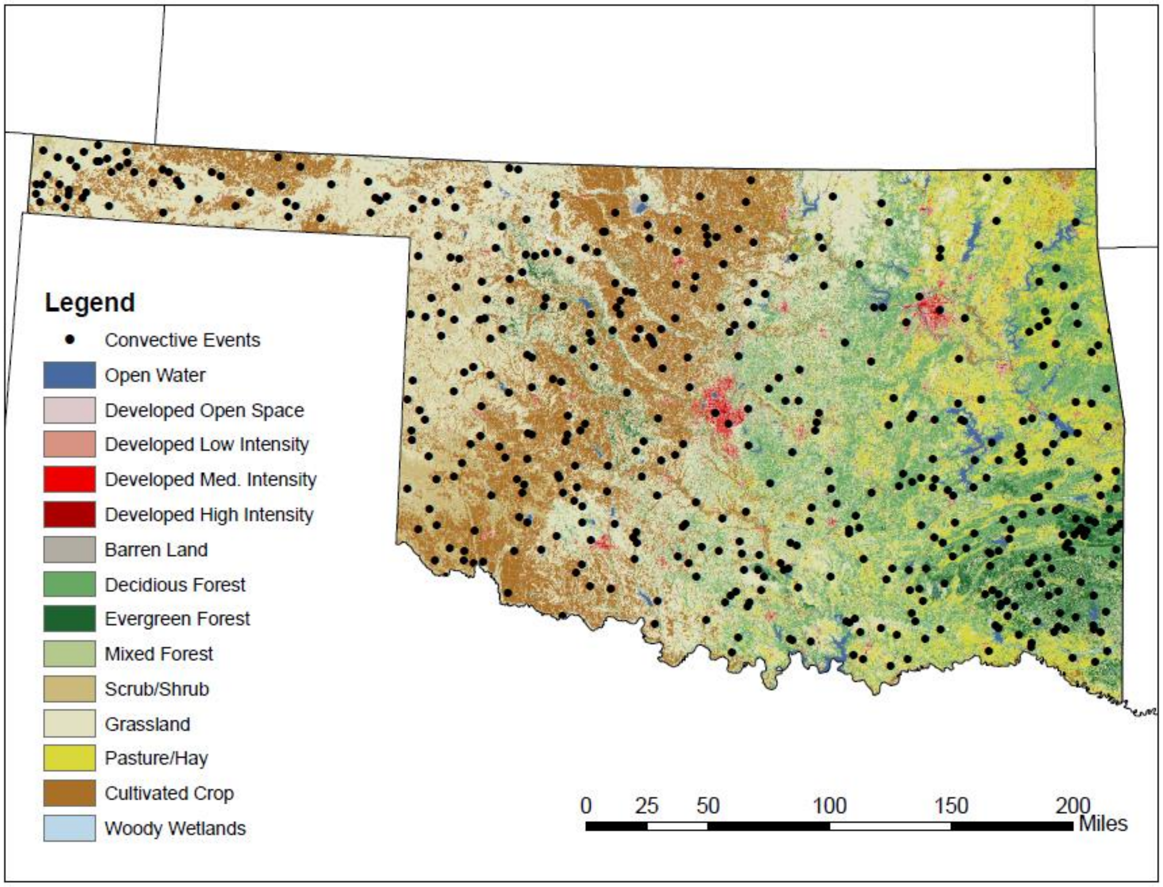


Figure 2. Location of all 477 convective events (black circles) identified between May and September, 2002 - 2012. The land cover, taken from the National Land Cover Dataset (http://www.mrlc.gov/), is also shown.

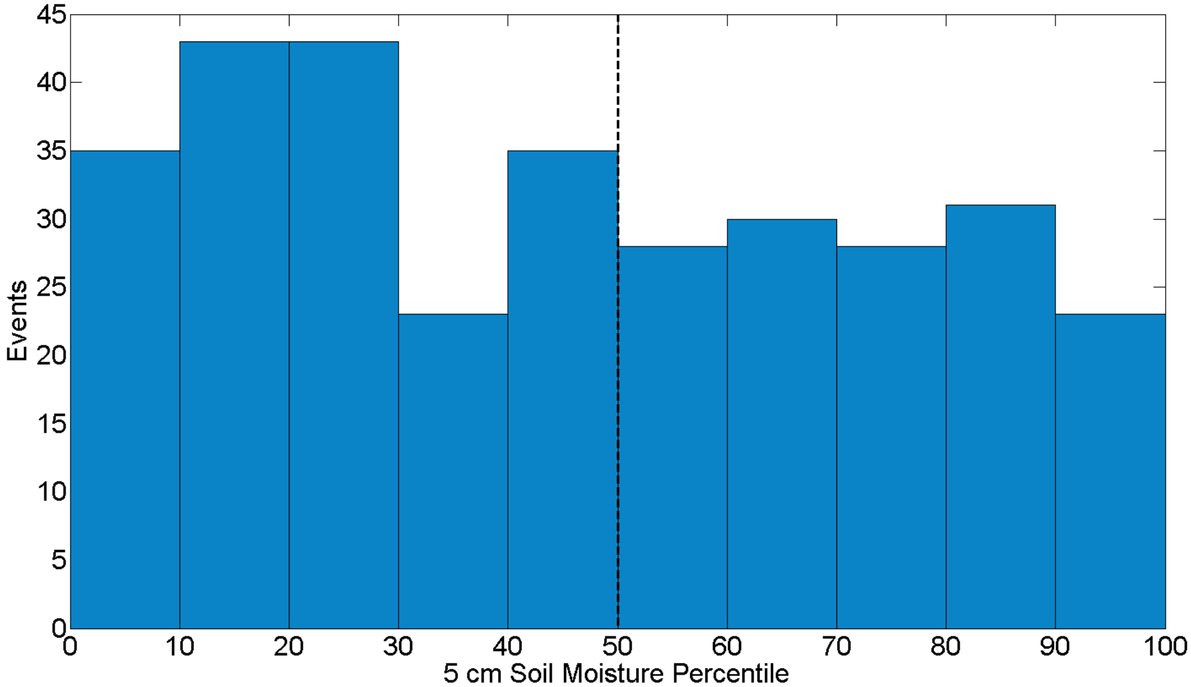


Figure 3. Top panel (a) shows the distribution of 5 cm soil moisture percentiles underlying all convective events identified. The dashed-black line represents the divide between relatively wet (> 50 percentile) and relatively dry (< 50 percentile) soils. The bottom panel (b) shows the distribution of differences between soil moisture associated with the location of precipitation initiation and each of the neighboring grid cells in a 3 x 3 window. Negative values represent conditions where soil moisture was lower at the location of precipitation initiation and higher in the neighboring grid cell.

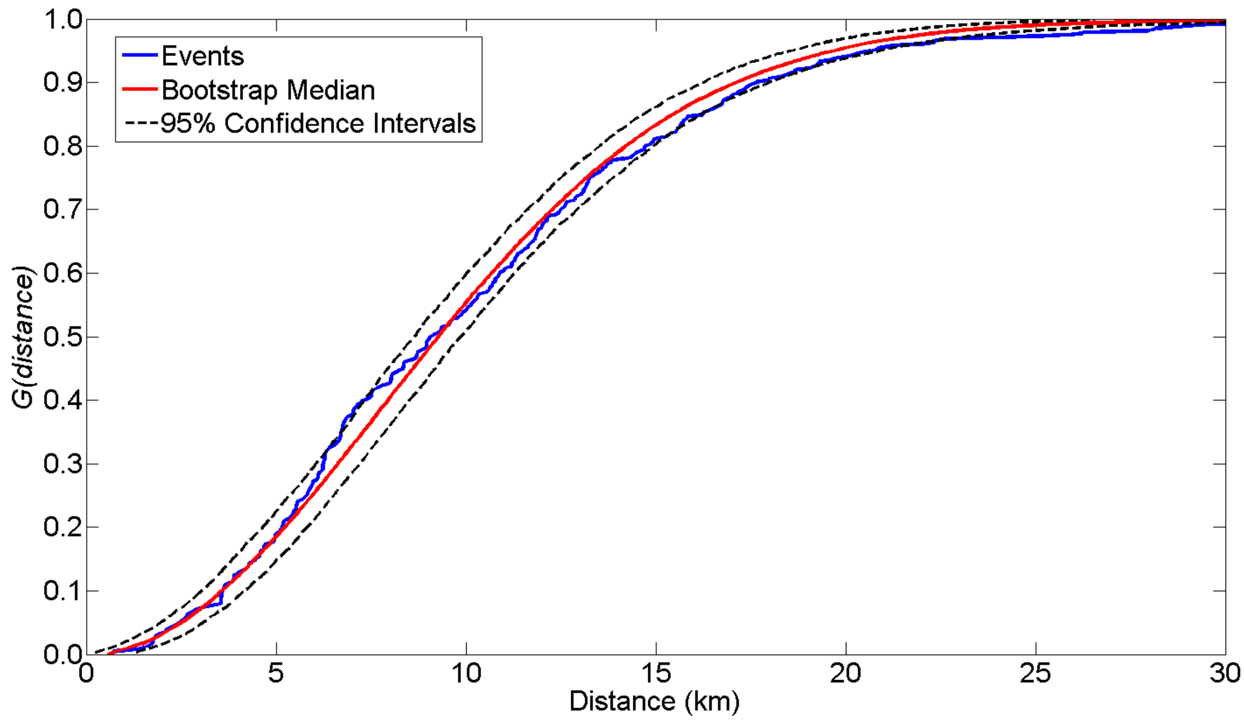
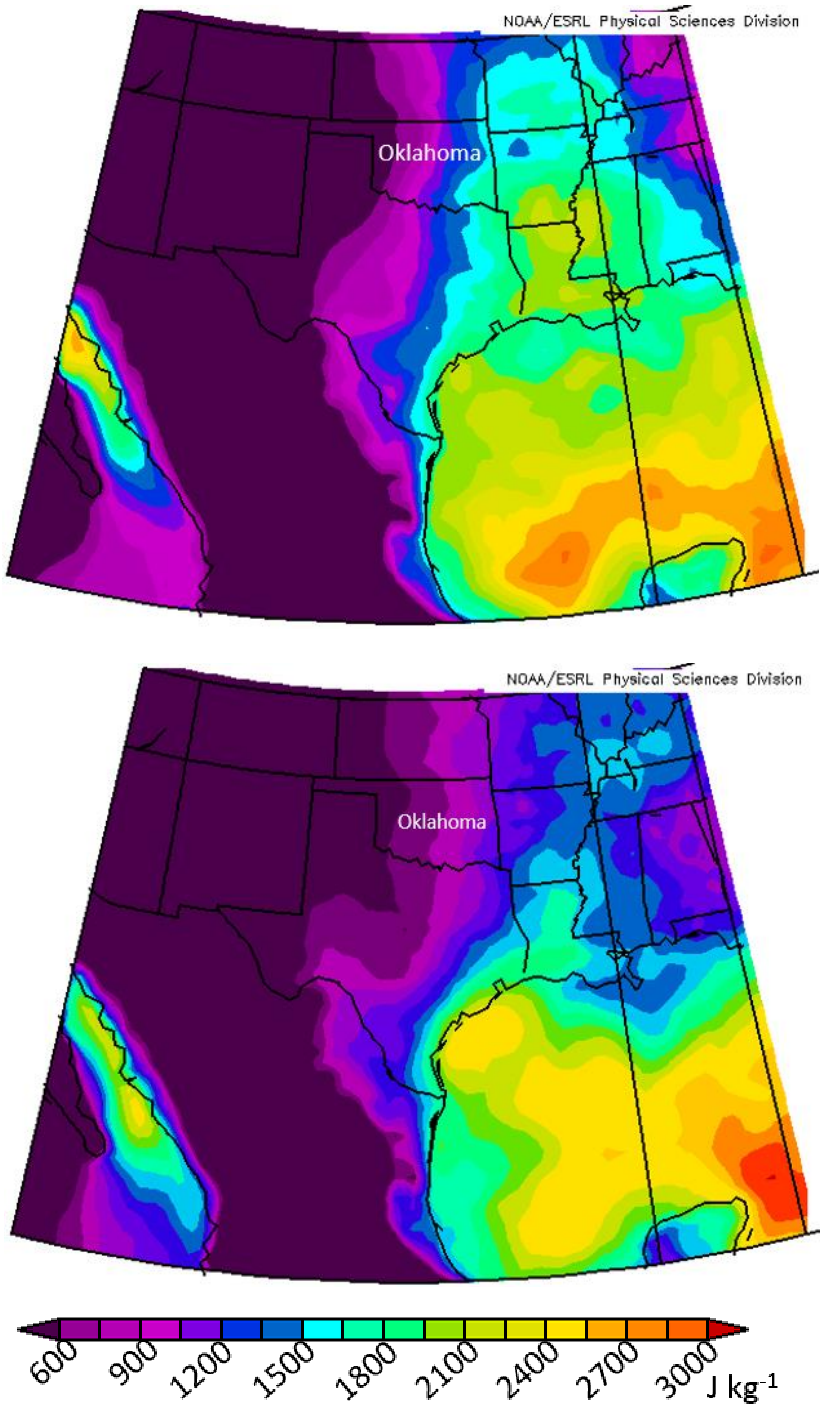


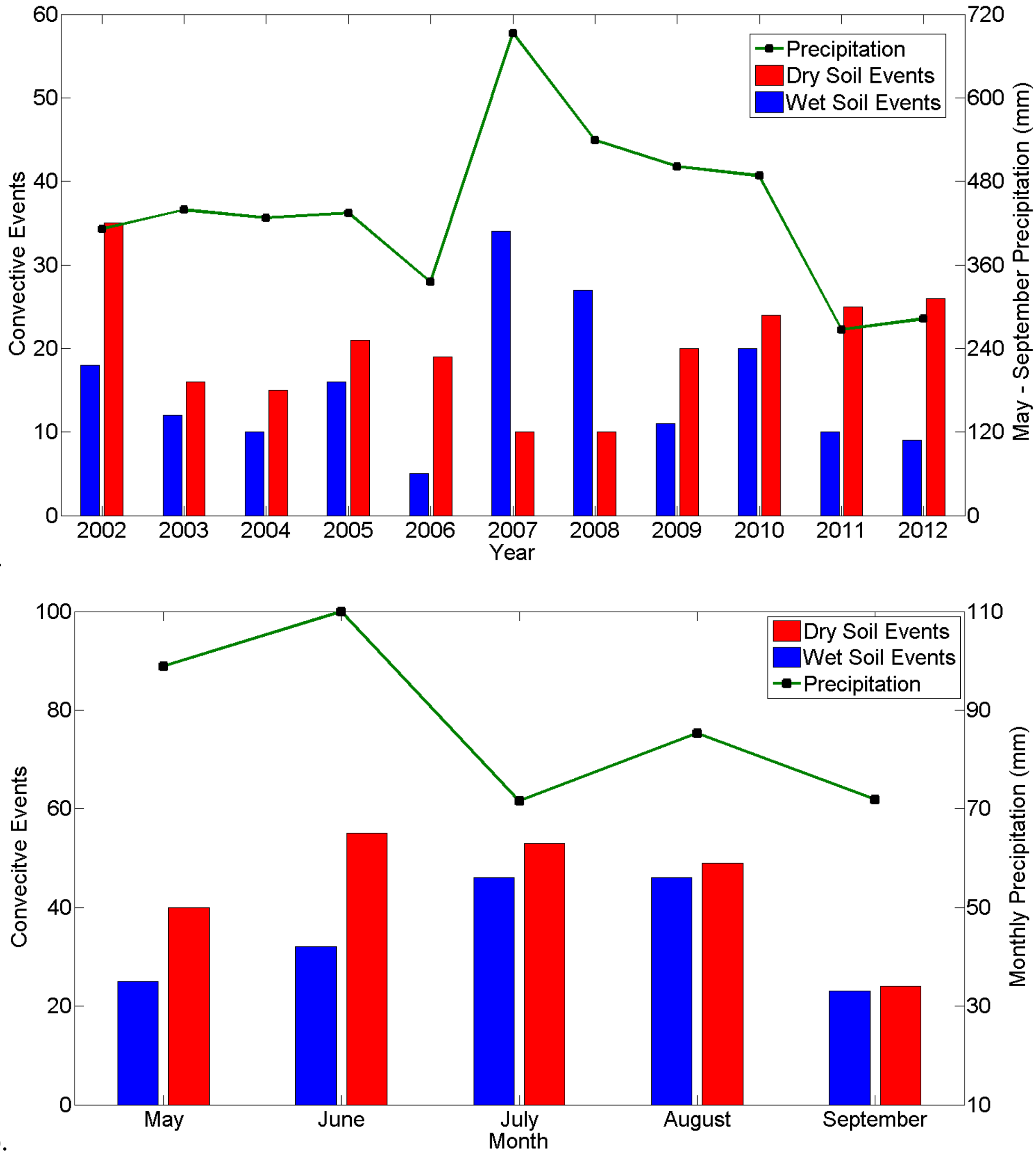
Figure 4. Cumulative distribution functions of nearest neighbor distances for all unorganized convective events (blue line), the bootstrapped median (red line) and 95% confidence envelopes (black lines). The bootstrapped samples are calculated from 1,000 iterations of 477 random events.



a.

b.

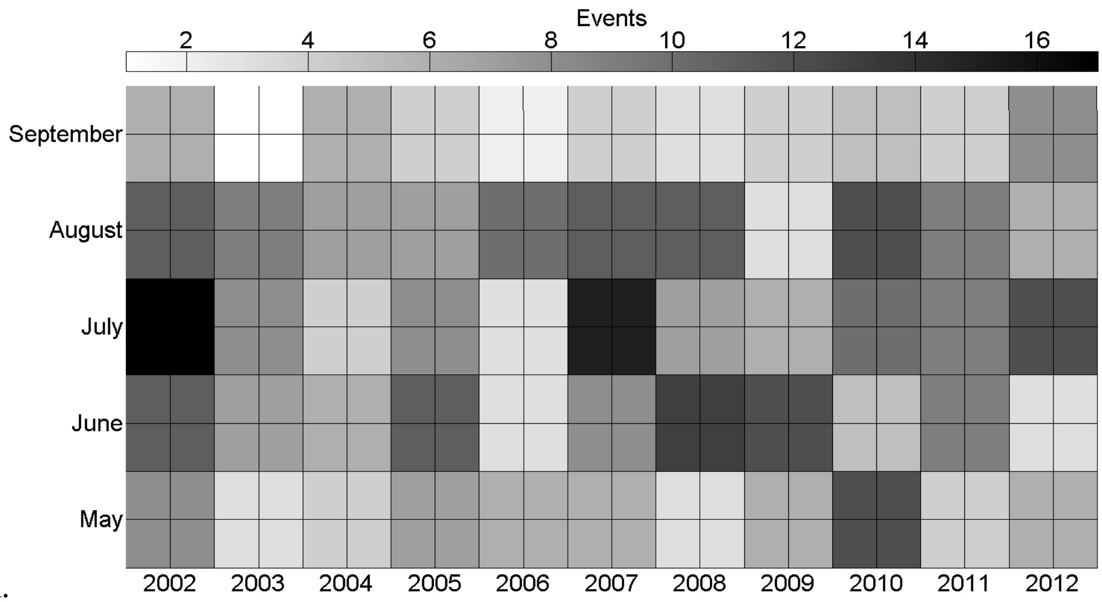
Figure 5. Composites of morning (0600 LST) convective available potential energy from (a) events clustered in southeast corner of the study region and (b) all other convective events.



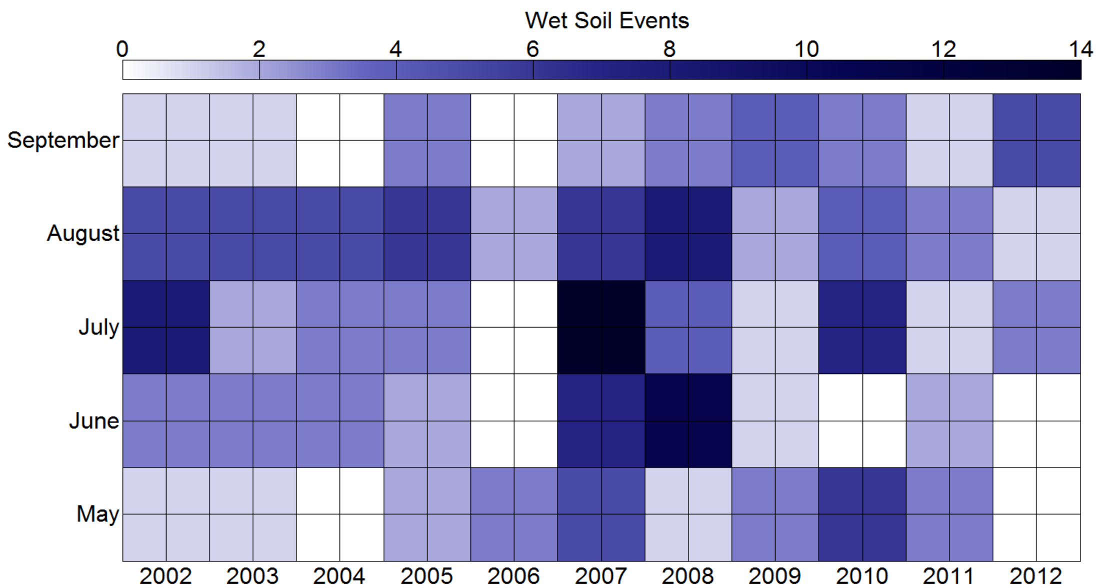
a.

b.

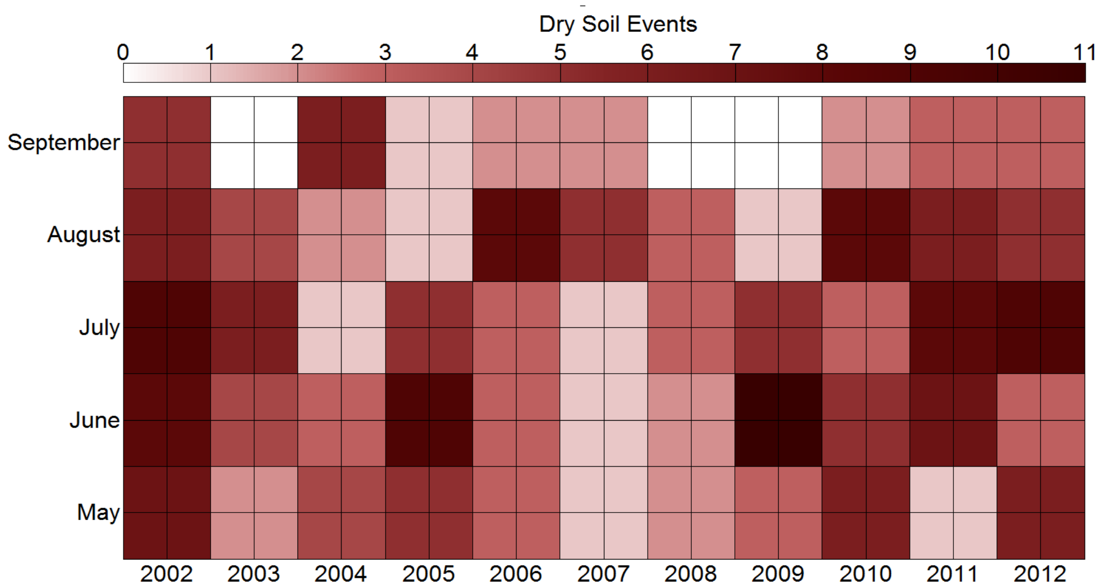
Figure 6. Top panel (a) shows the frequency of dry and wet events during each warm season between 2002 and 2012, as well as the total May – September precipitation (mm) for each year. The bottom panel (b) shows the monthly variability of all events, color-coded into dry and wet categories, as well as average (2002 – 2012) monthly precipitation (mm).


Events
2
4
6
8
10
12
14
16
September
August
July
June
May
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

a.


Wet Soil Events
0
2
4
6
8
10
12
14
September
August
July
June
May
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012

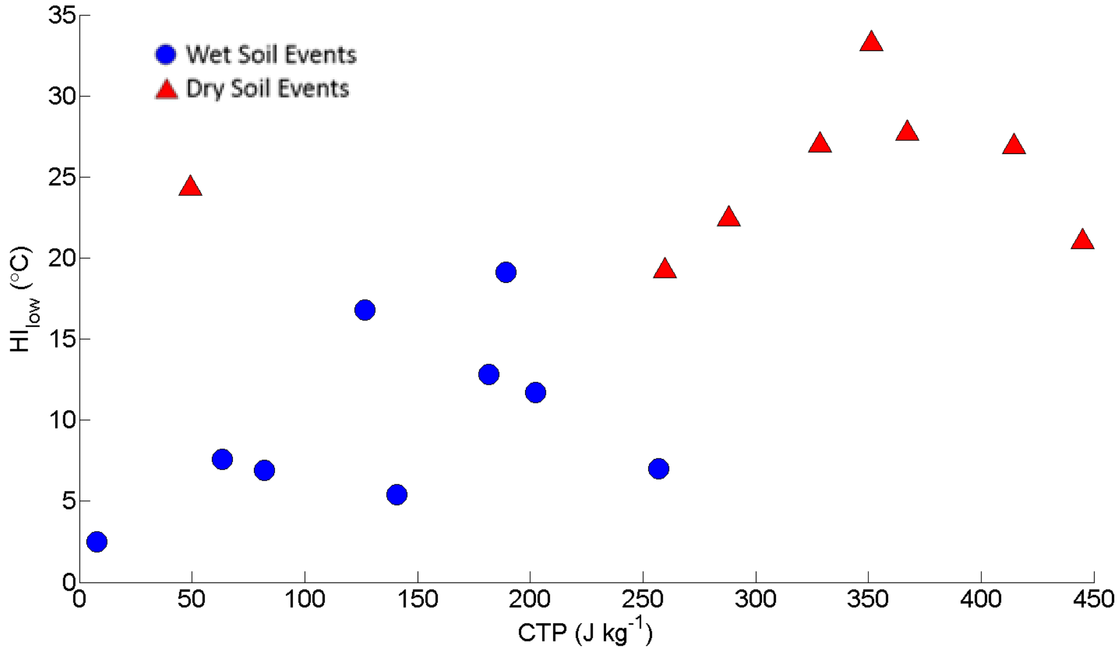
b.



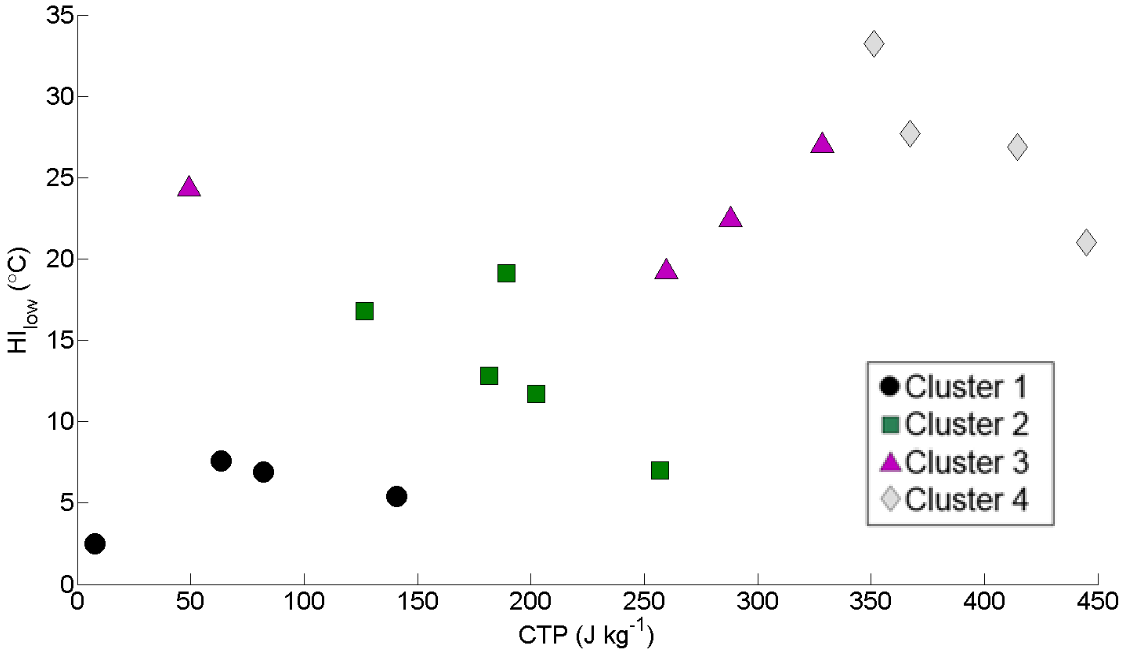
784 c.

785 **Figure 7**. Frequency of unorganized convective events in each month during the 2002-2012
786 study period. The top panel represents all events, the middle panel is the wet events and the
787 bottom panel is the dry events.

788

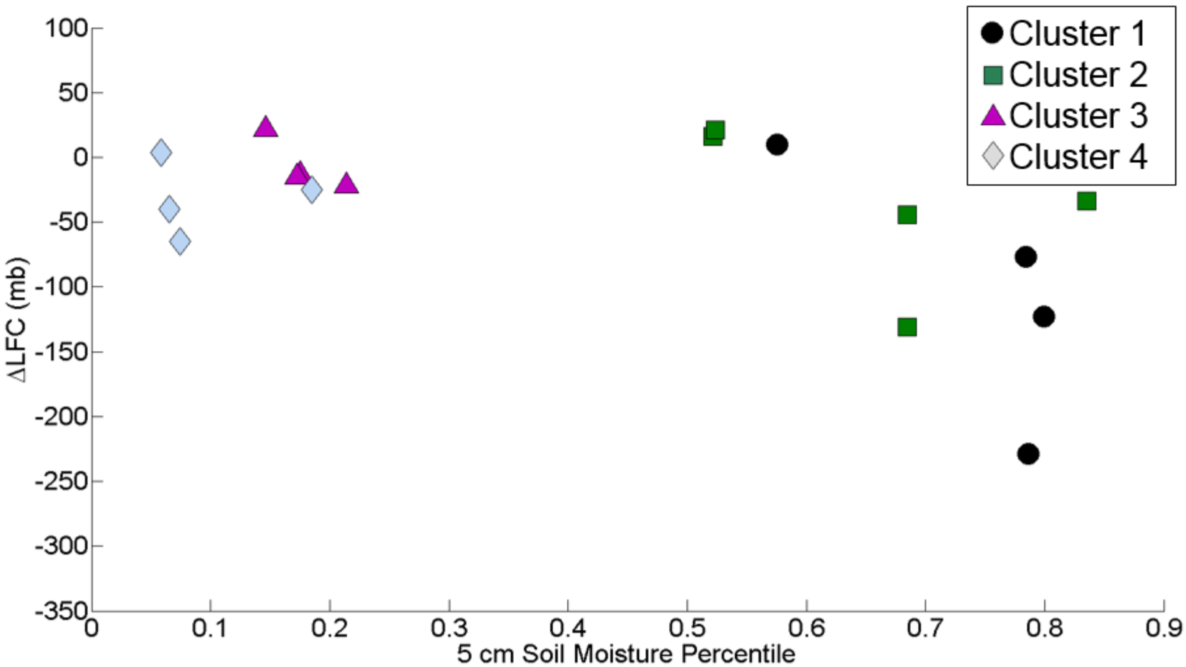


a.



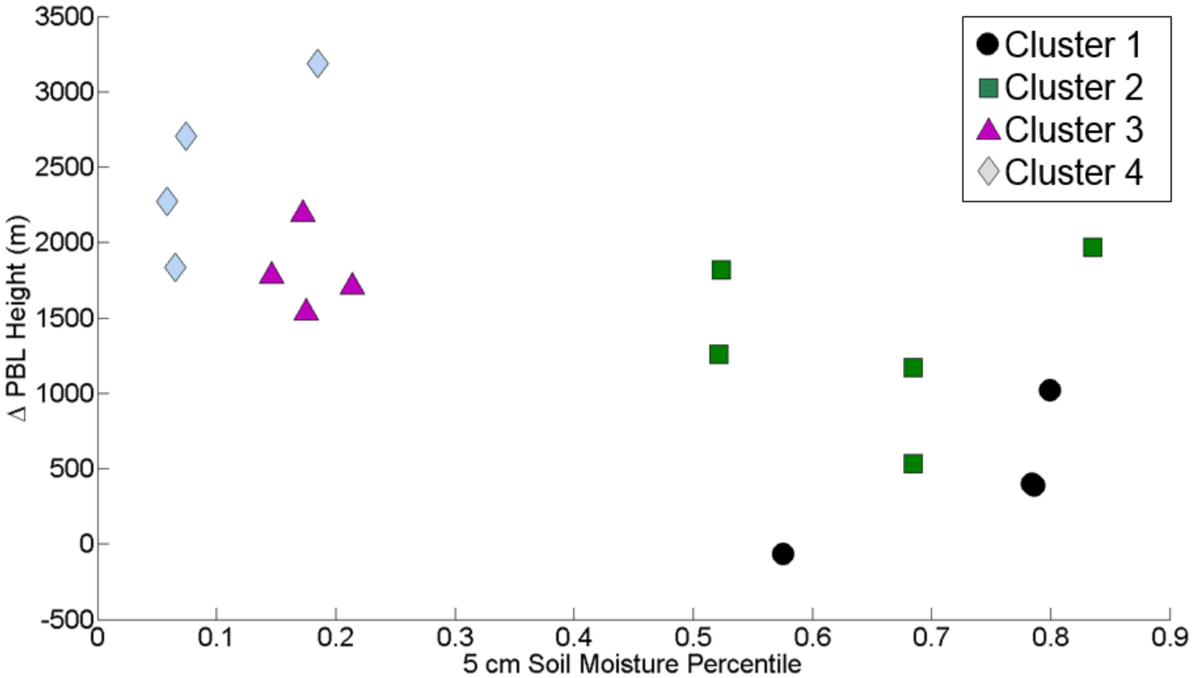
b.

Figure 8. Scatter plots of the 17 unorganized convective events that occurred near Lamont, OK in dual (0600 LST) convective triggering potential (J kg^{-1}) – humidity index (°C) space: (a) wet events are denoted by the blue circle and dry events are denoted by a red triangle. (b) Events are grouped into 4 clusters.



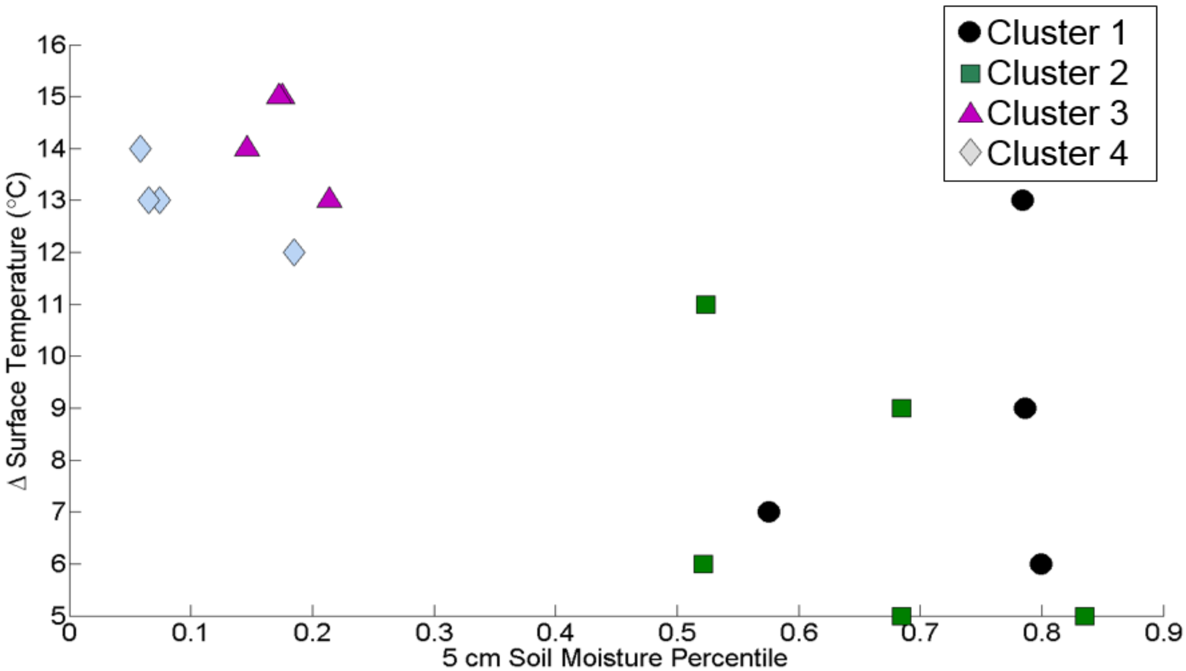
ΔLFC (mb)
5 cm Soil Moisture Percentile
Cluster 1
Cluster 2
Cluster 3
Cluster 4
100
50
0
-50
-100
-150
-200
-250
-300
-350
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

a.

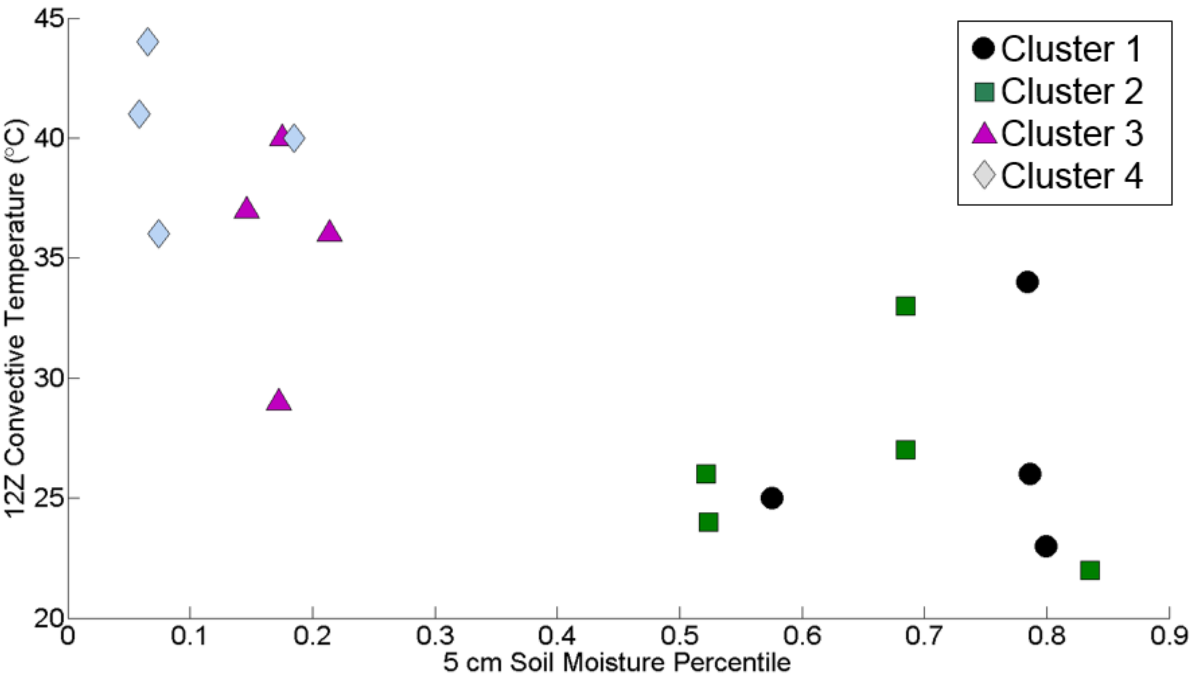


Δ PBL Height (m)
5 cm Soil Moisture Percentile
Cluster 1
Cluster 2
Cluster 3
Cluster 4
3500
3000
2500
2000
1500
1000
500
0
-500
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9

b.

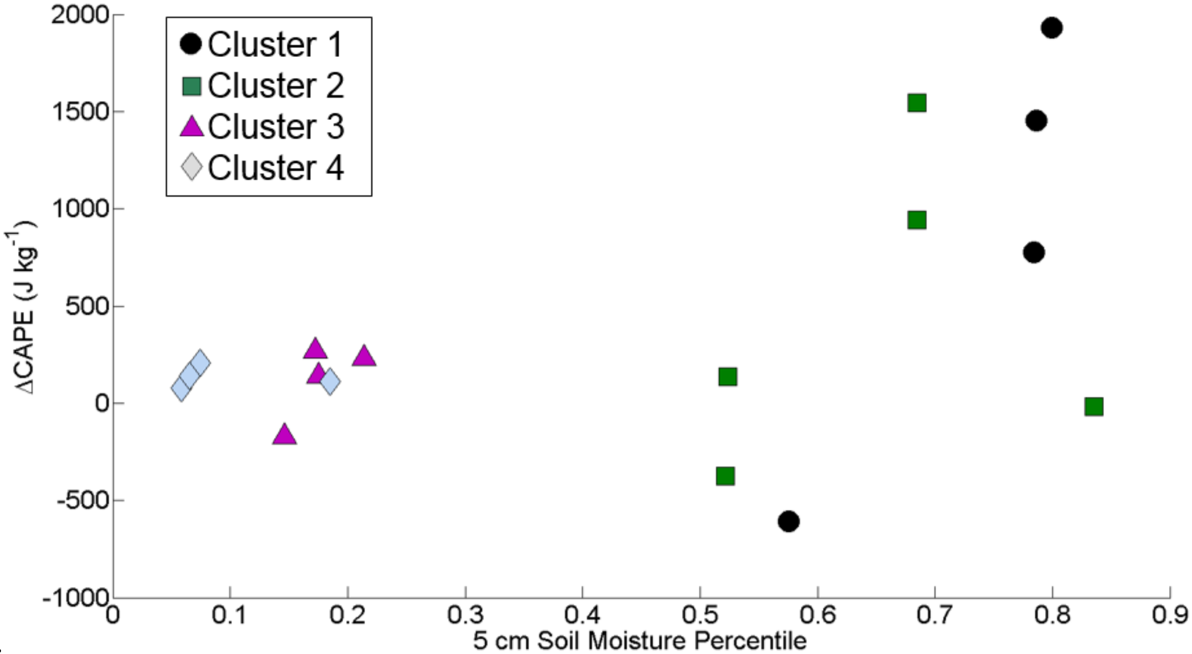


c.

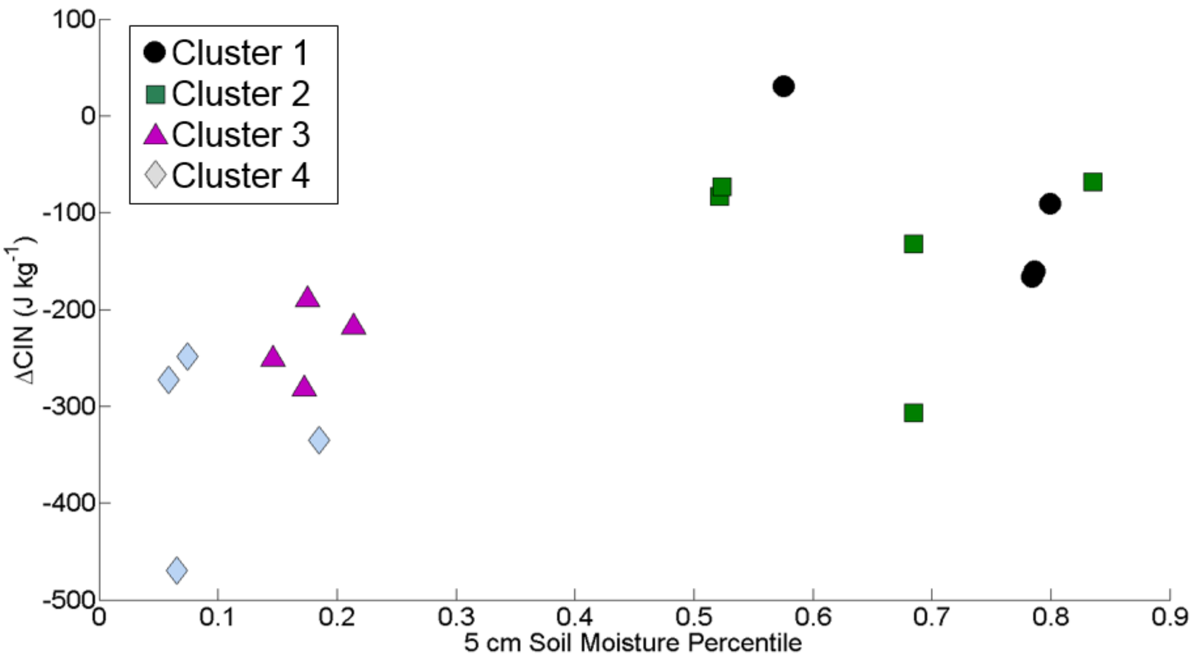


d.

Figure 9. Scatter plots of soil moisture percentiles and atmospheric conditions 17 unorganized convective events that occurred near Lamont, OK: (a) soil moisture percentiles versus changes in LFC height, (b) soil moisture percentiles versus changes in PBL height, (c) soil moisture percentiles versus surface temperature, and (d) soil moisture percentiles versus 1200 UTC convective temperature.



a.



b.

Figure 10. Scatter plots of soil moisture percentiles and (a) the change in convective available potential energy and (b) the change in convective inhibition between 0600 and 1200 LST. Events shown here occur within 50 km of Lamont, Oklahoma.

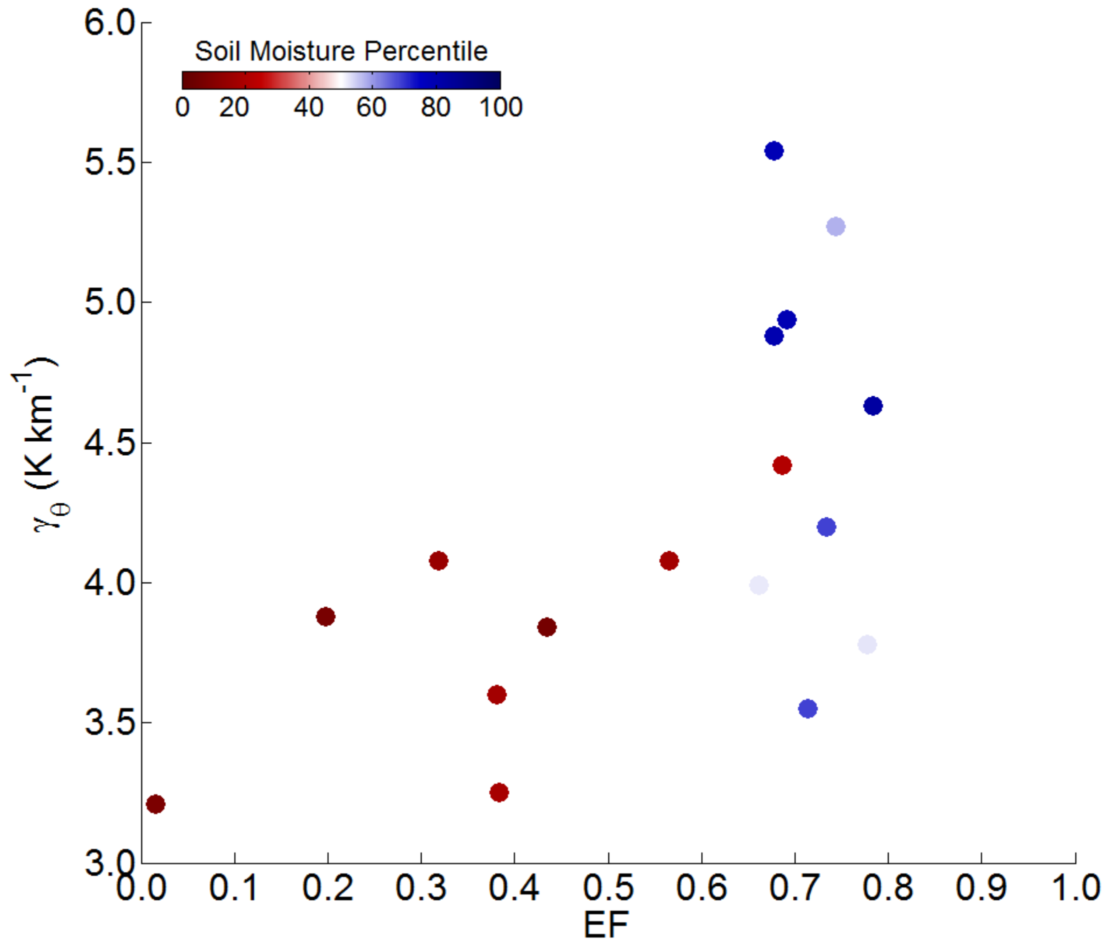


Figure 11. Convective events over Lamont, Oklahoma in terms of 1200 LST atmospheric stability (γ_θ,) and surface evaporative fraction. The scatter points are colored based on the 5 cm soil moisture percentile underlying each convective event.

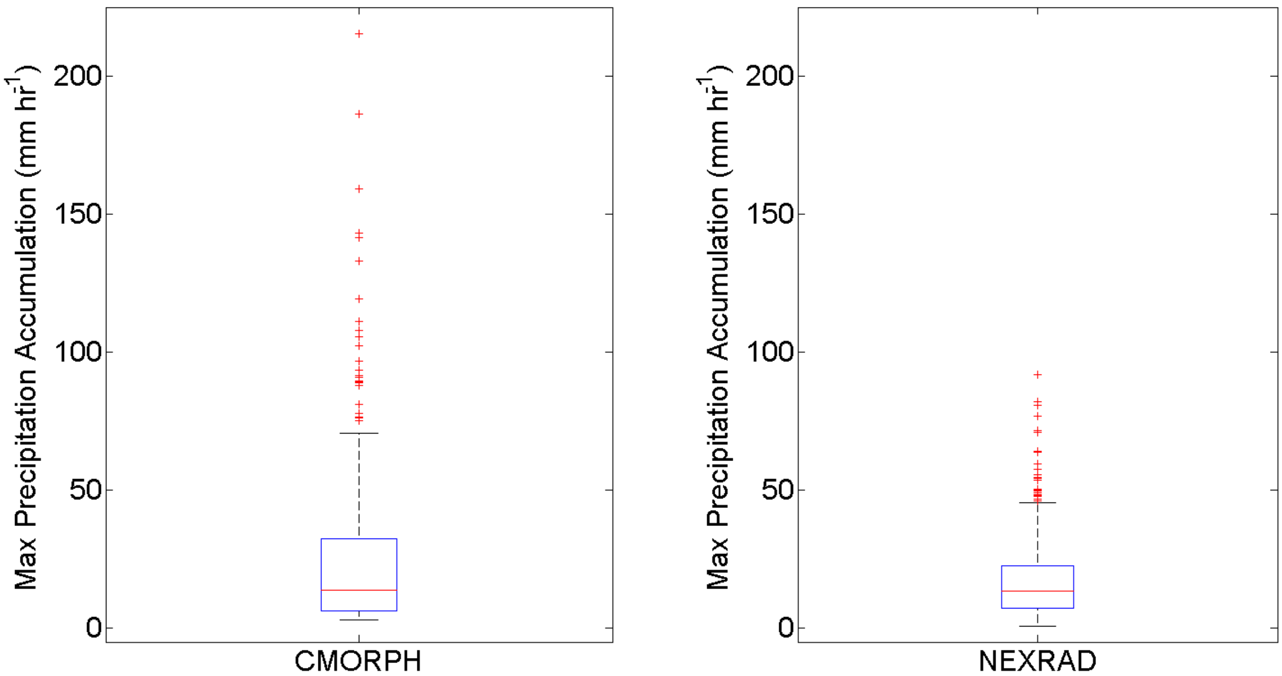


Figure 12. Maximum precipitation accumulation rates (mm hr^{-1}) composited from (left panel) 353 events identified by Ford *et al.* (in press) using CMORPH and (right panel) 477 events identified in this study with NEXRAD.

Table 1. Mean atmospheric conditions at 0600 and 1200 LST from atmospheric soundings, averaged by event cluster. Conditions summarized include convective available potential energy (J kg^{-1}), convective inhibition (J kg^{-1}), the level of free convection (mb), convective temperature (C), and the height of the planetary boundary layer (m). Mean convective event duration (hrs), size (pixels) and precipitation accumulation (mm) are composited by cluster as well.

Cluster	1	2	3	4
Soil Moisture (percentile)	0.74	0.65	0.18	0.10
CAPE-12Z (J kg-1)	1634.50	686.60	366.75	96.50
CAPE-18Z (J kg-1)	2522.50	1133.00	485.00	231.00
CIN-12Z (J kg-1)	144.70	190.20	324.00	426.50
CIN-18Z (J kg-1)	48.12	57.60	88.75	94.75
LFC-12Z (mb)	717.50	730.20	649.75	594.75
LFC-18Z (mb)	822.25	764.60	656.75	626.25
ConvTemp-12Z (°C)	27.00	26.40	35.50	40.25
PBL-12Z (m)	305.26	438.98	370.02	629.00
PBL-18Z (m)	743.70	1788.28	2173.84	3128.63
Event Duration (hrs)	4.25	3.25	3.75	2.75
Event Size (pixels)	23.00	10.75	18.5	7.25
Total Event Accumulation (mm)	1748.05	395.97	546.40	77.66