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precipitation  
coupling**

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# Soil moisture–precipitation coupling: observations from the Oklahoma Mesonet and underlying physical mechanisms

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## 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.

5 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, high resolution NEXRAD radar-derived precipitation to identify convective events, and then compare the location of precipitation initiation to underlying soil moisture anomalies the morning prior. 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 products to identify the region of maximum precipitation accumulation. We sub-sample 15 19 convective events occurring near Lamont, Oklahoma, where soundings of the atmospheric profile at 06:00 and 12:00 LST are also available. For these events, soil moisture is strongly, negatively correlated with the level of free convection, planetary boundary layer height, and surface temperature changes from 06:00 to 12:00 LST. We also find strong, positive correlations between morning soil moisture and morning-to-20 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 the atmosphere are relevant in this region of the United States.

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# 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. 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.

Land surface modification of the atmosphere consists of changes in the height of the lifting condensation level (LCL) and the potential for deep convection to initiate (Brimelow et al., 2011). The height of the afternoon LCL and level of free convection (LFC) are decreased with sufficient moisture flux from a wet land surface to the low-level atmosphere, which then erodes convective inhibition (CIN) and increases convective available potential energy (CAPE). These mechanisms act as a wet (positive) soil moisture precipitation feedback in which wetter than normal soils enhance atmospheric instability and strengthen the probability of subsequent convective precipitation (Findell et al., 2011). Conversely, increased sensible heating over drier than normal soils leads

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to increased LCL and LFC heights, which can enhance atmospheric stability (Frye and Mote, 2010a). However, enhanced surface heating over dry soils also increases planetary boundary layer (PBL) growth rate, and can more quickly erode capping inversions and CIN to increase the probability of deep convection. If the PBL can reach the LFC, deep convection can be initiated over drier than normal soils, albeit with generally less CAPE than convection generated over wet soils (Santanello et al., 2009). Convective initiation over drier than normal soils, following these mechanisms, is considered a dry (negative) soil moisture feedback.

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 US. 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 US 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 US 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). In contrast, observations have suggested both positive (Frye and Mote, 2010b) and negative (Santanello et al., 2013) soil moisture–precipitation feedbacks in this region. Taylor et al. (2012) found no preference for convective precipitation to fall over relatively wet or dry soils in the Southern Great Plains, suggesting the lack of significant soil mois-

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ture feedback on precipitation in the region. In contrast, Guillod et al. (2014) found that interactions between evaporative fraction and precipitation were connected to soil moisture in the Southern Great Plains. Ford et al. (2015) composite station-based soil moisture observations underlying afternoon precipitation events in Oklahoma, and find a significant preference for precipitation initiation over wetter than normal soils. The conflicting results from these and other studies are mostly attributable to the breadth of datasets and methodologies employed. However, based on the predominant literature, 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 land–atmosphere studies are uniquely capable of documenting land–atmosphere interactions while simultaneously accounting for region-specific factors which could confound the results. However, mesoscale soil moisture monitoring networks are uncommon. This study uses 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.

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## 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. Daily soil moisture observations from the Mesonet are high quality (Scott et al., 2013), and soil moisture monitoring station density in Oklahoma is among the highest in North America.

Daily (9 a.m.) 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 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.) 5 July 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  $0.25^\circ$  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.

### 2.2 Precipitation event identification

The majority of precipitation in the central United States is caused by stratiform or frontal activity (Raddatz and Hanesiak, 2008; Carleton et al., 2008). In these cases, moisture is advected into the region by mid-latitude cyclones or fronts, and synoptic-scale atmospheric conditions are not conducive to surface-modified convection (Matyas and Carleton, 2010). Therefore, analyzing the influence of soil moisture

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on those precipitation events will likely result in a weak or nonexistent relationship. Unorganized convection, as defined by Carleton et al. (2008), includes isolated convective events which occur in the absence of strong, synoptic-scale atmospheric forcing. Separating these afternoon precipitation events from those forced by synoptic-scale atmospheric processes will help to remove confounding factors (i.e., noise), and potentially 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 h (temporal) and  $0.25^\circ$  (spatial) resolution. Their precipitation event detection methodology (also implemented by Ford et al., 2015) identifies the grid cell that resides within a  $1.25^\circ \times 1.25^\circ$  box in which the maximum amount of precipitation occurred. It also identifies the grid cell(s) within the same  $1.25^\circ \times 1.25^\circ$  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 h 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.

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

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ergy. We use a cluster analysis 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 (06:00 LST) convective triggering potential and low level humidity conditions (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. Atmospheric stability measures combined with changes in atmospheric humidity and temperature are linked to underlying soil moisture conditions for the events surrounding Lamont. In this study, 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: Sect. 3 describes the preference for convection to occur over wet or dry soils, connections between soil moisture and atmospheric conditions are presented in Sect. 4, and Sect. 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 bins with percentiles ranging from 0 to 30 with the highest number of events are the driest soil bins.

We evaluate the statistical significance of the preference for precipitation initiation over dry soils using a bootstrapping methodology adopted from Ford et al. (2015). The procedure compares the frequency of convective events over dry and wet soils to the frequency of dry and wet soils from 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. If, for example, the frequency of convective events over dry soils represents the 98th percentile of the frequency distribution, then the probability of achieving that frequency from 477 randomly selected days is 2%. Based on this evaluation, the number of events that were 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.

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* and not just the location of maximum accumulation, and (2) the ability to discern between unorganized and larger-scale organized systems. 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

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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) are most likely due to differences in the data sets and methods used to identify events. A reanalysis of convective events identified in Ford et al. (2015) using methods adopted from Taylor et al. (2012) found that large-scale thunderstorms due to frontal activity, low pressure systems, and even tropical storms were grouped together with meso-scale unorganized convective events (Wang et al. in review). The ability to detect soil moisture impacts on convective precipitation initiation is hindered when analyzing events due to frontal activity and tropical storms, as these events do not actually initiate over the study region. The results presented in the present study, however, accurately identify unorganized convective events and 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 (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 event 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 is then compared against the theoretical distribution of distances generated from a sample of randomly generated points, the same size as the number of events. We use a bootstrapping procedure to iteratively generate 1000 samples of  $n$  random points ( $n = 477$ ) in Oklahoma. From this dataset, the 50th, 97th and 3rd percentile distributions are generated to represent the median and the confidence interval envelopes, respectively. If the shape of the convective event distribution falls within

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the interval envelopes (95% confidence intervals), the events are assumed to exhibit complete spatial randomness.

Figure 4 shows the cumulative distribution functions of nearest neighbor distances for the 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 is therefore concluded to exhibit complete spatial randomness. We repeated this analysis for only wet and only dry events, and both groups also exhibited statistically significant spatial randomness.

Despite the result 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 could 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 ( $\text{Jkg}^{-1}$ ) (Fig. 5). The left panel of Fig. 5 shows 09:00 LST CAPE composited from the events that are clustered in the southeast corner of the state, while the right panel shows 09:00 LST CAPE composited from all other events. 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 goes to increase the probability of convection, and could perhaps 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. Figure 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

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(<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. Concurrently, the years with the highest dry soil to wet soil event ratios (2002, 2006, 2011, 2012) experienced the four lowest seasonal precipitation totals. Interestingly, the total number of events per year does not seem to be connected to the seasonal precipitation totals, as a similar number of events occurred in the very dry 2011 season (28) as the wet 2008 season (29). Figure 6b shows the monthly variability of total events, broken into dry and wet. Overall 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, Fig. 7b and c is 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 is broken, however in 2007 and 2008 with a considerable increase in wet event frequency for nearly all months except September and May to a lesser extent. These two very wet years are followed by a pattern more or less similar to that of the first 5 years of the dataset. The wet event increase in 2007 and 2008 corresponds with a simultaneous decrease in dry events over the same time period. The warm season in 2007 was the 2nd wettest on record in Oklahoma, with total precipitation more than 237 mm in excess of the 30 year mean. Although the same time period in 2008 was less anomalous (25th wettest on record), precipitation was still > 75 mm above the mean. The abundant precipitation

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during these two warm seasons led to near-saturated soils for the majority of the time and therefore explains why convection was preferably initiated over wetter than normal soils.

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 exhibits considerable inter-annual and monthly variability. Wet soil events occurred most frequently in August during years with less-than-normal to normal precipitation. Seasons with dry and near-normal rainfall conditions coincided with a higher dry to wet event ratio, while convection over wet soils dominated during seasons with anomalously large precipitation totals.

### 3.4 Atmospheric pre-conditioning to convection

Our analysis 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. This section investigates the physical mechanisms that link the land surface and atmosphere. To do this, we composited convective events occurring within 50 km of Lamont, Oklahoma, where atmospheric soundings are taken daily at 06:00 and 12:00 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 over which convection occurred showed the same anomaly (wet or dry) as the Lamont grid cell. Based on these criteria, 19 events were selected for analysis.

The goal of this analysis is to document the differences in atmospheric conditions between 06:00 and 12:00 LST preceding convection and to account for atmospheric preconditioning to convection occurring over wet soils and that occurring over dry soils.

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We used the combined indices of convective triggering potential (CTP,  $\text{J kg}^{-1}$ ) and low-level humidity (HI,  $^{\circ}\text{C}$ ), adopted from Findell and Eltahir (2003) to distinguish events with a morning atmosphere preconditioned for convection over wet soils, dry soils, or convection regardless of the land surface. CTP is derived as the integrated area between the environmental temperature profile and a moist adiabat from 900 to 700 mb. The HI 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 (2003) 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, dry soils can decrease CIN, and increase PBL height through enhanced surface heating, while wet soils can increase CAPE and decrease the LFC height through enhanced moisture flux (Brimelow et al., 2011). Therefore morning (06:00 LST) atmospheric profiles and CTP-HI conditions over dry and wet soils are expected to be noticeably different. Figure 8a shows all 19 events composited around Lamont, plotted in dual CTP-HI. The scatter plot shows distinct separation of the dry and wet soil events, particularly in the vertical (HI) 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  $139 \text{ J kg}^{-1}$  and high humidity at low levels (mean HI of  $10^{\circ}\text{C}$ ). These conditions are similar to the findings of Findell and Eltahir (2003) for deep convection initiating over wet soils. Concurrently, atmospheric conditions prior to convection over dry soils have much higher CTP values (mean of  $313 \text{ J kg}^{-1}$ ) and higher HI (mean of  $25^{\circ}\text{C}$ ).

In addition to the separation of dry and wet events in CTP-HI space, there appears to be a distinction within dry and wet events (Fig. 8a). We clustered the 19 events using the 06:00 LST CTP and HI 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 range and increase in both CTP and HI, 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 06:00 to 12:00 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 06:00 and 12:00 LST are used to characterize conditions and modification from the morning to afternoon before convection occurs. At both 06:00 and 12:00 LST, we calculate the LFC (mb), PBL height (m) and surface temperature ( $^{\circ}\text{C}$ ). Additionally for the 06:00 LST sounding, we calculate convective temperature ( $^{\circ}\text{C}$ ) to represent the potential for convection given adequate surface heating. We calculate CAPE and CIN ( $\text{J kg}^{-1}$ ) 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 06:00 and 12:00 LST as well as the average 09:00 LST soil moisture percentile for events in each cluster. CAPE (CIN) values are much higher (lower) at both 06:00 and 12:00 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 06:00 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 06:00 and 12:00 LST.

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Figure 9 shows scatter plots of the soil moisture percentiles and the 12:00–06:00 LST difference in (a) LFC height (mb), (b) PBL height (m) and (c) surface temperature ( $^{\circ}\text{C}$ ), delineated by cluster. Additionally, Fig. 9d shows the same scatter plot, only with 06:00 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 typical of atmospheric response to strong sensible heat flux from a land surface that is moisture-limited (Santanello et al., 2011). 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 06:00 to 12:00 LST. This is characteristic of the atmospheric response to strong latent heating from a relatively wet land-surface (Gentine et al., 2013). Despite the small sample size, all of the relationships depicted in Fig. 9 are statistically significant. The coefficient 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 19 events, soil moisture percentiles at 09:00 LST still explain more than 25% of the variance in LFC height change from 06:00 to 12:00 LST.

Along with changes in the atmospheric temperature and LFC/PBL heights, we also relate soil moisture percentiles from the 19 events to atmospheric stability. Figure 10a shows scatter plots of soil moisture percentile and the change (difference) in CAPE ( $\Delta\text{CAPE}$ ,  $\text{Jkg}^{-1}$ ) between 12:00 and 06:00 LST. Figure 10b shows the same scatter plot, only showing the 12:00–06:00 LST difference in CIN ( $\Delta\text{CIN}$ ,  $\text{Jkg}^{-1}$ ) delineated by cluster. For clarity, negative  $\Delta\text{CIN}$  values represent a decrease in CIN (decrease in stability) between 06:00 and 12:00 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 in-

creased 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 06:00 and 12:00 LST. Concurrently, wetter than normal soils provide enhanced moisture flux to the atmosphere through increased latent heating. 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 19 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 06:00 and 12:00 LST (77 %) is captured by 09:00 LST soil moisture percentiles.

Through the manual event identification procedure, we were able to quantify individual event duration (hours), average size (pixels) and total volumetric precipitation (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 06:00 and 12:00 LST. Larger PBL growth (over predominantly drier soils) 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 06:00 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.

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## 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 anomalously wet soils increase latent heating, decrease surface temperatures, the lifting condensation level, and the level of free convection, and increase CAPE (Pielke, 2001; Pal and Eltahir, 2003; Ferguson and Wood, 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, surface heating, a decrease in CIN and increase in PBL height (Santanello et al., 2009; Taylor et al., 2012).

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 affiliated 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. (2015) using CMORPH (Fig. 11). The CMORPH events have a significant larger median maximum hourly accumulation rate, as determined using the Kruskal–Wallis test, than the NEXRAD events. However, the largest differences between the datasets are in the right tail of the distributions, with many CMORPH event accumulation rates exceeding  $100 \text{ mm h}^{-1}$ . 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. 2015)

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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 19 events near Lamont, OK where atmospheric soundings observations were available, we found strong connections between soil moisture and atmospheric modification between 06:00 LST and 12:00 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 06:00 to 12:00 LST change in CIN. In fact, as Table 1 shows, 06:00 and 12:00 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)

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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.

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**Table 1.** Mean atmospheric conditions at 06:00 and 12:00 LST from atmospheric soundings, averaged by event cluster. Conditions summarized include convective available potential energy ( $\text{J kg}^{-1}$ ), convective inhibition ( $\text{J kg}^{-1}$ ), the level of free convection (mb), convective temperature ( $^{\circ}\text{C}$ ), and the height of the planetary boundary layer (m). Mean convective event duration (h), 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 ( $\text{J kg}^{-1}$ )	1634.50	686.60	366.75	96.50
CAPE-18Z ( $\text{J kg}^{-1}$ )	2522.50	1133.00	485.00	231.00
CIN-12Z ( $\text{J kg}^{-1}$ )	−144.70	−190.20	−324.00	−426.50
CIN-18Z ( $\text{J kg}^{-1}$ )	−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 ( $^{\circ}\text{C}$ )	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 (h)	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

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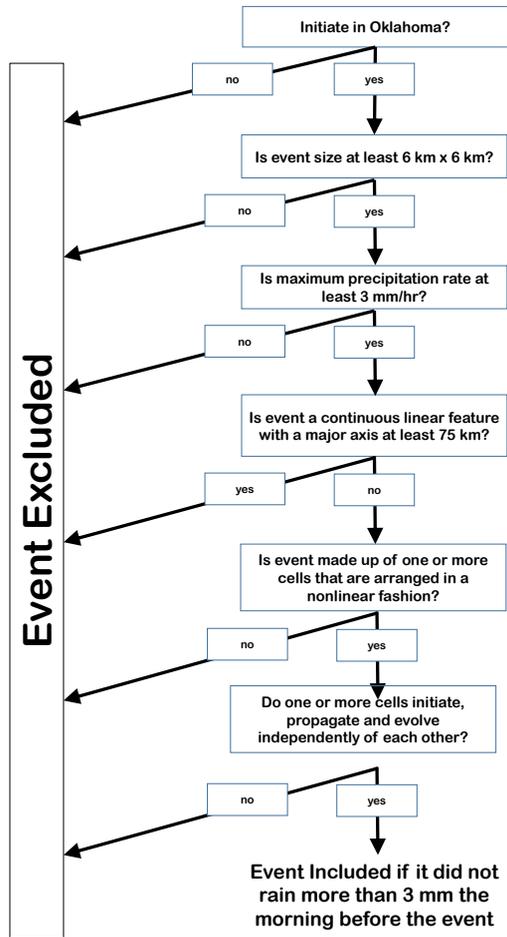
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**Figure 1.** Schematic of the decision tree that was used for manual identification of unorganized convective events.

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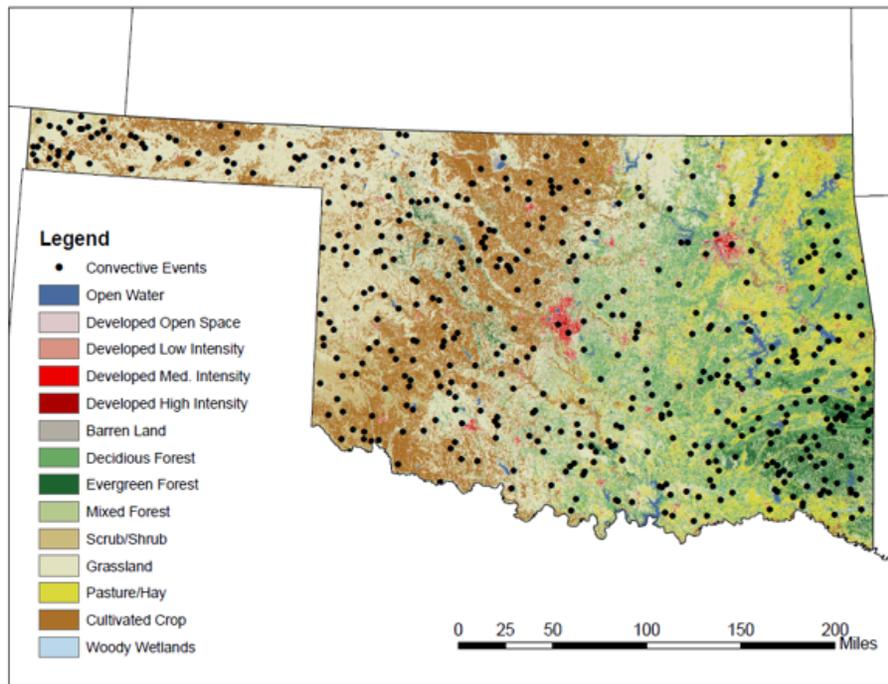
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**Figure 2.** Location of all 477 convective events (black circles) identified between May and September, 2002–2012. The land cover, taken from the National Land Cover Dataset (<http://www.mrlc.gov/>), is also shown.

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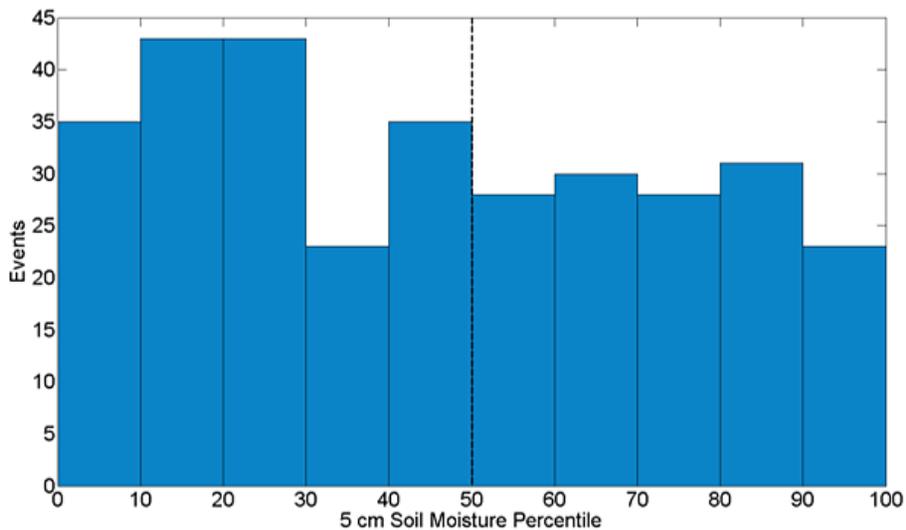
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**Figure 3.** Top panel (a) shows the distribution of 5 cm soil moisture percentiles underlying all convective events identified. The dashed-black line represents the divide between relatively wet (> 50 percentile) and relatively dry (< 50 percentile) soils.

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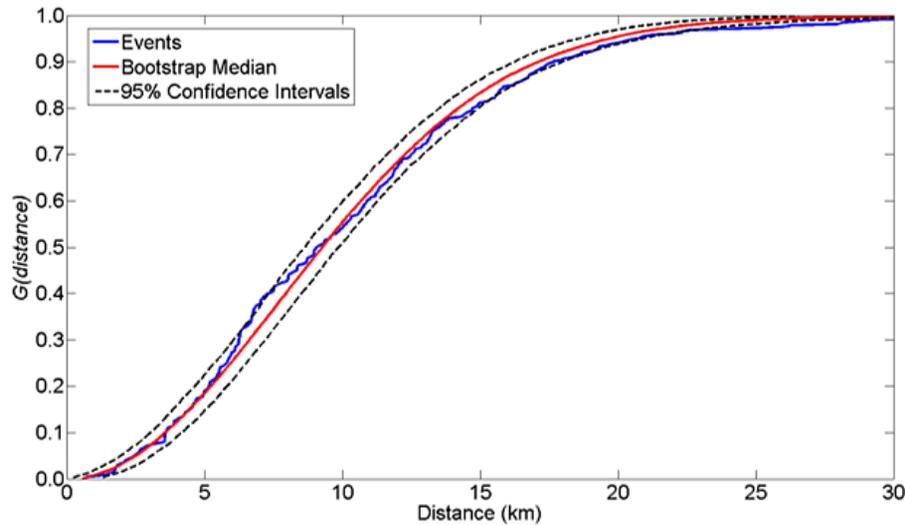
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**Figure 4.** Cumulative distribution functions of nearest neighbor distances for all unorganized convective events (blue line), the bootstrapped median (red line) and 95 % confidence envelopes (black lines). The bootstrapped samples are calculated from 1000 iterations of 477 random events.

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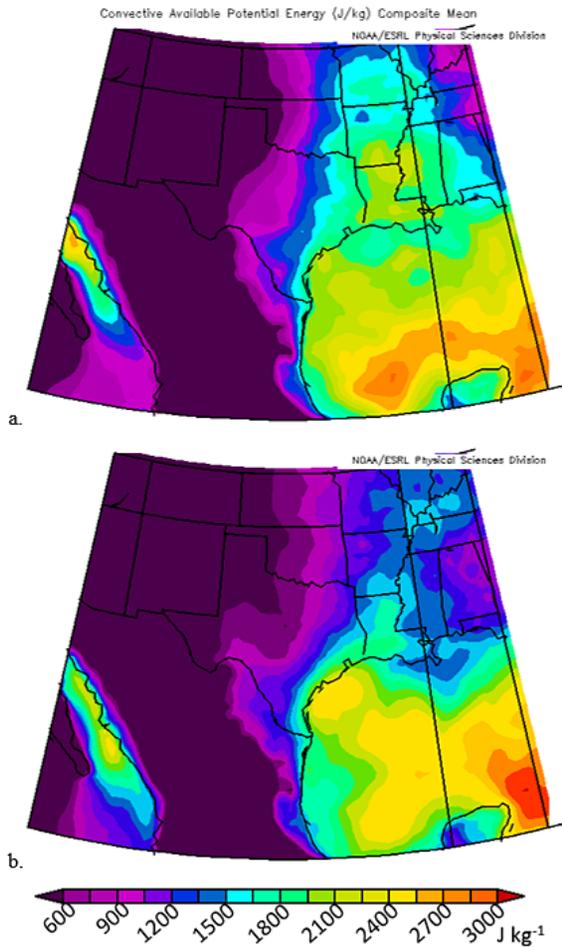
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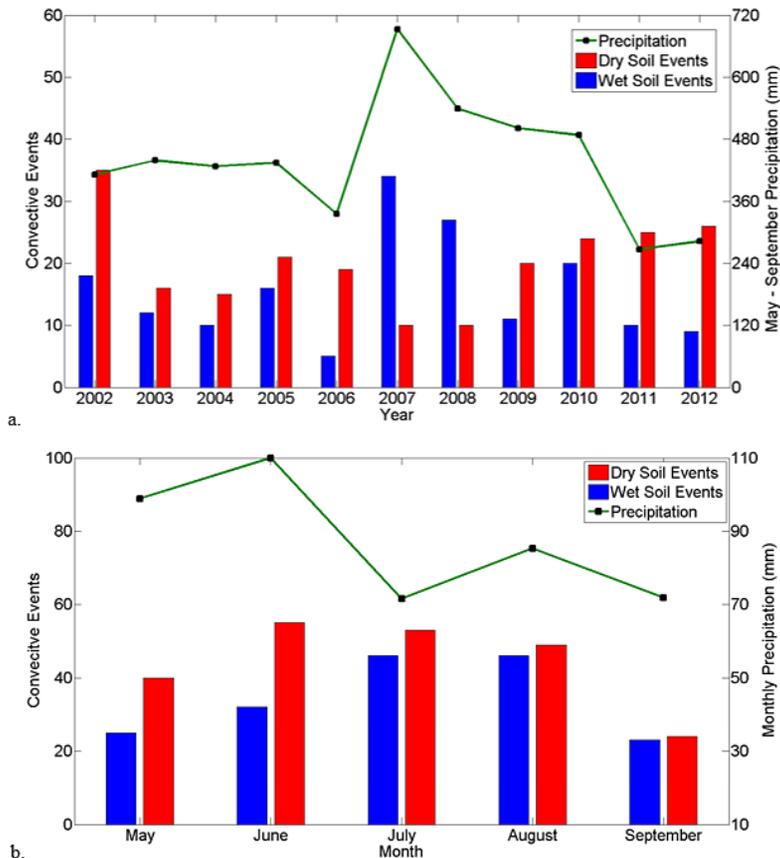




**Figure 5.** Composites of morning (06:00 LST) convective available potential energy from **(a)** events clustered in southeast corner of the study region and **(b)** all other convective events.

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**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).

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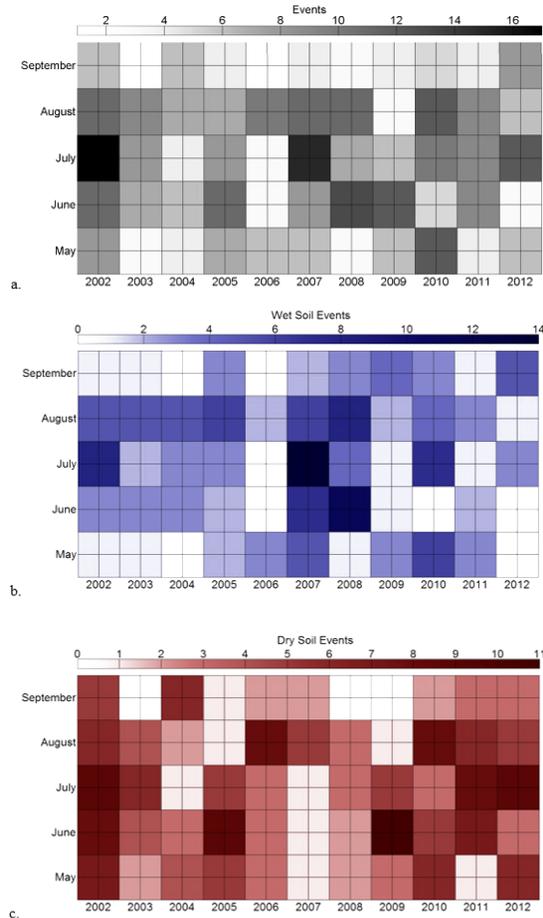
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**Figure 7.** Frequency of unorganized convective events in each month during the 2002–2012 study period. The top panel represents all events, the middle panel is the wet events and the bottom panel is the dry events.

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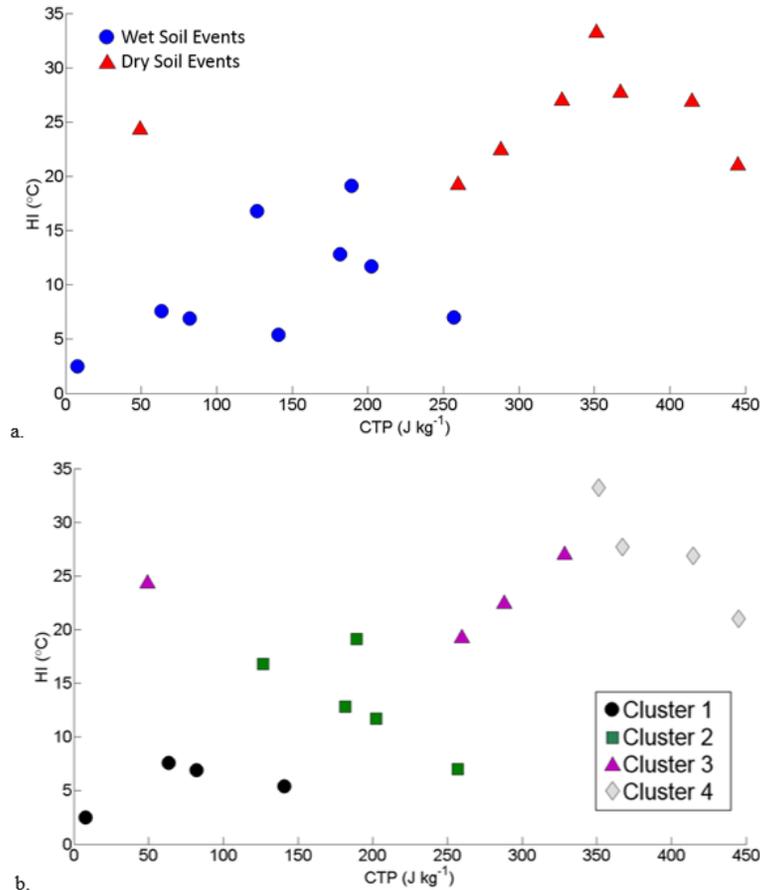
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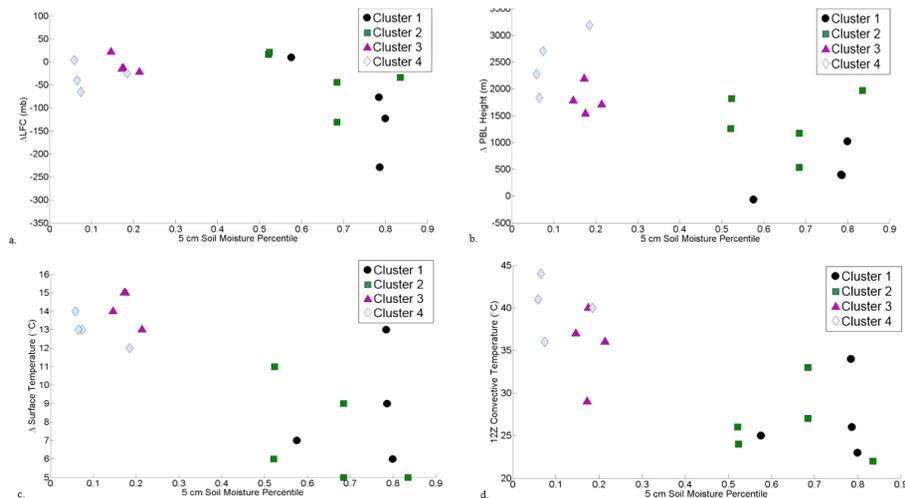
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**Figure 8.** Scatter plots of the 19 unorganized convective events that occurred near Lamont, OK in dual convective triggering potential ( $\text{J kg}^{-1}$ ) – humidity index ( $^{\circ}\text{C}$ ) space: **(a)** wet events are denoted by the blue circle and dry events are denoted by a red triangle. **(b)** Events are grouped into 4 clusters.

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**Figure 9.** Scatter plots of soil moisture percentiles and atmospheric conditions 19 unorganized convective events that occurred near Lamont, OK: **(a)** soil moisture percentiles vs. changes in LFC height, **(b)** soil moisture percentiles vs. changes in PBL height, **(c)** soil moisture percentiles vs. surface temperature, and **(d)** soil moisture percentiles vs. 12:00 UTC convective temperature.

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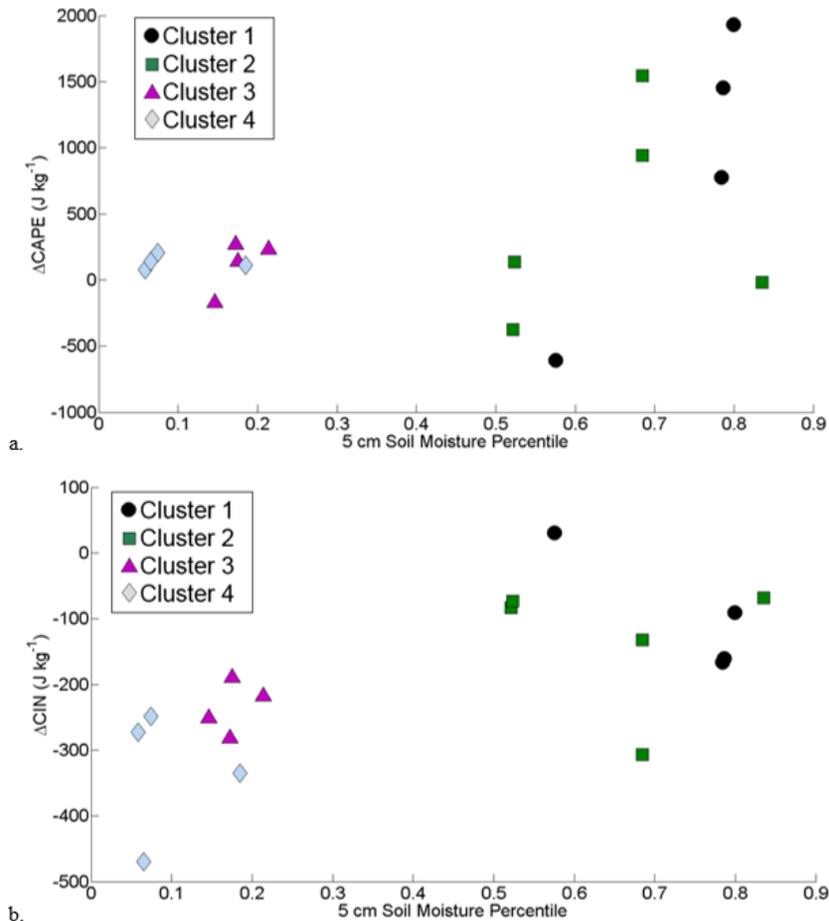
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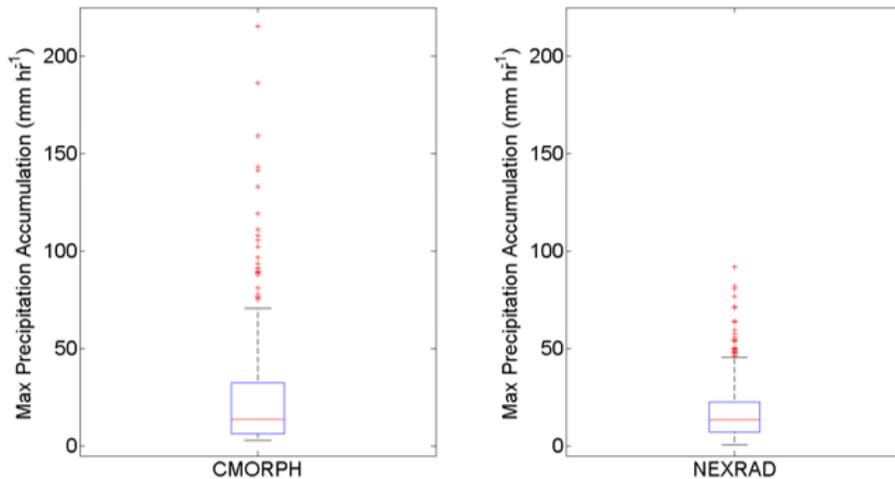
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**Figure 10.** Scatter plots of soil moisture percentiles and **(a)** the change in convective available potential energy and **(b)** the change in convective inhibition between 06:00 and 12:00 LST. Events shown here occur within 50 km of Lamont, Oklahoma.



**Figure 11.** Maximum precipitation accumulation rates ( $\text{mm h}^{-1}$ ) composited from (left panel) 353 events identified by Ford et al. (2015) using CMORPH and (right panel) 477 events identified in this study with NEXRAD.

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