AN ANALYSIS OF THE SOIL MOISTURE-PRECIPITATION RELATIONSHIP ACROSS THE CONTINENTAL UNITED STATES

By

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ABSTRACT

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Soil moisture-precipitation feedback is crucial in understanding land-atmosphere interactions. A lack of observations of soil moisture and precipitation at the same spatial scale makes it difficult to quantify the feedback and determine the proper spatial scale to detect this phenomenon. The goal of this study is to portray the soil moisture-precipitation relationship at a daily time scale across the continental United States (CONUS) during June, July, and August using the North American Regional Reanalysis (NARR) dataset (1979-2014). Following the framework established by Findell and Eltahir in 2003, the convective triggering potential (CTP), low-level humidity index (HI), and soil moisture conditions observed at 1200 UTC, as well as afternoon convective precipitation, are used to assess the soil moisture-precipitation relationship depicted by the NARR dataset. Convective precipitation occurred most frequently in the southeastern United States (US). When precipitation occurred, optimal values of CTP (100-300 J/kg) and HI (5-15 K) were indicated, which supports instability and moisture as factors for convection to occur. The Kolmogorov-Smirnov test displayed a significant difference in soil moisture fraction on rain days and non-rain days across many areas of the US. The Great Plains and parts of the southeast US experienced drier soil conditions on days with rain, while the Northeast, experienced wetter conditions. These results indicated that both wet and dry soil moisture conditions may contribute to convective precipitation in different regions with different climate conditions.

This thesis is dedicated to my family, my friends, and all my mentors that have supported me throughout my journey

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KEY TO ABBREVIATIONS

ARM – Atmospheric Radiation Measurement Program

CONUS – Continental United States

CTP – Convective Triggering Potential

EF – Evaporative Fraction

HI – Low-level Humidity Index

NARR – North American Regional Reanalysis

PBL – Planetary Boundary Layer

US – United States

CHAPTER 1: Introduction and Background

Land-atmosphere interactions are complex and vary greatly by region and climate. The land surface can have large impacts on the distribution of heat and moisture into the atmosphere on a daily basis. However, retrieving high-resolution hydrologic information has been a consistent hurdle in the hydrological and meteorological sciences. The lack of sufficient fine scale data, such as a large-scale soil moisture network (Ochsner et al., 2013), pose challenges in exploring land-atmosphere interactions. The objective of this research is to understand the spatial variability of the soil moisture-precipitation relationship across the continental United States (CONUS) using the North American Regional Reanalysis (NARR). The NARR provides a dataset to analyze this relationship at a large spatial scale across the CONUS and high temporal resolution at every 3 hours.

This study investigates the daily process between soil moisture and convective precipitation. Previous studies have indicated that the morning land and atmosphere can provide initial conditions for afternoon convective precipitation (Findell and Eltahir, 2003a&b, Findell et al., 2011). As the day progresses, these morning conditions are affected by daytime heating that allow for evapotranspiration to occur and heat exchange at the surface through sensible and latent heat. These processes give the atmosphere the potential to produce convection.

Convection can be initiated over both wet and dry soils. A positive (negative) feedback indicates that precipitation is more likely to occur over wet (dry) soils. A recent observational study done across the globe indicated that afternoon precipitation falls preferentially over drier soils (Taylor et al., 2012), but previous studies have also indicated a positive feedback regime in some areas (Findell and Eltahir, 1997; Findell and Eltahir, 2003a&b, Findell et al., 2011). Illinois was the study area in a study done by Findell and Eltahir (1997) using the Illinois Climate

Network station data, where they found that convection was mainly initiated over wetter soils, indicating a positive feedback. This study was expanded in 2003 to use a one-dimensional model with the morning atmospheric sounding and pre-determined soil conditions to determine the likelihood of afternoon convection (Findell and Eltahir, 2003a&b). The first part of the study concluded that convection in Illinois occurred over both wet and dry soils. The second part took this framework and applied it to the CONUS where they identified regions of positive feedback, negative feedback, transitional regions, and atmospherically controlled regions (Findell and Eltahir, 2003b). The authors characterized the morning atmosphere based on the convective triggering potential (CTP) and low-level humidity index (HI). In this current study, those variables have been used to help describe features of the atmosphere and will be further described in the Methods subsection in Chapter 2.

The ability for convection to occur is dependent upon the level of free convection and the growth of the boundary layer (Findell and Eltahir, 2003a). The growth of the boundary layer can be strongly dependent on soil moisture and its wetness. Over wet soil, the boundary layer tends to increase slowly and steadily through the afternoon, while over dry soil the boundary layer tends to rise more quickly and then drop off in the afternoon (Findell and Eltahir, 2003a). This process is influenced by the latent and sensible heat fluxes that occur off of the surface. Wetter soils are reliant on moisture and the latent heat flux, which is usually associated with small boundary layer growth. Dry soils have the ability to produce a strong sensible heat flux and that heat transfer from the surface to the lower atmosphere can cause the boundary layer to rise more rapidly. Therefore, using variables such as CTP and HI help to quantify the conditions in the atmosphere that can be influenced by soil moisture.

The framework established in the original study (Findell and Eltahir, 2003a) was carried out across the United States (US) in the supplemental study (Findell and Elathir, 2003b), and the feedbacks across the CONUS are shown in Figure 1.1. A positive feedback region was established across the eastern US. The western US was mainly characterized as atmospherically controlled, where precipitation is dominated by atmospheric and oceanic processes (Findell and Eltahir, 2003b). The Central Plains area was recognized in some cases as a transitional region, where neither soil moisture condition was favored, and a small region of negative feedback existed in parts of Arizona, New Mexico, and Texas. Simulations that include irrigation have borne this suppression effect out (Pei et al., 2016). This study was critical in understanding possible areas that would be likely to generate positive and negative feedbacks (Findell and Eltahir, 2003b).

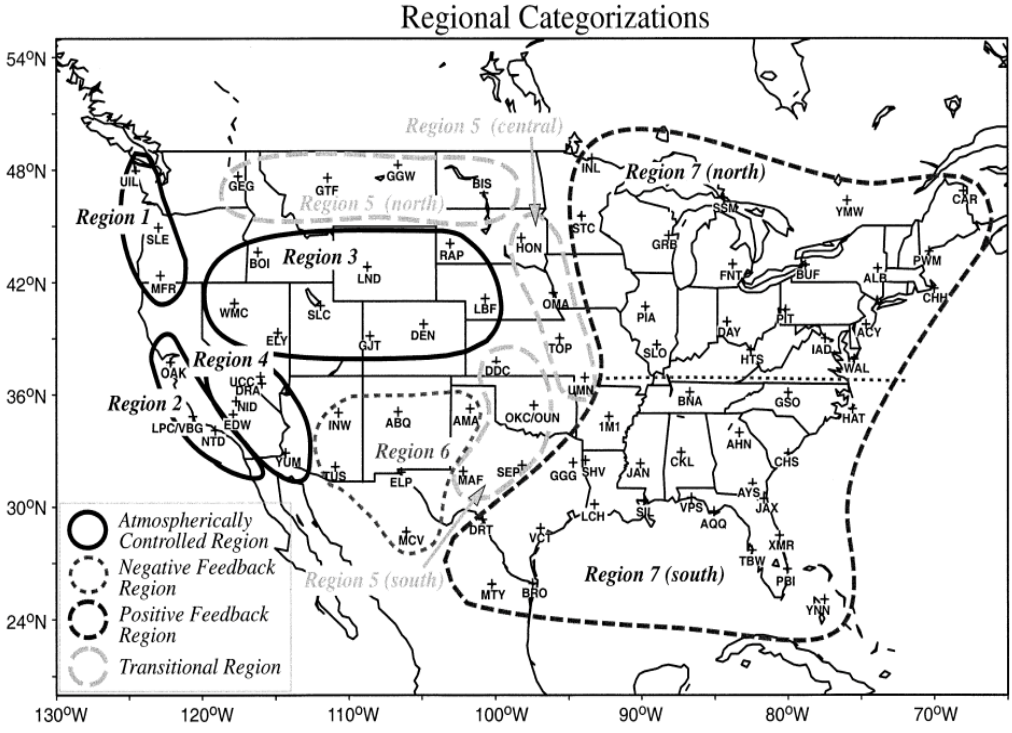


Figure 1.1: *Regional Categorizations*. Feedback regions across the continental United States based on CTP-HI scatterplots for 89 stations with at least 10 years of data (Figure from Findell and Eltahir, 2003b).

The initial land surface conditions of the soil moisture state must have 3 main components to have an impact on precipitation, which are: 1. The initial soil moisture anomaly must be large, 2. Evaporation must be sensitive to a given soil moisture anomaly, and 3. Precipitation must be sensitive to a given evaporation anomaly (Koster and Suarez, 2003). In general, these conditions highlight the processes that must occur from the land surface to the upper atmosphere to promote convection. Latent and sensible heat fluxes off of the surface induce evaporation from the ground surface, and that evaporation can help supply the moisture to set up a primed atmosphere for precipitation. A more recent study, expanded these three criteria to understand the influences of evaporative fraction on the planetary boundary layer (PBL), the evolution of the PBL with sensitivity to entrainment, and the feedback between the top of the PBL and surface energy partitioning (Santanello et al., 2011). These criteria help to denote the structure of the feedback, but there are ultimately many factors that contribute to this process. This research follows the structure similar to that of Koster and Suarez (2003).

The Findell et al. (2011) study investigated the 3rd criteria from the Koster and Suarez (2003) work, by looking at evaporative fraction (EF) and precipitation from the NARR dataset (Findell et al., 2011). The analysis was based on the feedback between before-noon EF and afternoon precipitation, which resulted in displaying a positive feedback region over the eastern US indicating that higher EF leads to increased afternoon rainfall probabilities (Figure 1.2) (Findell et al., 2011). This positive feedback region of the eastern US, where higher values of triggering feedback strength occurred was also supported by Findell and Eltahir (2003b).

Circulation models have also been used over the last two decades to diagnose this feedback and the coupling strength between the land and atmosphere. Koster et al. (2004 & 2006) used atmospheric general circulation models and identified the Great Plains in the US as

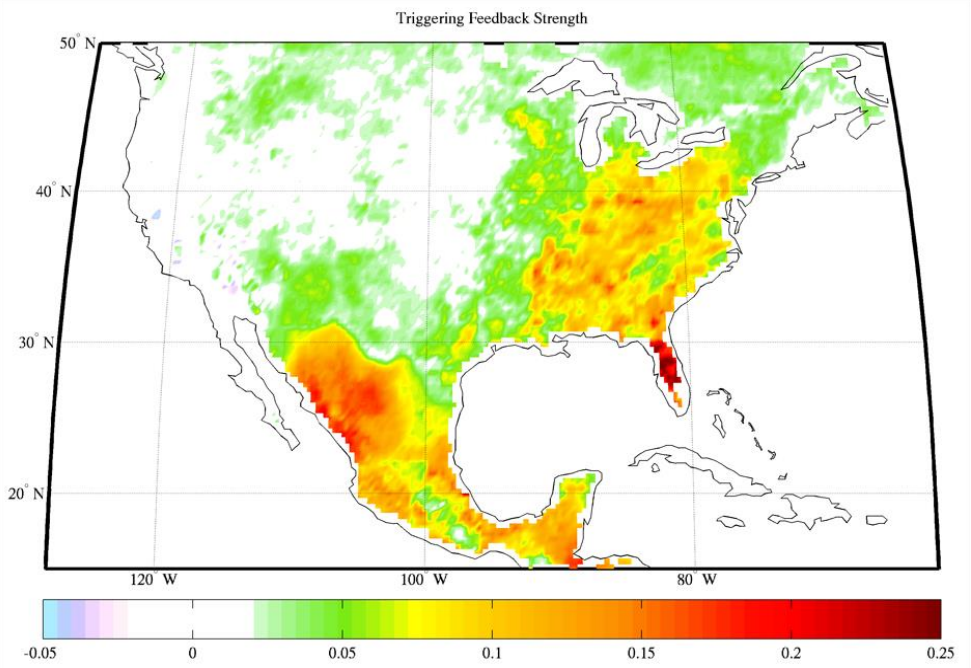


Figure 1.2: *Triggering Feedback Strength*. Triggering feedback strength; units of probability of afternoon (12pm-6pm) rain (Figure from Findell et al., 2011).

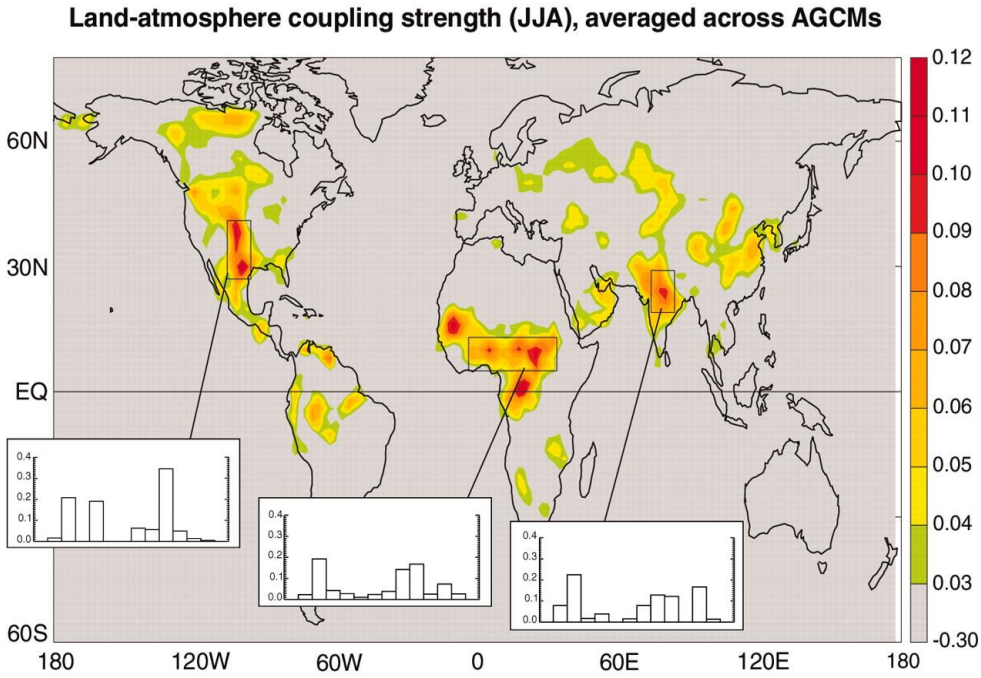


Figure 1.3: *Land-Atmosphere Coupling Strength*. Land-atmosphere coupling strength for JJA averaged across all AGCMs. Box plots indicate different AGCMs and their coupling strength for that region (Figure from Koster et al., 2004)

an area that had strong coupling strength between the land and atmosphere (Figure 1.3). It is important to note that in the study done by Findell et al. (2011), the positive feedback region (Figure 1.2) was defined by a calculation of triggering feedback strength. This area differs from the Great Plains "hot spot" that was found in the Koster et al. (2004 & 2006) study (Figure 1.3). Even though the Koster et al. (2004 & 2006) had the advantage of analyzing the sensitivity between evapotranspiration and soil moisture, there were some significant inter-model differences, which can be seen in the box charts of Figure 1.3. Due to some of these model specific relationships, the results of both studies remain valid, but these discrepancies leave this research area with some more questions. A recent study using the heated condensation framework found that, although there is contradiction in the literature to the types of feedbacks that occur, positive and negative feedbacks can both occur (Tawfik et al., 2015).

This "hot spot" in the Great Plains was supported with other models, observational data, and the NARR dataset (Mei and Wang, 2012). Other "hot spot" regions that were identified in the Koster et al. (2004) study were the Sahel, tropical South America, and India. These "hot spot" regions were also supported using the circulation model in Lintner and Neelin (2009), which was also able to display that soil moisture caused 20% of the variability in precipitation near the convective margin.

Although the analysis of this current research is focused on the US, some influential studies of soil moisture-precipitation feedback have been conducted for other areas, such as the Sahel. The Sahel is a region that has been indicated as an area with strong coupling strength (Koster et al., 2004; Koster et al., 2006; Lintner and Neelin, 2009). A couple of studies done on the Sahel have looked at the spatial variability of soil moisture and precipitation. One particular study (Clark et al., 2004) indicates that the spatial variability of precipitation can affect the

surface energy budget of heat fluxes in the days following the precipitation event due to changes in soil moisture conditions. These changes in variability of soil moisture allow for latent and sensible heat fluxes to take place and initiate new convection. In a later study, Taylor et al. (2011) used daily soil moisture estimates from satellite data to understand the probability of precipitation in the following days. The results of the study indicated that convective initiation was doubled over strong soil moisture gradients compared to uniform soil moisture (Taylor et al., 2011). There was also no clear relationship between soil moisture and convective initiation, but a strong relationship was indicated with soil moisture anomalies, which indicated that drier soils were favored one third of the time more than wetter soils (Taylor et al., 2011). Although these studies are focused on the Sahel, they indicate the importance of soil moisture conditions and soil moisture gradients. Similar studies, were conducted in the Great Plains of the US due to the semi-arid climate and large coupling strength indicated by Koster et al. (2004 & 2006). In these semi-arid regions the soil moisture can be very sensitive to surface fluxes, especially sensible heat from drier soils (Taylor et al., 2012).

Frye and Mote (2010) focused their study in the semi-arid Southern Great Plains, where they could assess the impacts of synoptically primed days versus synoptically benign days, which also included the influence of the low-level jet. The low-level jet in the Great Plains region supplies moisture to the upper atmosphere around 850 hPa from the Gulf of Mexico (Frye and Mote, 2010). This feature can have a significant influence on the structure of the upper atmosphere and may diminish the effect of soil moisture in initiating convection. The study identified that on days with a low-level jet, convection is more likely over drier soil moisture conditions and days without a low-level jet, convection is more likely over wetter soil conditions (Frye and Mote, 2010). It was also noted in this area, similar to the Sahel, that where the soil

moisture gradient is largest, the likelihood for convection is stronger (Frye and Mote, 2010). Therefore, atmospheric factors can have a large influence on the potential feedback that occurs.

Another study done in the Southern Great Plains, using the Department of Energy Atmospheric Radiation Measurement Program (ARM) field observations and NARR data, showed that at a pentad time scale of precipitation was linked to negative surface radiation anomalies (Ruiz-Barradas and Nigam, 2013). This implies that there was little evapotranspiration taking place, and drier soil was favored. An observational study using the Oklahoma Mesonet, also showed that drier than normal soils favored afternoon convection in Oklahoma (Ford et al., 2015). Moving farther north in the Midwest region, results have indicated that a positive correlation between soil moisture and subsequent precipitation to occur is likely due to the autocorrelation of stratiform precipitation, which is influenced by large scale atmospheric processes (Alfieri et al., 2008). When solely analyzing convective precipitation, positive and negative feedback areas were identified in the upper Midwest, which are dependent upon whether heat fluxes from the surface can initiate convection and induce instability in the boundary layer (Alfieri et al., 2008). These studies indicate the prominence of atmospheric conditions to influence the production of convection and therefore, a goal of this study is to gain a better understanding on how the soil and atmosphere work together to initiate convection.

A study done by Ferguson and Wood (2011), investigated land atmosphere coupling using remote sensing products and reanalysis data, while also adopting and modifying the CTP-HI framework created by Findell and Eltahir 2003a. In this study they found that on a global scale, wet soils that initiated convection had the largest extent and dry soils had the smallest extent, compared with atmospherically controlled and transition regions (Ferguson and Wood 2011). This wet coupling was shown to be dominant in the Southeast US for the datasets

included in the Roundy et al. (2013) study. However, in this region the coupling is controlled by advection (Roundy et al., 2014) and the humidity index, while soil moisture affects the persistence of the coupling (Roundy et al. 2013). Therefore, in this region the interaction between soil moisture and low-level moisture (HI) should have a strong influence on convection.

In a previous study of time lagged correlations between soil moisture and the subsequent 30 days of precipitation across the globe, a negative soil moisture-precipitation correlation was dominantly identified (Wei et al., 2008). This correlation is attributed to a combination of soil moisture memory and precipitation variability. In general, lagged correlations can be challenging to analyze due to atmospheric and oceanic influences that can persist for long time periods (Koster, 2011). Part of the analysis done in this study will analyze lagged correlations. These lagged correlations however will not just be done between soil moisture and precipitation, but other atmospheric variables, including CTP and HI. In this current analysis proper caution was taken when analyzing such results because lagged correlations do not identify causal relationships between the variables, such as soil moisture and precipitation (Wei et al., 2008).

This research advanced the Findell et al. (2011) study by investigating the soil moisture impacts along with CTP and HI on the ability to trigger convection. From the previous studies there has been much research done looking at the influence of soil moisture on precipitation, but this study fills the gap between understanding the relationship between variables not only at the surface, but variables in the upper atmosphere. This study investigates low-level moisture and instability in the upper atmosphere and how these morning conditions may have an impact on convective precipitation later in the afternoon. These relationships that CTP and HI have with soil moisture and precipitation are essential in understanding the complete structure of this phenomenon.

Research Questions and Objectives

Question 1: What relationships exist between soil conditions and the initiation of convection across the continental United States?

The goal of this study was to analyze the relationships between soil moisture fraction, CTP, HI, and convective precipitation. The main focus is on the soil moisture-precipitation relationship, but also the impact that atmospheric variables can have on the initiation of convection. The analysis was strongly focused on how these relationships vary by region during the summer months of June, July, and August. Different locations were chosen to address the different climates that exist across the CONUS.

Question 2: Instead of the hypothetical situations used in Findell and Eltahir (2003a&b), what can a reanalysis dataset show us about this feedback?

The NARR combines model and observations through data assimilation techniques to provide continuous and complete regional atmospheric conditions over North America every 3 hours. The NARR was used to represent atmospheric conditions and soil moisture fraction across the CONUS. The analysis was completed by analyzing each day in the months of June, July, and August for 1979-2014. To analyze the soil moisture-precipitation relationship the framework established in Findell and Eltahir (2003a&b) was used. CTP and HI were calculated from the NARR dataset in the local morning at 1200 UTC. However, unlike the Findell and Eltahir (2003a&b) studies, soil moisture conditions are not predetermined, but are values from the NARR dataset.

CHAPTER 2: Methods, Data, and Results

2.1 Methods

This section describes the atmospheric variables that have an impact on the soil moisture-precipitation relationship. In order for convection to occur, it is necessary for there to be a source of moisture, instability, and lift. Therefore, it is important to not only understand the relationship between soil moisture and precipitation, but also, other atmospheric variables. In this study, the variables that will be focused on are moisture and instability. To quantify these measures, the framework established by Findell and Eltahir 2003a was used. The framework established two variables, convective triggering potential (CTP) to quantify instability, and low-level humidity index (HI) to quantify moisture.

Convective triggering potential is based on an atmospheric sounding and is defined as the area between the environmental temperature and the moist adiabat originating 100 hPa above the surface to 300 hPa above the surface (Findell and Eltahir, 2003a). Figure 2.1 displays the area that is being integrated and the full equation is shown below:

$$CTP = g \int_{Z_{Psurf-100}}^{Z_{Psurf-300}} \left(\frac{T_{parcel} - T_{env}}{T_{env}} \right) dz \qquad (2.1)$$

where Z is the geopotential height at 100 or 300 hPa above the surface, T_{parcel} is temperature of the air parcel, T_{env} is temperature of the environment, and g is the gravitational constant (Ferguson and Wood, 2011).

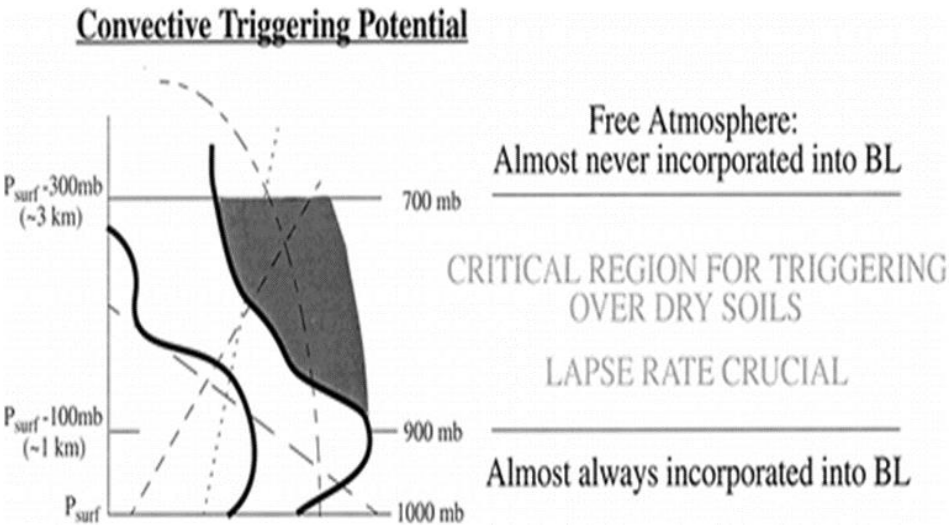


Figure 2.1: *Convective Triggering Potential*. Diagram explaining the definition of convective triggering potential. Thick solid lines are the temperature and dew point temperature profiles; straight long-dashed line is a dry adiabat (constant potential temperature); straight short-dashed line is constant temperature; straight dotted line is constant mixing ratio; curved short-dashed line is a moist adiabat (constant equivalent potential temperature). The CTP is determined by integrating the area between the observed temperature profile and a moist adiabat originating at the observed temperature 100 hPa above the surface. Adapted Findell and Eltahir 2003a.

To solve the parcel temperature, it is critical to calculate the moist adiabat based on the observed temperature at 100 hPa above the surface. The moist adiabat is a line drawn on an atmospheric sounding that describes the ascent of a parcel rising from the surface that is saturated. The equation that represents the moist adiabat (Γm) is shown below (Randall, 2009):

$$\Gamma m = \Gamma d\left[\frac{1+\frac{L*q(T,P)}{Rd*T}}{1+\frac{(L^2)*q(T,P)}{Cp*Rv*T^2}}\right] \quad (2.2)$$

where Γd is the dry adiabatic lapse rate, L is the latent heat of vaporization, q is saturation mixing ratio, Rd is the gas constant of dry air, Rv is the gas constant of water vapor, and Cp is specific heat. This calculation accounts for the parcel temperature profile and the integration can

then take place. In general, convective triggering potential is identifying how likely it is for a parcel of air from the surface to rise in the atmosphere and initiate convection.

The low-level humidity index is the sum of dew point depressions at 50 and 150 hPa above the surface (Findell and Elathir, 2003a). The equation of HI is below:

$$HI = \left(T_{Psurf-50} - T_{d,Psurf-50}\right) + \left(T_{Psurf-150} - T_{d,Psurf-150}\right) \quad (2.3)$$

where $T_{Psurf-50}$ represents the temperature 50 hPa above the surface, $T_{d,Psurf-50}$ represents the dew point temperature 50 hPa above the surface, and the second part of the equation represents the temperature and dew point 150 hPa above the surface. This quantifies the low-level moisture in the atmosphere.

Both of these variables, CTP and HI, were calculated at 1200 UTC across the CONUS. The 1200 UTC was used to represent the morning atmospheric and soil moisture conditions. Although that induces time differences between locations across the CONUS in terms of local time, it was assumed that changes to the boundary layer conditions and low-level moisture were small, similarly to the Findell and Eltahir (2003b) study. The convective precipitation was accumulated between 1800 UTC and 0600 UTC of the following day. In the analysis, the results begin with the spatial structure of each of the four variables, CTP, HI, soil moisture fraction, and convective precipitation. Then time lagged scatter plots were constructed to demonstrate the correlations between each of the variables. A statistical analysis was also conducted to focus on the soil moisture-precipitation relationship.

2.2 Data

The NARR is a combined model and dataset, which combines NCEP's high resolution (32km) ETA model with the Regional Data Assimilation System (RDAS) to provide an improved dataset for reanalysis (ESRL, n.d.). The NARR also provides an analysis on land hydrology and land-atmosphere interactions with the Noah land-surface model (Mesinger et al., 2006). The NARR can provide data every 3 hours, which was used to represent atmospheric and soil conditions during the months of June, July, and August from 1979 to 2014. The soil moisture fraction and the calculations for CTP and HI were calculated from the 1200 UTC data. Soil moisture fraction from the top three layers (0-10cm, 10cm-40cm, 40cm-100cm), which was simulated from the Noah land surface model, was used to calculate soil moisture fraction for the top 1 meter of the soil (Mesinger et al., 2006). To calculate CTP the NARR variables that were needed were; temperature profile, geopotential height profile, and surface pressure. To calculate HI the specific humidity profile was needed to aid in the calculation of the dew point temperature. The NARR also extends 45 layers in the vertical (Mesinger et al., 2006). The NARR fits to rawinsondes for temperature and wind throughout the troposphere have shown improvements and are closer to the observations than the Global Reanalysis (Mesinger et al., 2006). The afternoon precipitation was represented by the accumulated convective precipitation from 1800 UTC to 0600 UTC at three hour intervals. The value at 1800 UTC represents the accumulated convective precipitation between 1800 UTC to 2100 UTC (Bukovsky and Karoly, 2007). The precipitation in NARR is an assimilation of observed precipitation that is converted to latent heat (Lin et al., 1999). This helps to ensure that the precipitation is close to what is observed and the hydrologic cycle is fairly accurate (Mesinger et al., 2006). The NARR is expected to be less accurate where rain gauge data is sparse such as the Intermountain Western

US because it effects the quality of the precipitation being assimilated (Hamill et al., 2008). Compared to other reanalysis datasets the NARR captures and represents the afternoon maximum precipitation over the southeast US, the organization of convection over the Great Plains, and it can handle the western topography (Bukovsky and Karoly, 2007). The western topography can pose challenges, which was identified in the West et al. (2007) study of spurious grid-scale convection. The convection produced in the NARR was inefficient when the assimilated precipitation and modeled precipitation were not similar causing changes in the latent heat profile (West et al., 2007). Another source of error in NARR precipitation data over the CONUS, is from the method of disaggregating daily into hourly analyzed precipitation (West et al., 2007). The quality of convective precipitation in the NARR is not guaranteed because there are not direct observations of convective precipitation for validation. Many studies have used the NARR dataset to analyze soil moisture-precipitation feedback (Wei et al., 2008, Findell et al., 2011; Mei and Wang, 2012; Ruiz-Barradas and Nigam, 2013, Tawfik et al., 2015), therefore this study provides a comparable analysis to enhance the understanding of this phenomenon.

2.3 Results

The four variables of interest in this study were soil moisture fraction, convective precipitation, CTP, and HI. The first part of the results displays the spatial variability of each of the four variables. The second part describes the relationships between all four variables, emphasizing the soil moisture fraction and convective precipitation relationship.

To display the variations in the four variables, different locations were picked to represent a region and these places were compared. Many locations were analyzed across the CONUS to evaluate which location best represented certain regions of the US. The four locations that were chosen in this analysis were southern Ohio, southern Kansas, northern Florida, and

western Utah. Southern Ohio was chosen to represent areas with low HI and CTP values that were identified as positive feedback regions (Findell and Eltahir, 2003b; Findell et al., 2011). Florida was chosen because of the high frequency of convective precipitation days. Florida is considered a tropical climate that experiences hotter and humid conditions than the rest of the East Coast. Kansas was chosen because of its placement in the southern Great Plains. This area was identified in previous studies as an area that has large coupling strength (Koster et al., 2004; Koster et al., 2006; Mei and Wang, 2012). Also, the Great Plains in the summer can produce very strong convective storms along fronts and dry lines. Utah was chosen to represent the Intermountain Region of the western US and exemplify an area with a warmer and drier climate that experiences higher CTP and HI values.

2.3.1 Spatial Variability

CTP is a value that attempts to estimate the instability in the atmosphere. A negative CTP value represents an atmosphere that is too stable for rain and a positive value represents an unstable atmosphere that could produce convection (Findell and Eltahir, 2003a). A large positive value of CTP tends to favor convection over drier soils, while a small positive value tends to favor convection over wetter soils (Roundy et al., 2013). The drier soils tend to produce a strong sensible heat flux that increase heat off of the surface, which causes greater instability. Wetter soils reduce the sensible heat and rely on moisture and the latent heat flux to initiate convection, which is associated with weaker instability. The spatial variability of CTP is seen in Figure 2.2, 2.3, and 2.4. Figure 2.2 shows the average over each day in June, July, and August for all years (1979-2014). CTP values are lower in the eastern US and increase toward the west. In the western US, the warm, dry climate causes CTP values to rise up to an average value over 300 J/kg. On the East Coast, there tends to be more stable, moist conditions in the upper atmosphere

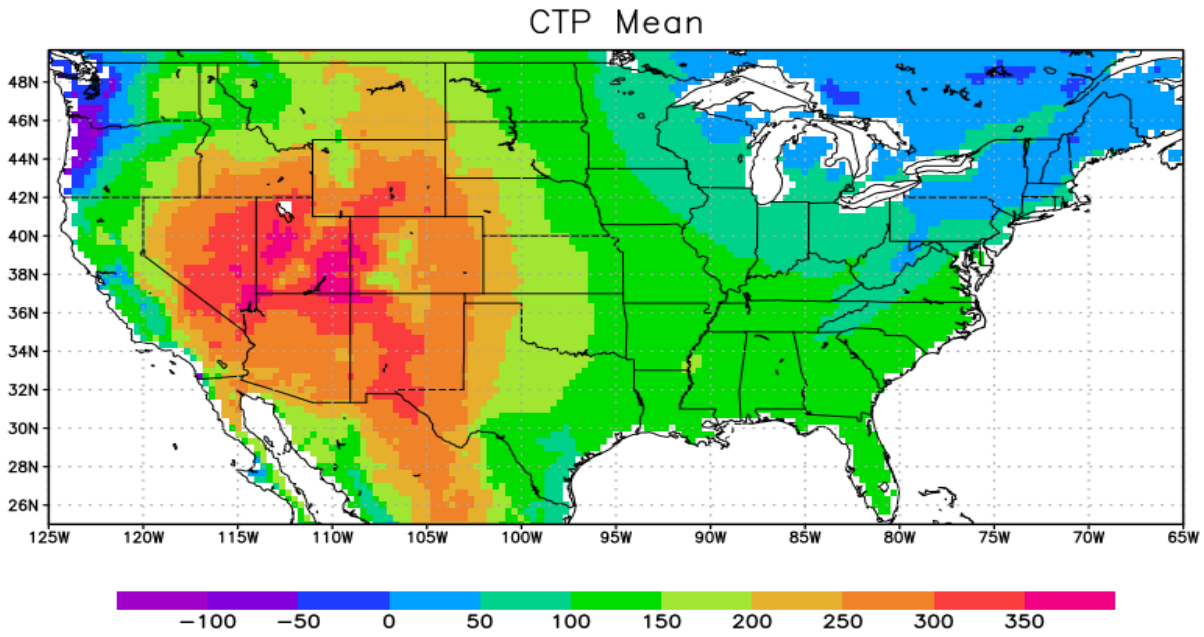


Figure 2.2: *CTP Mean*. A US map representing the average for CTP for June, July, and August from 1979-2014. This represents the average for 3312 days.

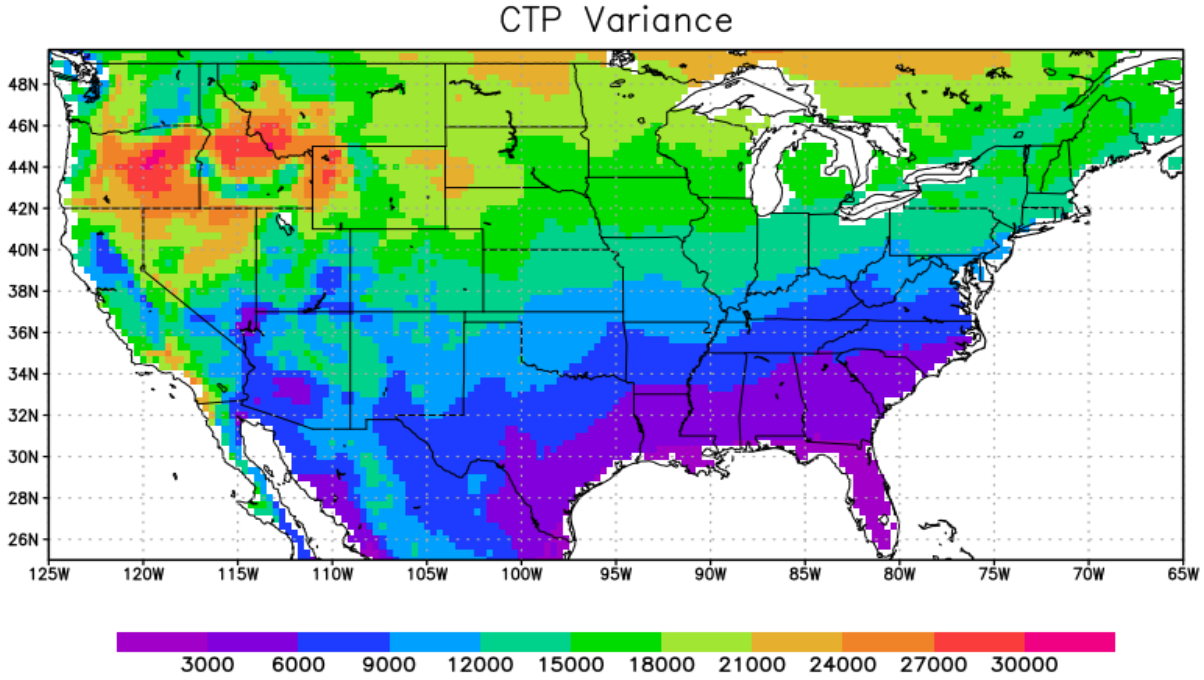


Figure 2.3: *CTP Variance*. A US map representing the variance of CTP for June, July, and August from 1979-2014. This represents the variance for 3312 days.

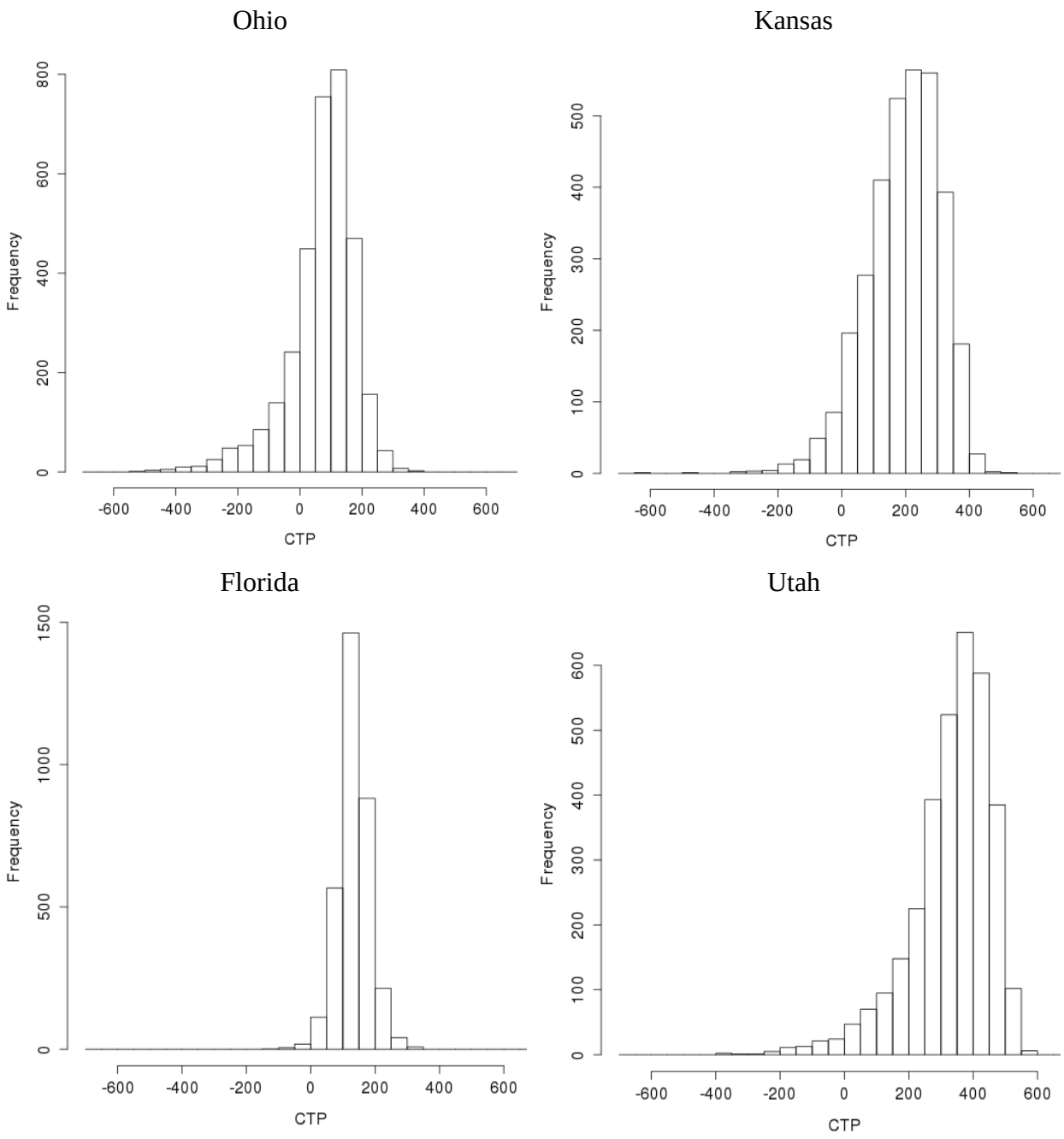


Figure 2.4: *Histograms of CTP*. Histograms of CTP for each of the four locations. (Note the y-axis changes)

and the average value range is between 50 J/kg and 100 J/kg. The western US displays a strong gradient that starts at 200 J/kg and reaches up to 350 J/kg. The variance of CTP is quite large because on the West Coast there are large ranges of positive CTP and on the East Coast there is a large range between positive and negative CTP values (Figures 2.3 and 2.4). There also is a trend from south to north where the variances tend to be larger in the northern areas of the US especially, in the East Coast region. The larger variation in CTP in the north could be explained by the different climates, where it is not always hot and humid, and has stronger variation on a daily basis. The CTP histograms also display that the East Coast has the highest frequency at lower CTP values than the central and western US. Ohio and Florida have the most days in the CTP range of 100 J/kg to 150 J/kg, while Kansas has the highest frequency at a range of 200 J/kg to 250 J/kg and Utah between 350 J/kg and 400 J/kg.

The spatial variability of HI is similar to that of CTP, which is displayed in Figure 2.5 2.6, and 2.7. The spatial distribution of HI values indicates smaller values over the eastern US and the values increase moving to the west. This was expected due to the variability in climate, where low (high) HI represents moist (dry) conditions. The East Coast in the summer is a moist climate compared to the arid climate out west, and has greater day-to-day variability, which is shown by the standard deviation of HI (Figure 2.6; top panel). Over the entire East Coast the average values of HI are about 10 K, which are fairly low. These average values extend to the central US before HI gets very large over the southwest US which experiences very dry conditions during the summer. The bottom panel of Figure 2.6 displays the standard deviation divided by the mean of HI. This shows that the New England states tend to have a greater fraction of variance relative to the mean. In the West, the values decrease, especially in the southwestern US where values are close to 0.30. On the West Coast, the standard deviation

indicates larger variance, but relative to the mean the variance is smaller. On the East Coast, the day-to-day variation is smaller, but the relative variance to the mean is greater. The HI histograms (Figure 2.7) also display that the East Coast has the highest frequency of days at lower HI values than the central and western US. Ohio and Florida have the most days in the HI range of 5 K to 10 K, while Kansas has the highest frequency at a range of 15 K to 20 K and Utah 30 K to 35 K.

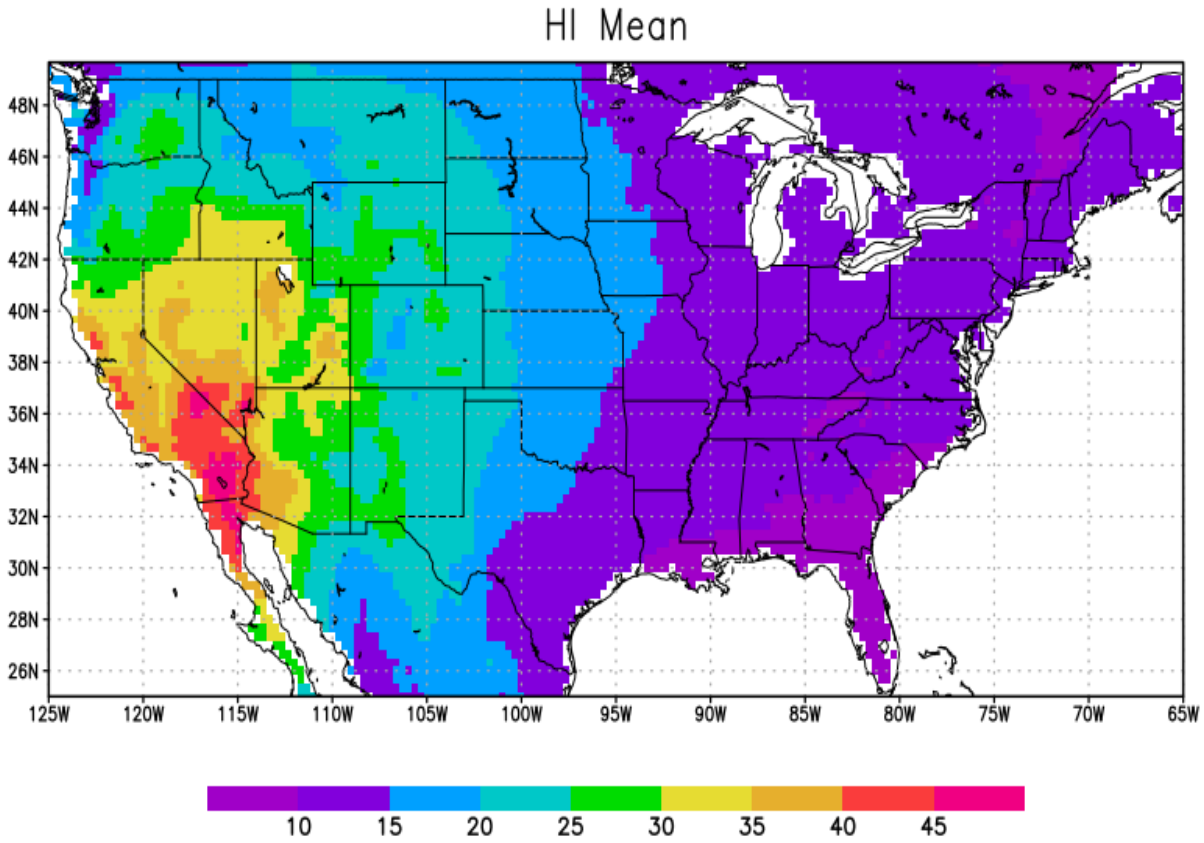


Figure 2.5: *HI Mean*. A US map representing the average for HI for June, July, and August from 1979-2014. This represents the average for 3312 days.

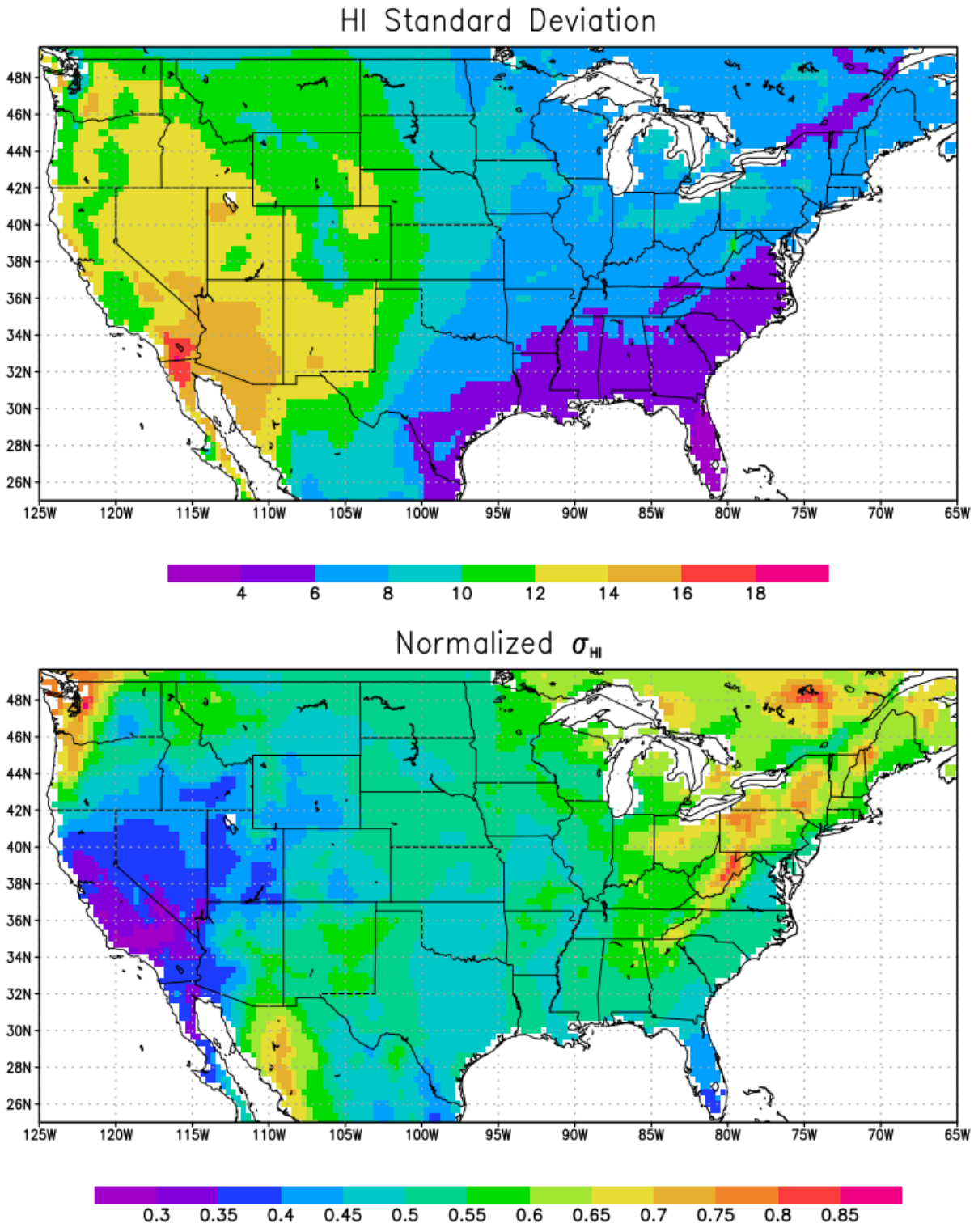


Figure 2.6: *Standard Deviation and Normalized σ_{HI}.* Top panel: A US map representing the standard deviation of HI. Bottom panel: A US map representing the normalized value (standard deviation ÷ mean) for HI. These maps represent the values over the 3312 days.

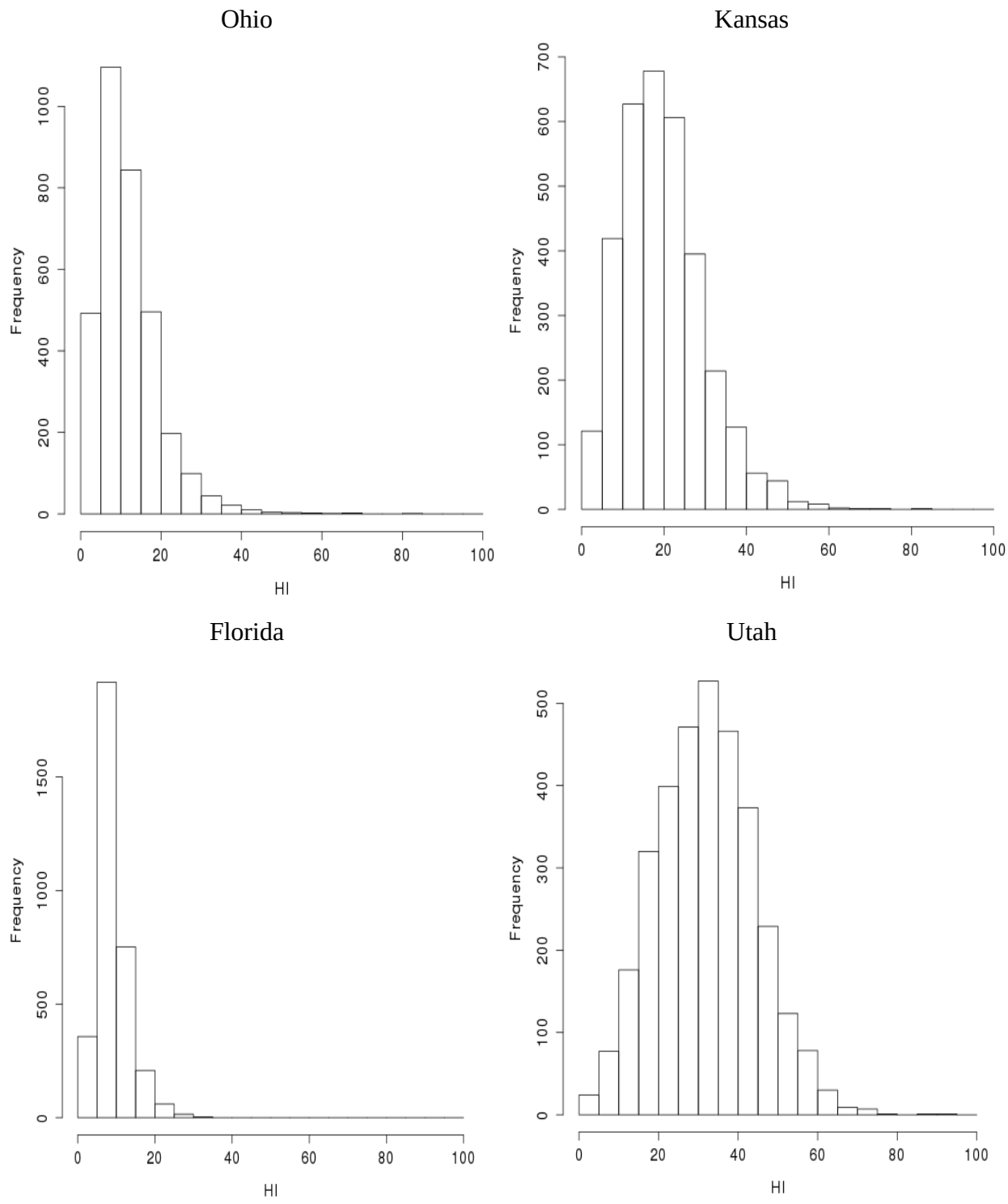


Figure 2.7: *Histograms of HI*. Histograms of HI for each of the four locations. (Note the y-axis changes)

The spatial variability of soil moisture fraction is expressed in Figure 2.8. The central US is outlined as an area that averages the lowest soil moisture fraction. These lower values of soil moisture (0.12-0.15) also extend to the southwest US where the high values of HI also existed. This is mostly due to the hot, dry climate in these areas. The central US which identifies with dry soil moisture conditions, also matches well with the Koster et al. (2004) paper that highlights this area where strong coupling between the land and atmosphere exists. The results from the Findell and Eltahir (2003b) study indicate that this area corresponds with the transition regions and the negative feedback region that exists in the south central US. Transition regions tend to correspond with strong coupling strength regions because between wet and dry climates evapotranspiration is more sensitive to soil moisture (Koster et al., 2004; Guo et al., 2006; Wei and Dirmeyer, 2012). Outside of that region the East Coast averages 0.27 for soil moisture fraction, indicative of a wetter climate. However, the majority of the West Coast has soil moisture fraction average values between 0.18 and 0.24, indicative of a drier climate. It should be noted that these average soil conditions are not only affected by the climate of the region, but also soil type, which is not explicitly discussed here.

The probability map of convective precipitation (Figure 2.9) is shown as the number of rain days divided by the total number of days (3312 days). The areas that have highest probability of convective precipitation are in Florida and east of the mountains in Colorado. The East Coast tends to have a probability over 0.5 and the Southeast has the highest frequency of convective rainfall close to a value of 1. The West Coast experiences the lowest probabilities of convective rainfall.

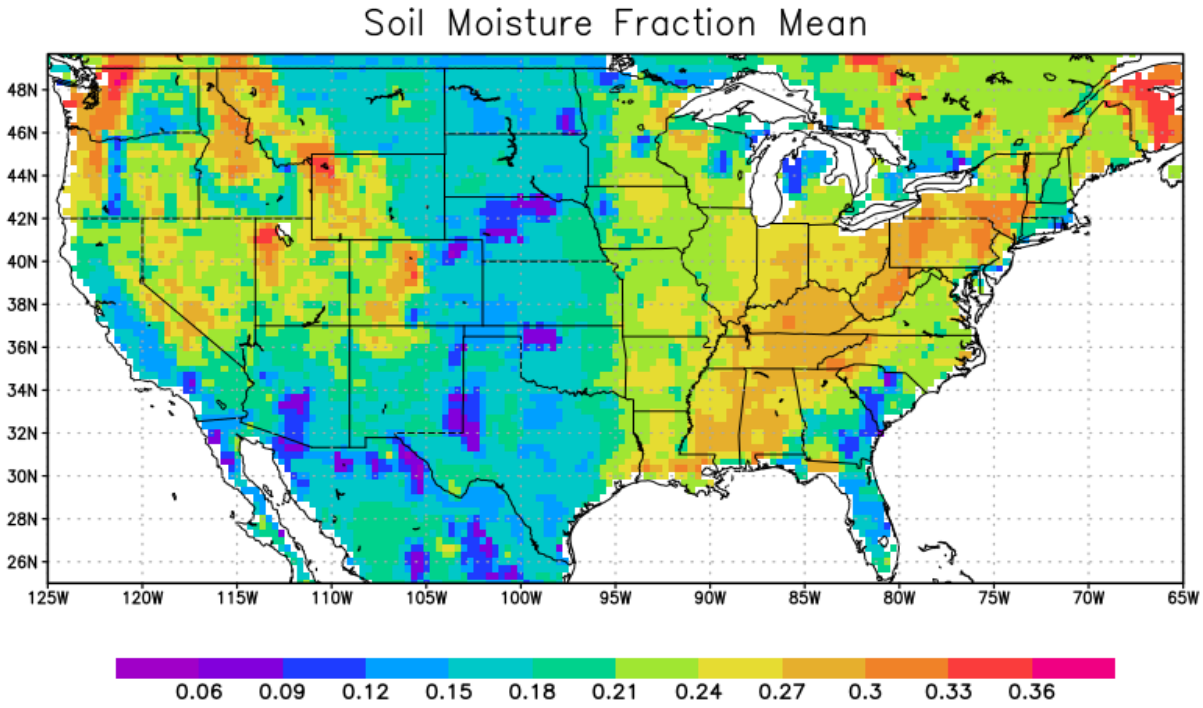


Figure 2.8: *Soil Moisture Fraction Mean*. A US map representing the average for soil moisture fraction for June, July, and August from 1979-2014. This represents the average for 3312 days.

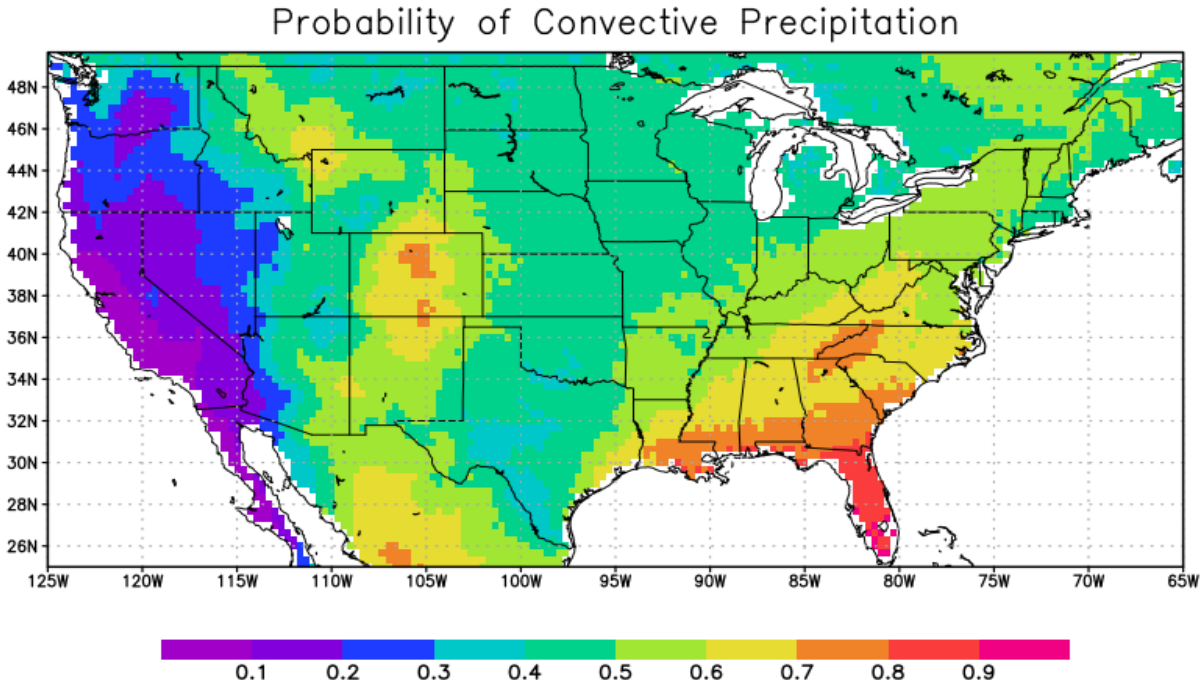


Figure 2.9: *Probability of Convective Precipitation*. A US map representing the probability for convective precipitation for June, July, and August from 1979-2014. This represents the probability out of 3312 days and the threshold for convective precipitation was any value greater than 0.01 mm.

2.3.2 Relationships between Each of the Four Variables

Time lagged scatter plots are produced to show the interaction between CTP, HI, soil moisture fraction, and accumulated convective precipitation across the CONUS. This shows the relationships between the morning conditions and time lagged correlations with precipitation. A statistical analysis was then conducted to emphasize the relationship between convective precipitation and soil moisture fraction.

Instability and moisture are vital elements in the process to initiate convection. In this study, CTP is representing the instability and HI is representing the moisture. The scatter plots in Figure 2.10 show two 6 panel plots, describing the relationship between each of the variables. The two plots are representative of southern Ohio and southern Kansas. The first two panels show the relationships between convective precipitation and the atmospheric variables, CTP and HI. These two plots indicate that there are optimal values for CTP and HI when precipitation occurs. For CTP these values exist between 100 J/kg and 300 J/kg, which suggests that there is instability in the atmosphere during days with precipitation. For HI, these optimal values are between 5 K and 15 K, which signifies that moisture is essential to produce significant precipitation. The third panel signifies the CTP versus HI relationship, which in Ohio shows a smaller range of CTP and HI values than in Kansas. Ohio experiences more days where the atmosphere is too stable to produce rain (negative CTP) and HI remains below 25 K a majority of the days. Kansas has a linear structure of this relationship and CTP and HI values extend up to and sometimes past 400 J/kg and 40 K, respectively. This relationship is caused by the hotter and drier conditions experienced in Kansas, which is not seen in Ohio.

The next relationship, soil moisture fraction versus HI, investigates the influence of soil moisture fraction on the low-level moisture at that location. The soil moisture can influence

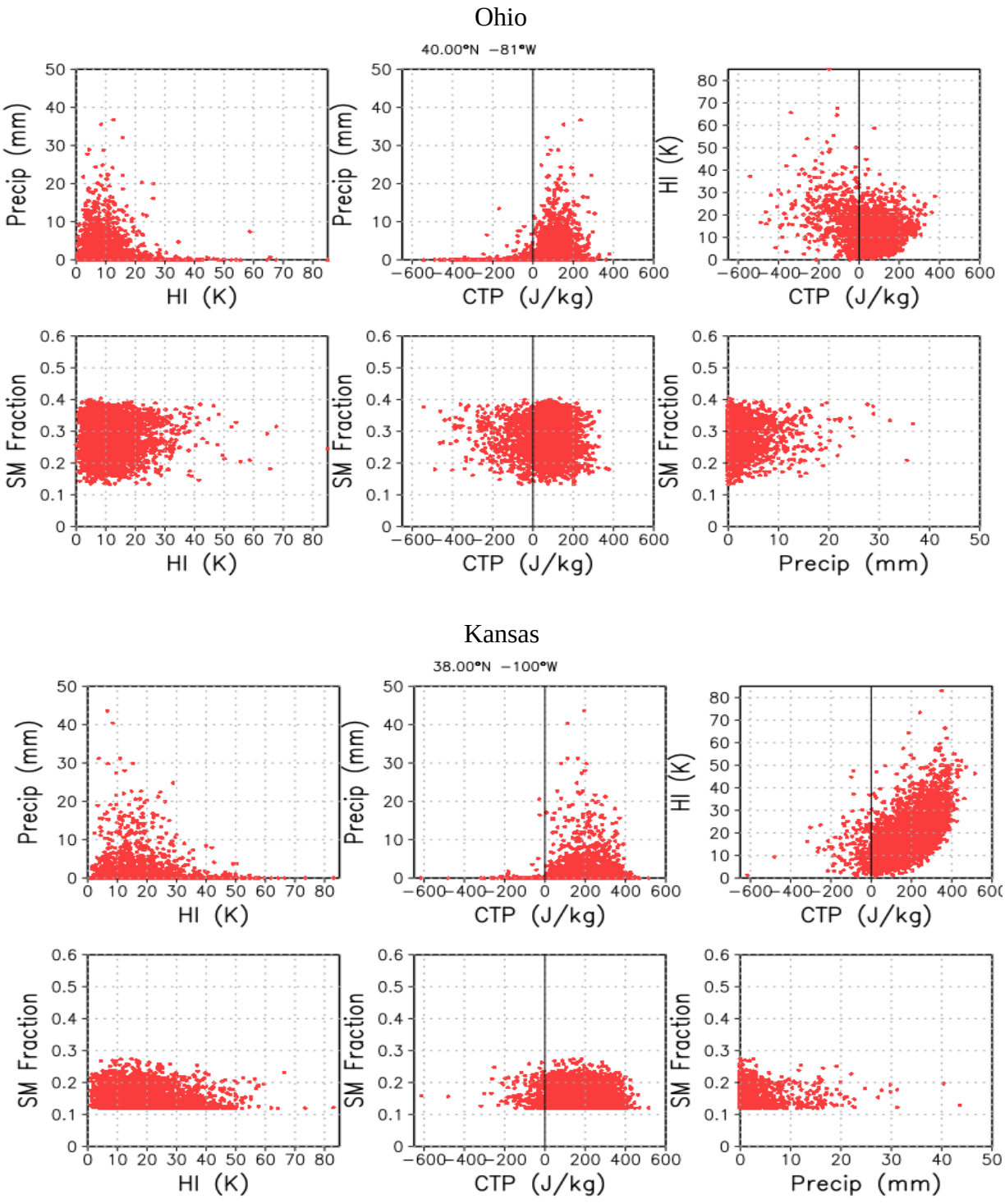


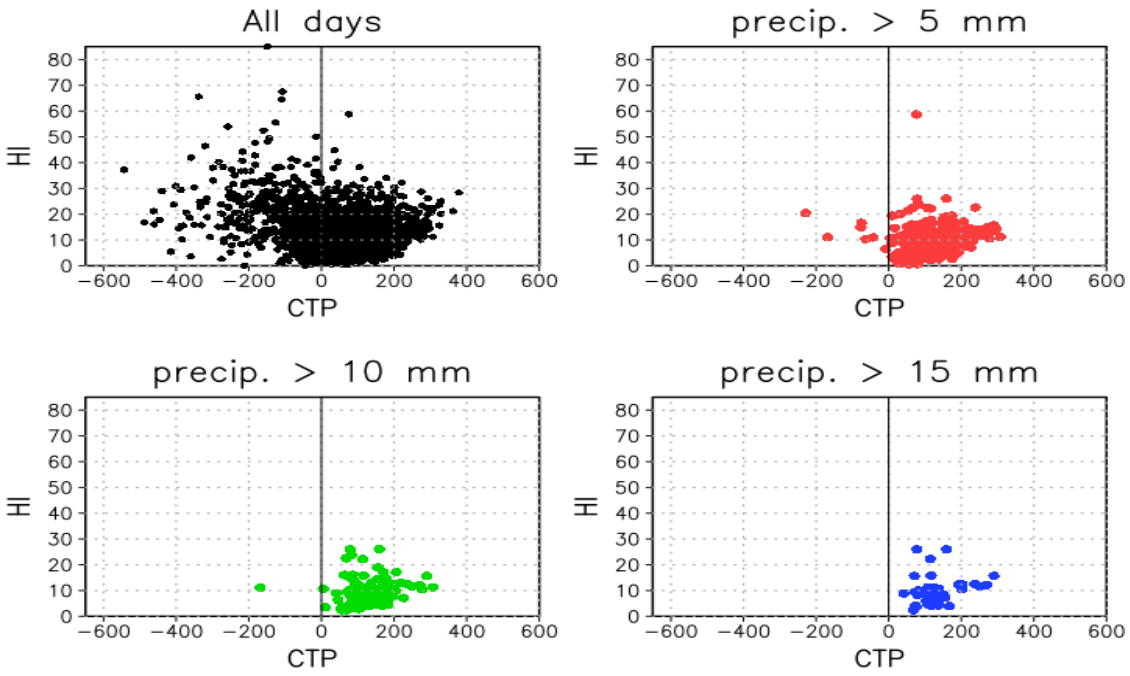
Figure 2.10: *Six Panel Scatter Plots*. Scatter plots representing relationships between each of the four variables. Top set of six panels represents Kansas and the bottom six panels represents Ohio. Top left panel: HI vs. CTP; top middle: Precipitation vs. CTP; top right: Precipitation vs. HI; bottom left: Soil moisture fraction vs. HI; bottom middle: Soil moisture fraction vs. CTP; and bottom right: Soil moisture fraction vs. Precipitation.

sensible and latent heat fluxes off of the surface, which impact the moisture content in the atmosphere at low levels. Previous work had indicated that soil moisture and HI have a linear relationship, where wetter soils were correlated with lower HI values (Ferguson and Wood, 2011). However, in this analysis a strong relationship between soil moisture fraction and low-level moisture was not apparent. This finding is interesting because it was expected that different soil moisture conditions would have a strong impact on HI.

The instability measure, CTP, also has an insignificant relationship with soil moisture fraction. Especially on the East Coast, where the soil moisture fraction has a larger range of values, a favorable condition of CTP is not shown.

Soil moisture fraction also did not necessarily indicate a relationship with convective precipitation. Areas of a wet or dry soil advantage could not be identified in the relationship between soil moisture fraction and convective precipitation in these time lagged scatter plots. Previous literature that investigates soil moisture-precipitation feedback at a daily timescale (Findell and Eltahir 2003b, Findell et al. 2011) associates the East Coast as a positive feedback area that favors wet soils. However, these results show that the wettest soils are not always favored with convection. Wetter soil moisture conditions could dampen the sensible heat flux and reduce the heat flow off the surface, which causes weaker instability. The hypothesis for the scatter plots was that the soil moisture fraction impacts the amount of water being evaporated from the surface, which influences the low-level moisture (HI) and the instability (CTP), to initiate convection. However, the scatter plots indicate that there is not a favorable environment for this to occur across a majority of the US. The scatter plots did show that the ranges in soil moisture fraction varied more in the eastern US and less in the western US, where it tends to be

Ohio



Florida

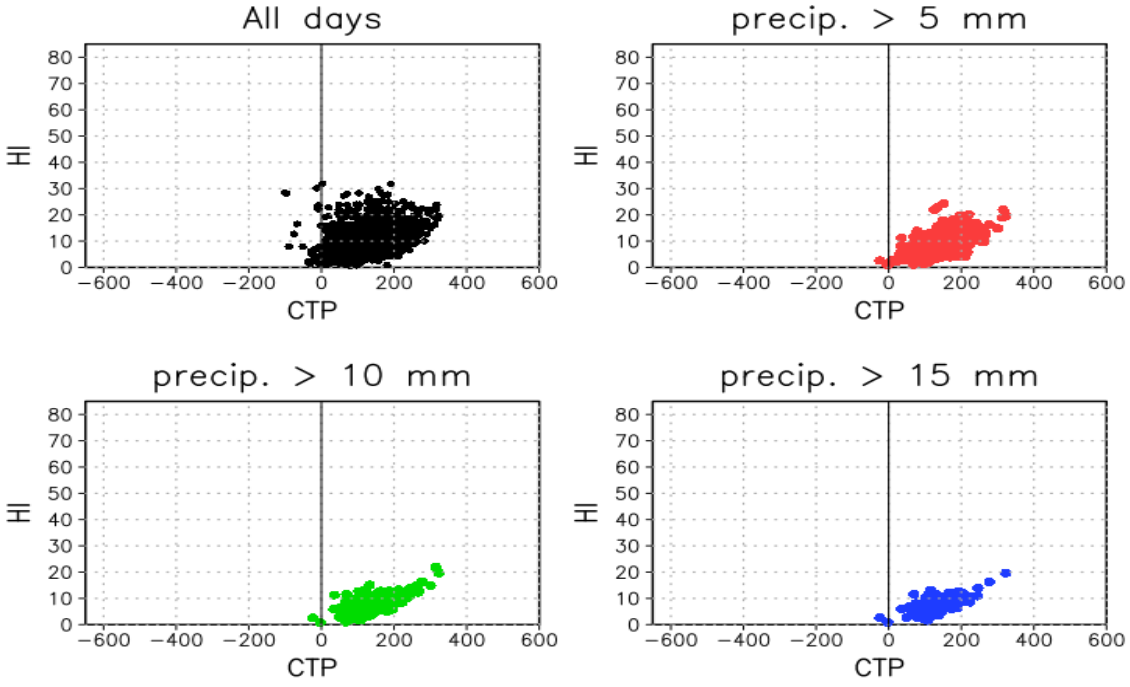
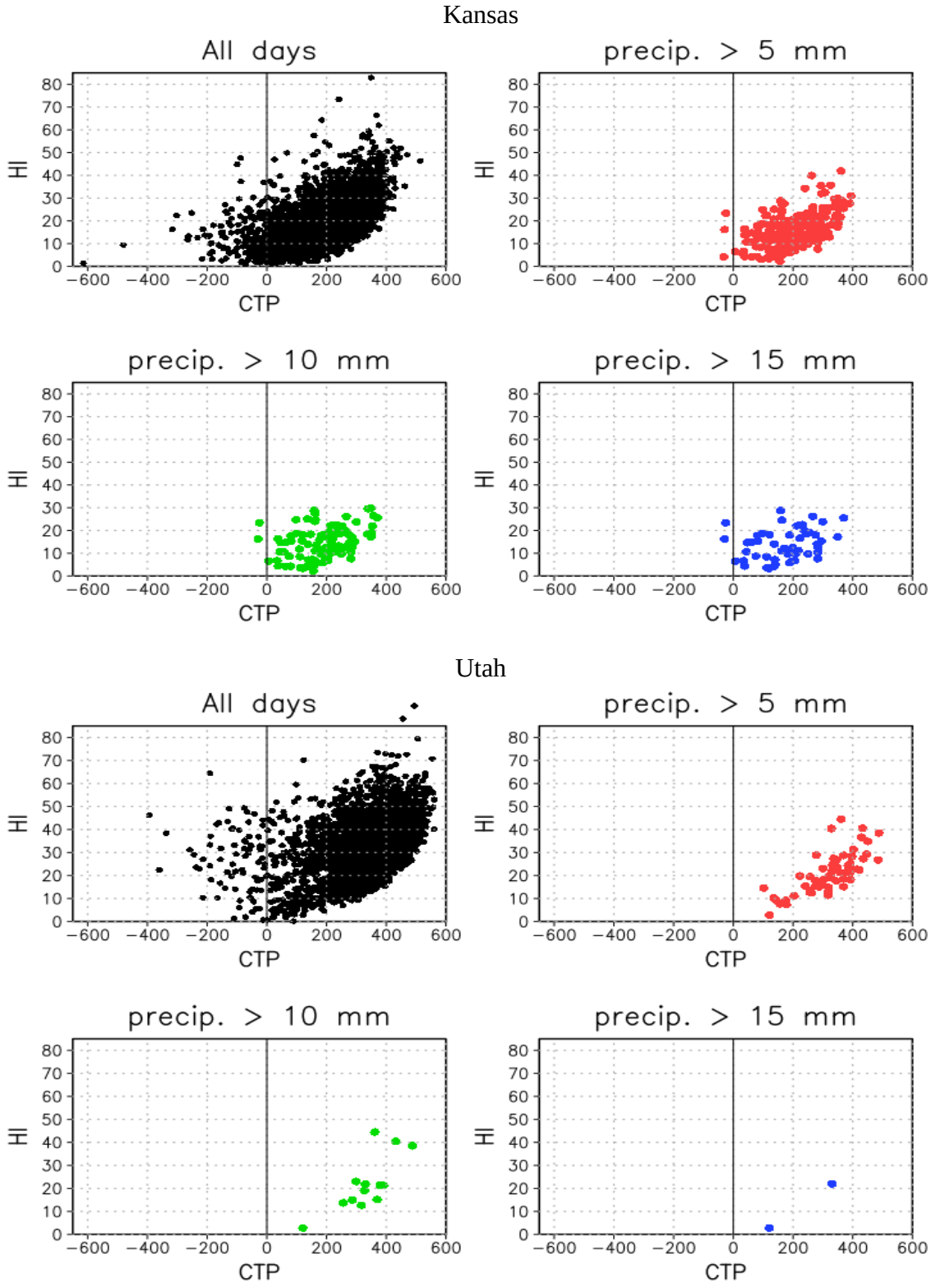


Figure 2.11: *HI vs. CTP*. Scatter plots of the HI versus CTP relationship, stratified by the amount of convective precipitation. The top four panel plots represent Ohio and the bottom four panels represent Florida. The top left panel: convective precipitation greater than 0 mm; top right: convective precipitation greater than 5 mm; bottom left: convective precipitation greater than 10 mm; bottom right: convective precipitation greater than 15 mm.

Figure 2.11 (cont'd). The top four panels represent Kansas and the bottom four represent Utah.



drier during the summer months. To enhance the analysis, figures are created to look at the differences between rain and non-rain days.

First, refined scatter plots are constructed at the four locations to emphasize the CTP, HI relationship with convective precipitation (Figure 2.11). The four locations, Ohio, Kansas, Florida, and Utah, show very similar pictures of the HI, CTP relationship. From these diagrams it indicates that ideal conditions for CTP and HI to initiate convection and produce heavy precipitation occur between the values of 100 J/kg and 300 J/kg for CTP and 0 K and 15 K for HI. However, Utah indicates convection over some larger values of CTP and HI due to the dry climate. These relationships were expected given the spatial maps of CTP and HI across the CONUS and the scatter plots. These results indicate that convection is most likely when there is low-level moisture and marginal instability.

To further understand the relationship between soil moisture fraction and precipitation, bar frequency charts are created for rain and non-rain days (Figure 2.12). Starting with Ohio, it displays a fairly normal distribution with a large range of soil moisture values. The highest frequency of convective precipitation occurs at a soil moisture fraction between 0.30 and 0.35. This indicates that convection occurs most of the time under a wet soil advantage in this area. Kansas shows a skewed distribution with highest frequency of precipitation occurring at drier soil moisture conditions between 0.10 and 0.15. This area experiences predominantly dry soil conditions. Florida indicates a slightly normal distribution with the soil moisture fraction range being between 0.15 and 0.20 when the greatest frequency of precipitation occurs. This location also reveals a larger range for soil moisture conditions between 0.00 and 0.30 and indicates a high frequency of precipitation days at dry soil moisture conditions. Previous literature denotes Florida as a positive feedback area (Findell and Eltahir, 2003b; Findell et al., 2011), so the

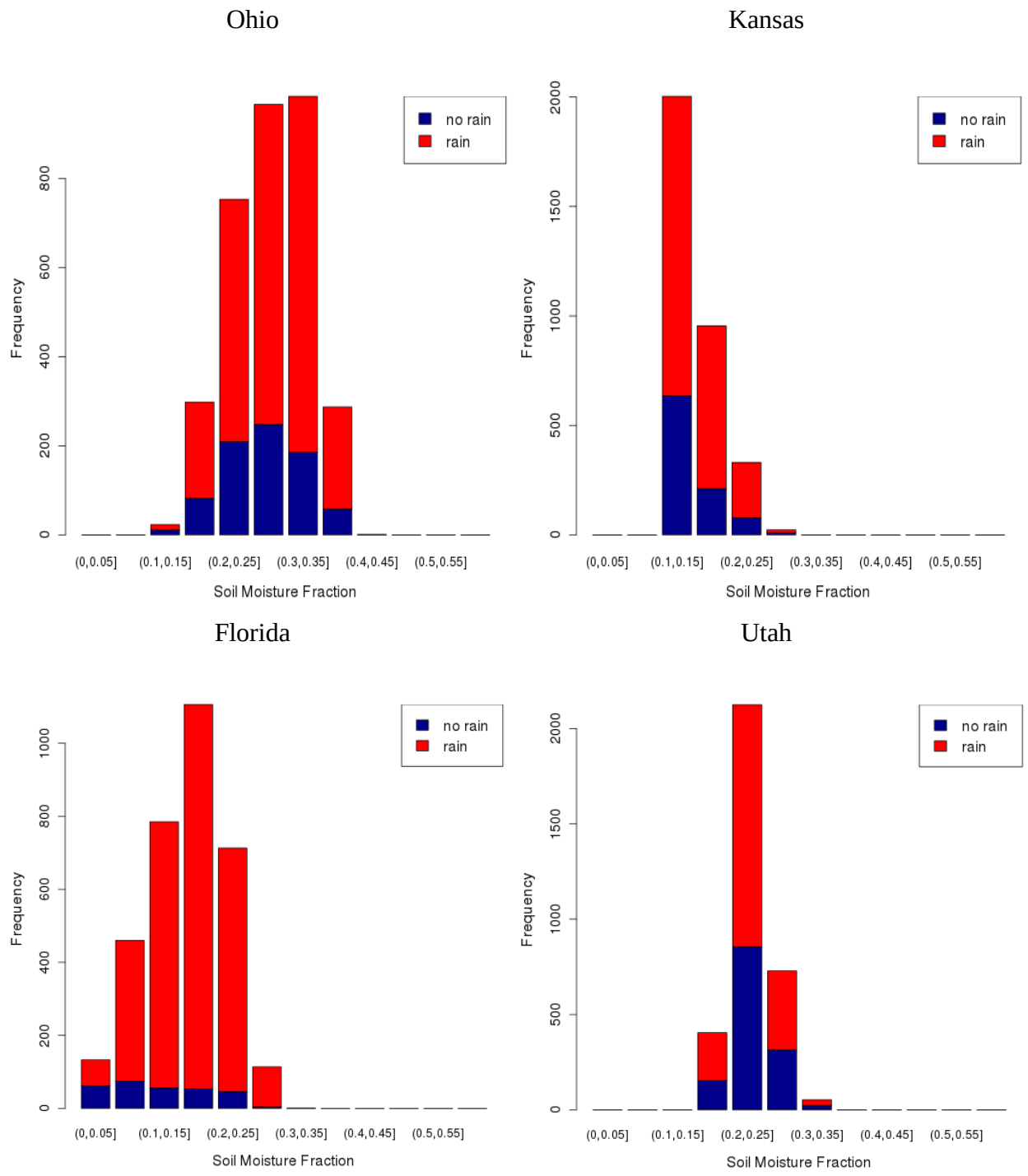


Figure 2.12: *Precipitation Frequency vs. Soil Moisture*. Precipitation frequency versus soil moisture fraction bar charts. 1 or red represents rain days and 0 or blue represent non-rain days. The y-axis of precipitation frequency is in number of days. Soil moisture fraction is separated into bins the width of 0.05 on the x-axis.

expectation was that the soil moisture values would be wetter in this area. However, Florida produced precipitation at dry soil moisture conditions, which was also indicated in the soil moisture fraction mean map (Figure 2.8), where the average value is about 0.15. This is the same average value seen in the central US where large coupling strength also exists. Therefore, the convection triggered over Florida is sensitive to soil moisture conditions and heat fluxes off the surface.

Utah has the most frequent precipitation when soil moisture conditions occur in the range of 0.20 to 0.25. The majority of all the days fall into this bin, which makes it uncertain if this area has a wet or dry soil advantage. These charts indicate that the highest frequency of precipitation has favorable soil conditions at each location. The results in Ohio show the likelihood for precipitation to occur under higher soil moisture fraction. The central US location, Kansas, identifies precipitation at low soil moisture fractions, but as the soil moisture fraction increases there are more rain days than non-rain days. This wet soil advantage is also evident in Ohio and Florida. While Utah experiences a small range of soil moisture conditions and it is inconclusive if wetter or drier soils are favored.

The Kolmogorov-Smirnov (KS) test is used to further examine the relationship between soil moisture fraction and convective precipitation. The KS test is based on the empirical cumulative distribution of two datasets. The two datasets that are being compared are soil moisture on days that it rained and soil moisture on days that it did not rain. The KS test determines whether the two datasets are statistically significantly different by testing the distance between the empirical cumulative distributions of both datasets. The KS test provides a D-statistic that is used to test the significance with a p-value. The D-statistic is calculated as the largest distance between these two distributions. In this study, the two-tale significance is based

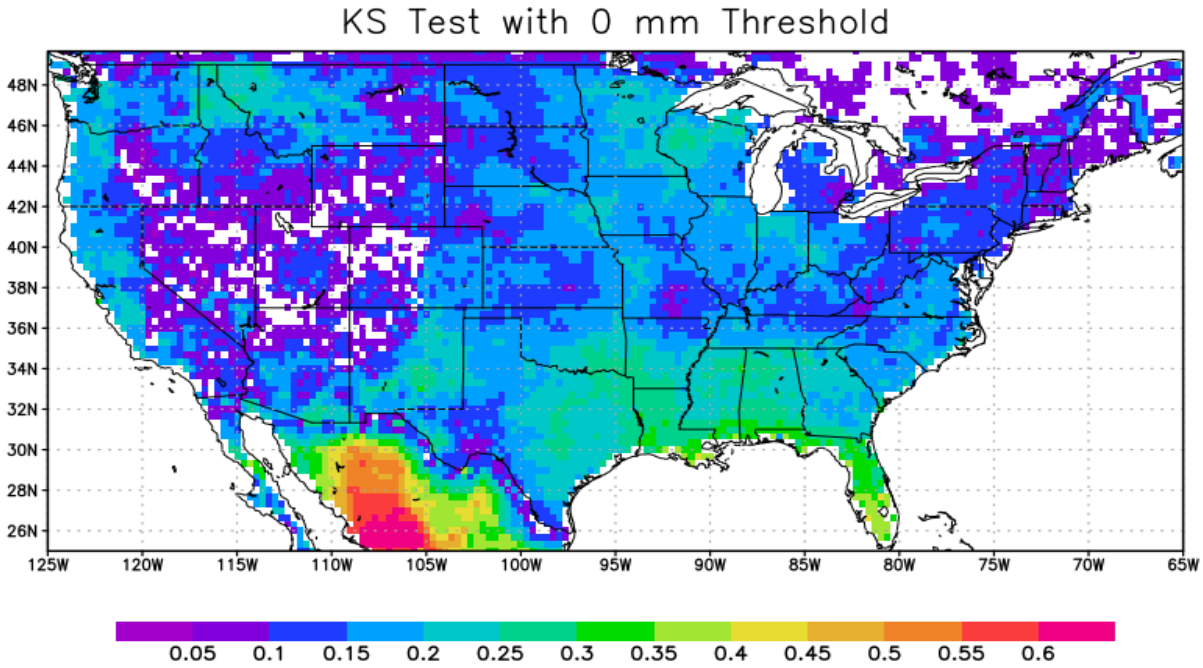


Figure 2.13: *KS Test with 0 mm Threshold*. The KS test done with the distribution of soil moisture fraction on rain and non-rain days. The shaded area represents the D-statistic and the values are represented by the color bar. Only the shaded area is significant at a p-value of 0.05. The white areas are not significant.

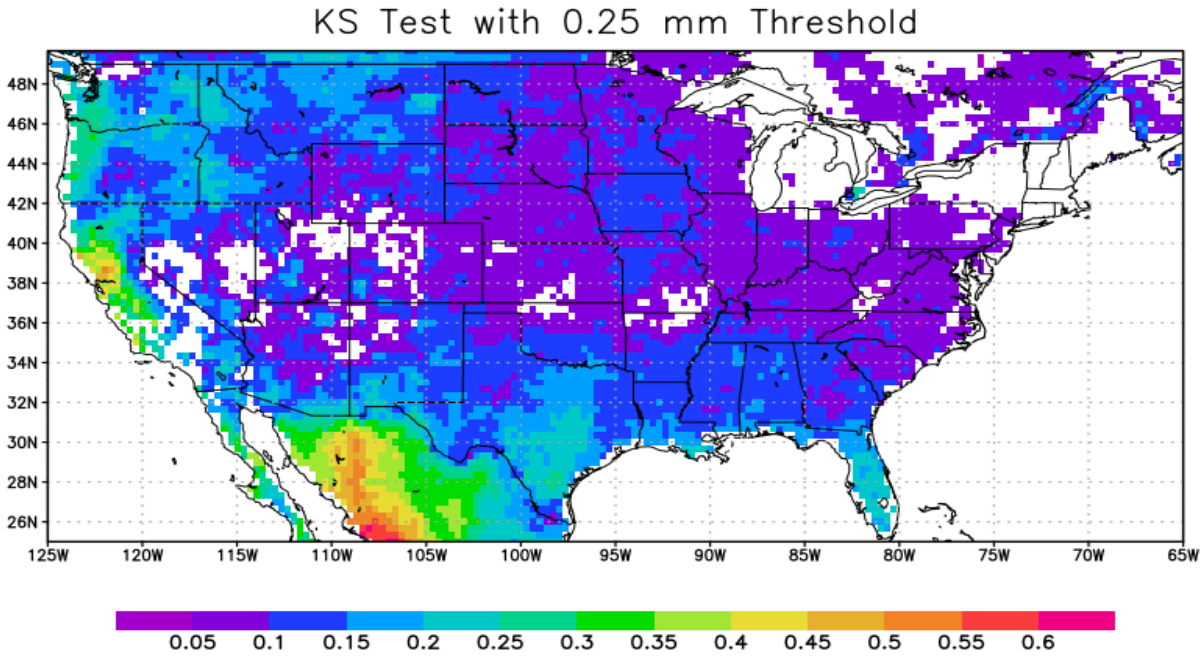


Figure 2.14: *KS Test with 0.25 mm Threshold*. The KS test done with the distribution of soil moisture fraction on rain and non-rain days. Where non-rain days are include days that have up to 0.25 mm of rain. The shaded area represents the D-statistic and the values are represented by the color bar. Only the shaded area is significant at a p-value of 0.05. The white areas are not significant.

on a p-value less than 0.05. The first test uses soil moisture fraction on rain and non-rain days and it shows that the majority of the US produces a D-statistic that is significantly different (Figure 2.13). However, there are a few small areas over the mountains that are not statistically significant, which could be caused by the topography in this area.

The same test was done using a threshold for precipitation of 0.25 mm (Figure 2.14). This considered days with less than 0.25 mm of rain as a non-rain day, which signifies a relationship between soil moisture fraction and convective precipitation intensity. The KS test indicates different results, especially in the Great Lakes Region. Most of the state of Michigan and the New England states are not statistically different. This may be caused by the lake-induced climate in these areas. There are also a few small regions of insignificance in the central US, but the majority of US still shows a significant difference between soil moisture on rain and non-rain days. This implies that the soil moisture anomaly contributes to the process of convective initiation (a necessary condition), but it is not always a sufficient condition alone to generate significant rainfall. In other words, in regions with positive feedback, convective precipitation is more likely associated with wetter soil conditions, but a wetter soil condition does not guarantee a convective storm in the afternoon.

The empirical cumulative distributions of soil moisture on rain and non-rain days can be visualized in Figure 2.15. The examples are taken from the four main locations that are representative of the test using 0 mm as the threshold. Starting on the East Coast in Ohio, the biggest gap in the distributions occurs at a soil moisture fraction of approximately 0.30. Also, the distribution for rain days is shifted to the right of the non-rain distribution. This indicates that as the soil gets wetter it becomes more likely it will rain, indicative of a wet soil advantage. The other eastern US location, Florida, shows very large distances between the distributions of rain

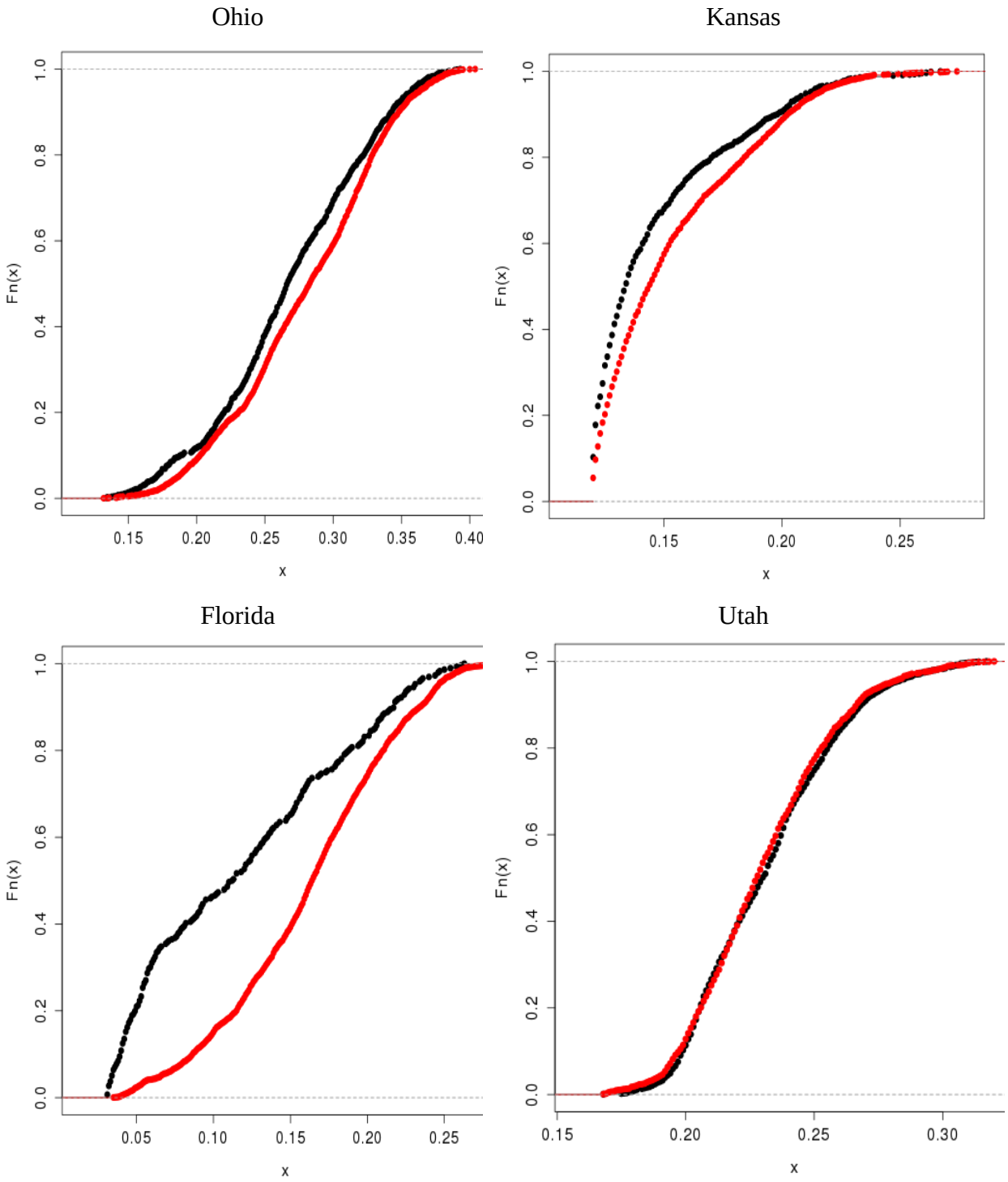


Figure 2.15: *Empirical Cumulative Distributions*. The empirical distribution of soil moisture for rain days and non-rain days. The red line represents the distribution on rain days and the black line represents the distribution on non-rain days.

and non-rain days. This occurs at small soil moisture fraction values between 0.05 and 0.15. The steep rise in the distribution on non-rain days indicates that very dry conditions in Florida do not favor convection. The overall range of soil moisture fraction values in Florida are fairly dry. Yet, this location also indicates a wet soil advantage on days with rain due to the rightward shift of the rain cumulative distribution compared to the cumulative distribution on non-rain days. Moving to the west, Kansas has the greatest distance in distributions at a soil moisture fraction between 0.15 and 0.20. The shape of the distributions indicate that soil moisture conditions are skewed toward drier soils. However, as the soil moisture fraction increases, it becomes more likely that it will rain, also indicating a wet soil advantage. In Utah, due to the limited nature of precipitation days and the dry summer conditions, the cumulative distributions remain fairly similar to each other and there is not a strong difference. That is indicative in the KS test map where areas in Utah are not significant at a p-value of 0.05. Due to the insignificance in the Great Lakes region at the 0.25 mm threshold, the distribution from New York is also shown (Figure 2.16). This also shows the insignificance in this area where the distributions are close together.

Overall, the KS test displayed that convective precipitation is sensitive to soil moisture conditions on that day. Some areas show a distinct difference, such as Florida, while Utah had very small differences between the distributions.

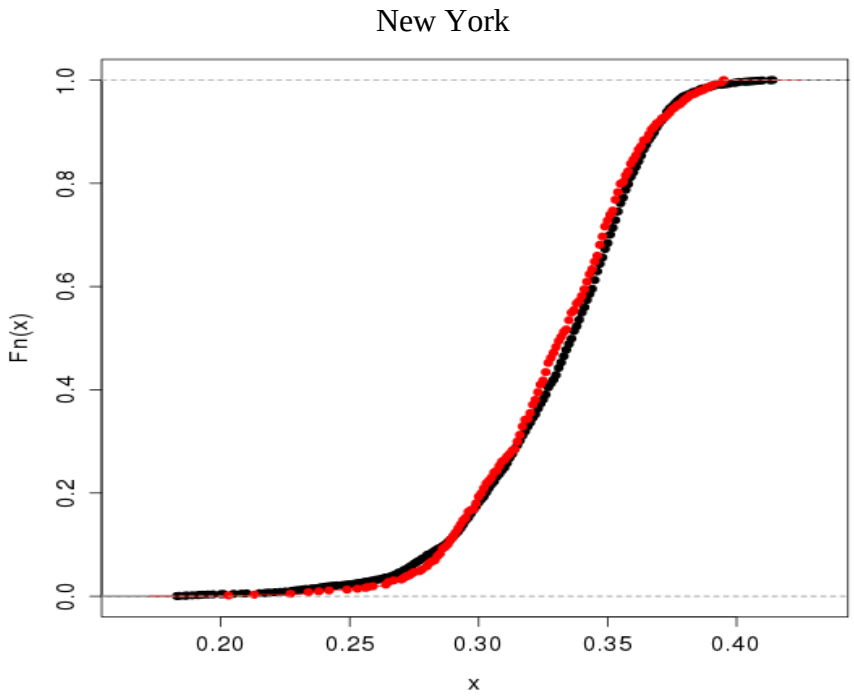


Figure 2.16: *New York Empirical Cumulative Distribution*. The empirical distribution of soil moisture for rain days and non-rain days for Central New York. The red line represents the distribution on rain days and the black line represents the distribution on non-rain days that are classified as less than 0.25 mm.

CHAPTER 3: Conclusion and Discussion

The first objective of this research was to identify the relationships between CTP, HI, soil moisture fraction, and convective precipitation. Scatter plots were developed to analyze these relationships. These results mainly indicated optimal values for CTP (100-300 J/kg) and HI (5-15 K) when convective precipitation occurred. Identifying regions of a wet or dry soil advantage from the scatter plots was inconclusive. Therefore, a statistical analysis was conducted to focus on the soil moisture-precipitation relationship on rain and non-rain days.

These results indicated favorable soil conditions for convection in each area and the KS test identified that soil conditions were significantly different on rain and non-rain days. The soil moisture fraction and precipitation frequency results determined that the majority of the eastern US had a greater potential to produce rain over wet soils, while in the Central Plains area and Florida, rain was mainly produced over dry soil conditions. The Central Plains area was previously noted as an area with strong land-atmosphere coupling and a transition region (Koster et al., 2004; Koster et al., 2006; Findell and Eltahir, 2003b). Florida, which has been distinguished as a positive feedback area (Findell and Eltahir, 2003b; Findell et al., 2011), showed that soil conditions tend to be drier in this region. However, Florida consistently experiences low values of HI indicative of significant low-level moisture. Therefore, the hot, humid climate along with atmospheric processes, such as the sea breeze, could have a strong effect on convection in this area. In the Intermountain West it was unclear if a specific soil wetness was favored to initiate convection due to the oceanic influence and the small amount of rain that does occur in a majority of this region during the summer.

The KS test revealed that there are differences in soil moisture when comparing rain versus non-rain days. It was noted that a wet soil advantage occurred in Ohio, Kansas, and

Florida. These results imply that soil moisture has an impact on convective initiation. However, the soil moisture condition may not always be sufficient enough to produce precipitation. This is a crucial finding: convective precipitation is sensitive to soil moisture conditions throughout the majority of the US. Although wet and dry soil advantages can be determined in some areas of the US, this does not isolate convection to just those soil moisture conditions.

This study also went on to further investigate wet and dry soil advantages by stratifying the data by mean sea-level pressure. The mean sea level pressure was used as a threshold in forming the six panel scatter plots. Pressure values below 1015 hPa were excluded to eliminate days that were driven by atmospheric forces. These would include low pressure systems, frontal passages, and possible dry lines. Therefore, omitting these days would ensure that the influence of soil moisture and surface conditions would have a prominent role in the process of initiating convection. However, when the data was stratified by pressure, there were only slight changes in the ability to identify areas where wet or dry soils were favored. In the Central Plains region, it appeared that locations showed favorable conditions to produce convection with drier soil moisture fraction, which was also indicated in the previous results.

Some future work that could be considered is to focus on a small domain or region, instead of individual points. This would allow for the surrounding soil conditions to be included in the evaluation of precipitation that occurs within a given domain. Using a domain would also account for moisture transport and provide the ability to look at downwind effects. In another study it was found that transported moisture dominates over evapotranspiration in the southern Great Plains (Ruiz-Barradas and Nigam, 2013). Soil moisture has been noted to have a nonlocality effect and to produce precipitation downwind of where soil moisture and evaporation have the most variability (Lintner and Neelin, 2009, DeAngelis et al., 2010). Previous work done

in Europe, found that convective initiation was favored downwind of drier surfaces, where the soil moisture was transitioning toward wetter conditions (Seneviratne et al., 2006; Taylor et al., 2015). If the results from this current study could be broadened into analyzing a small domain, it could provide a more complete analysis of the soil moisture-precipitation relationship.

Understanding the soil moisture-precipitation relationship is very complex due to the atmospheric responses that are necessary for precipitation to occur. The spatial and temporal scale of this feedback is crucial to acknowledge in this research field. Although the NARR dataset provides this research with comprehensive spatial and temporal data, the horizontal resolution may not be fine enough to capture the mesoscale features of this process. In land-atmosphere interactions research, there has been a growing necessity to investigate these processes with higher resolution data. There is also a need for better lower-atmosphere field measurement systems, like the Oklahoma Mesonet (ex: Ford et al., 2015). The triggering of convection is complicated and the ability to capture the fine-scale processes is still a difficult task. There have been some studies that have analyzed the soil moisture-precipitation relationship at a smaller scale, such as a basin or small region, where the land-atmosphere processes are less variable (Findell and Eltahir, 1997; Findell and Elathir, 2003a; Frye and Mote, 2010; Zamora et al., 2014; Taylor et al., 2011; Taylor et al. 2015). Studies like these are very beneficial to enhance the knowledge on this topic, but there are also benefits to understanding these interactions over larger areas, such as the CONUS.

This study demonstrates the large scale variability of soil moisture and its effect on convective precipitation. It also displays that although soil moisture can have an incident effect on heat fluxes from the surface and evapotranspiration, it does not always lead to precipitation. The initial six panel scatter plots did not show a relationship between soil moisture fraction and

HI, CTP, or convective precipitation. Therefore, these impacts of soil moisture can be relatively small in the process of the soil moisture-precipitation relationship. The atmospheric processes can also override the soil moisture impacts and have a large influence on the development of convection. While soil moisture is still essential to this process, it is important to acknowledge that there are ultimately other processes that happen between the surface layer and the upper atmosphere that impact the ability for convection to occur.

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