# Observation-Driven Characterization of Soil Moisture-Precipitation Interactions in the central United States

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**Key Points:**

- The sign and strength of soil moisture-precipitation coupling was assessed using thousands of convection events points in the central US
- Multiple regions show signs of both wet and dry soil feedbacks, with strong coupling between soil moisture and surface heat flux
- Climatological assessment and process-based metrics confirmed wet- and/or dry-soil feedbacks leading to convection in the central US

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## Abstract

Soil moisture feedbacks that initiate, enhance, or suppress convection initiation and precipitation are important components of regional hydroclimatology. However, soil moisture feedbacks and the processes through which they operate are notoriously challenging to observe and study outside of model environments. In this study, we combine a climatological assessment of event frequency-based measurements of soil moisture-precipitation coupling in the central United States with a process-based analysis of the mechanisms by which wet- and dry-soil feedbacks may operate in the region. We use the Thunderstorm Observation by Radar (ThOR) algorithm to identify the location of convection initiation, circumventing the issue of using precipitation accumulation as a proxy for convection initiation. Results show substantial spatial variability in the climatological sign and strength of soil moisture-precipitation coupling in the central United States, including regions that exhibit signs of both wet- and dry-soil feedbacks. Within the regions with the strongest feedback signals, we find consistently strong coupling between soil moisture and the partitioning of surface heat flux, and strong coupling between surface heat flux – particularly sensible heat flux – and diurnal change in Planetary Boundary Layer height. In all three regions assessed, the process-based metrics confirmed the potential of wet- and/or dry-soil feedbacks leading to convection initiation.



## Plain Language Summary

Soil moisture can affect the occurrence, location, and intensity of precipitation in many global regions. Observations of the drivers of so-called soil moisture feedbacks are important for constraining models; however, feedbacks are challenging to observe and study outside of model environments. We use a dataset of thousands of thunderstorm initiation locations with model-based soil moisture to measure the sign, strength, and variability in soil moisture feedback to precipitation in the central United States. We denote three regions with strong evidence of both wet-soil and dry-soil feedbacks to precipitation.

## 1. Introduction

Soil moisture has an integrative role in the regional-scale environment, and directly influences atmospheric processes (Seneviratne *et al.* 2010; Miralles *et al.* 2019). Soil moisture is also a key variable for land-atmosphere interactions because it governs and partitions surface-atmosphere energy flux (Ford *et al.* 2014; Schwingshackl *et al.* 2017). It is through modifications to latent and sensible heat flux that soil moisture can affect precipitation and near-surface air temperature (Wakefield *et al.* 2019; Lawston-Parker *et al.* 2021). Such soil moisture linkages with atmospheric processes and resultant precipitation or temperature patterns occur on a spectrum of timescales, generally ranging from diurnal to seasonal (Saini *et al.* 2016; Talib *et al.* 2022; Liu *et al.* 2022). At one end of the spectrum, large scale soil moisture patterns can influence subseasonal to seasonal anomalies of precipitation and temperature to varying degrees (Teng *et al.* 2016; Chevuturi *et al.* 2021), providing an important form of predictability at those timescales (Prodhomme *et al.* 2016). On diurnal timescales, soil moisture-driven anomalies of surface heat fluxes can modify planetary boundary layer (PBL) growth, aiding or impeding local- to regional-scale convection initiation and precipitation (Ek and Holtslag, 2004; Cioni and Hohenegger *et al.* 2017). Numerous studies have demonstrated – via observations and models – the importance of such diurnal-scale soil moisture feedbacks to the hydroclimatology of many global regions (Taylor *et al.* 2011; Duerinck *et al.* 2016; Bieri *et al.* 2021; Wang and Quiring, 2021).

Prior research suggests wetter soils tend to partition a larger proportion of surface-atmosphere energy flux as latent heat, which can lower the lifting condensation level (LCL) height and, along with potentially increasing convective available potential energy, create an environment conducive to convection initiation and precipitation (Santanello *et al.* 2013; Lawston-Parker *et al.* 2021). While dry soils can act to suppress this pathway to precipitation, they can also initiate deep convection via strong surface sensible heat flux and corresponding PBL growth. Strong PBL growth supports entrainment of cooler, drier air and increases the potential of parcels reaching the LCL and subsequent precipitation (Yang *et al.* 2018; Qiu and Williams, 2020). These processes describe the general pathways of wet soil and dry soil feedbacks, respectively. Furthermore, several observation and modeling studies have established process chains to understand and model the pathways through which soil moisture feedbacks may operate (Lawston-Parker *et al.* 2021; Martius *et al.* 2021). These studies generally refer to separate wet and dry soil feedback process chains, which are further decomposed into terrestrial (i.e., soil moisture to surface flux) and atmospheric (i.e., surface flux to boundary layer atmosphere) legs (Baker *et al.* 2021).

Despite the general scientific consensus that diurnal soil moisture feedbacks play an important role in shaping regional hydroclimatology, prior studies show less agreement as to the feedbacks' sign and strength. Modeling- and observation-based studies have found evidence for either or both wet and dry soil feedbacks to precipitation in many global regions (Guillod *et al.* 2015; Vecellio *et al.* 2019; Klein and Taylor, 2020; Huggannavar and Indu, 2020; Graf *et al.* 2021; Jach *et al.* 2021). The inconsistencies between studies are attributable to multiple factors, such as (1) the paucity of high-quality observations from vadose zone to boundary layer and the consequential reliance on regional- to global-scale models, (2) the challenge of establishing causality of a soil moisture feedback to precipitation in the face of many confounding factors, and (3) the frequent inference of feedback sign and strength from a single metric applied to a relatively large spatial area. In regard to the last of these issues, many metrics used to study soil moisture feedbacks have been shown to be highly sensitive to datasets used (Ford *et al.* 2018), spatial resolution (Taylor *et al.* 2013; Yuan *et al.* 2020), and the background synoptic environment (Tuttle and Salvucci, 2017; Welty *et al.* 2020).

The ability of Earth system models to properly simulate soil moisture feedbacks at diurnal timescales is dependent on constraining such models with high quality observations of soil moisture, surface heat flux, planetary boundary layer modification, and precipitation. Therefore, a better understanding of land-atmosphere interactions, both through observational and modeling studies, can improve simulation accuracy of these interactions and resultant convective precipitation in operational and experimental models. With this in mind, we seek to build on prior studies and provide an observation-driven analysis of soil moisture-atmosphere interactions leading to convection initiation in the central United States. We combine frequently used statistical metrics for characterizing soil moisture feedbacks with a process-based deconstruction of the wet- and dry-soil pathways through which the feedbacks operate. Additionally, we use a large dataset of observed convection events to ensure robust analysis of regional-scale feedbacks. While this study does not seek to address all shortcomings and limitations of previous research, we do undertake a detailed assessment of the connections between land and atmosphere, and leverage a unique dataset to remark on the relevance of these connections to precipitation in the central US.

## 2. Data & Methods

### *2.1 Convection Initiation*

Most previous observation-based land-atmosphere interaction studies have been limited to using precipitation accumulation or location as a proxy for convection initiation. However, the dynamic and thermodynamic mechanisms responsible for coupling the terrestrial and atmospheric segments of the feedback process occur prior, and likely upwind of the location of precipitation initiation. To circumvent this issue, this study uses the Thunderstorm Observation by Radar (ThOR, Houston *et al.* 2015) algorithm to identify the location of convection initiation. ThOR is an automated method for identifying deep convection that utilizes WSR-88D radar data, cloud-to-ground lightning observed by the National Lightning Detection Network, and storm motion grids form the North American Regional Reanalysis. Houston *et al.* (2015) verified ThOR against 166 manually analyzed deep convection tracks and using descriptive statistics applied to a large sample (~35,000 tracks). ThOR has been used to study the factors regulating deep convection (Lock and Houston, 2014), for surveying the spatiotemporal patterns of deep convection across the central United States, and for characterizing the sensitivity of soil moisture-precipitation coupliFng sign/strength to soil moisture datasets (Ford *et al.* 2018). The ThOR algorithm runs at an effective spatial resolution of 1 km across the contiguous United States (Houston *et al.* 2015).

This study uses over 80,000 afternoon (1200 – 2000 LST), warm season (May-September) thunderstorm initiation points over the time period 2005 – 2017 (supplemental Figure S1) to determine the location of convection initiation in the central United States, defined here as 25° - 50°N latitude x 109° - 88°W longitude.

### *2.2. Soil Moisture*

The soil moisture datasets available for geospatial analysis can be generally divided into four categories: (1) *in situ*, (2) satellite-based, (3) model-based, (4) assimilated or hybrid (Brocca *et al.* 2017). *In situ* observations are ideal for accurately depicting soil moisture conditions, but their spatial representativeness can range from a few kilometers to just a few meters depending on land cover, soils, and topography (Dorigo *et al.* 2011). Microwave satellite remote sensing provides a spatially comprehensive and cohesive observation of soil moisture (Babaeian *et al.*

2019), but typically can only observe the top 5-10 cm of the soil column (Brocca *et al.* 2017). Often, this is insufficient in regions where surface-atmosphere energy exchange is modulated more by vegetation root uptake and transpiration than by direct soil evaporation. Land surface models can simulate root zone soil moisture dynamics, but like any model, they are constrained by uncertainties in model physics and input data quality (Ford and Quiring, 2019). The final category, hybrid soil moisture datasets, leverage the observation advantage of satellite products with the soil depth advantage and internal consistency of land surface models by assimilating satellite surface observations in a land surface model.

In this study, we represent soil moisture underlying convection initiation using a hybrid product called SoilMERGE (SMERGE, Tobin *et al.* 2019). SMERGE represents root zone (0 – 40 cm) soil moisture by merging observations from the European Space Agency's Climate Change Initiative (ESA-CCI, Dorigo *et al.* 2017) product with the Noah land surface model as part of the North American Land Data Assimilation System (NLDAS-2). SMERGE provides daily soil moisture at a 0.125° spatial resolution across the NLDAS domain.

### *2.3. Surface Heat Flux & Boundary Layer Conditions*

Soil moisture-atmosphere interactions rely on surface-atmosphere energy flux to link the terrestrial and atmospheric segments of the process. Therefore, the study uses hourly sensible and latent heat flux information from ERA5 reanalysis (Hersbach *et al.* 2020) to represent that linkage and test for coherency between the anomaly of soil moisture and the corresponding anomaly in surface heat flux partitioning. In comparison with observations and other reanalysis products, Martens *et al.* (2020) found ERA5 provides high quality surface heat fluxes. In this study, ERA5 sensible and latent heat flux are used at their native spatial resolution (approximately 31 km) to calculate evaporative fraction (EF), which is the ratio of latent heat flux to the sum of latent and sensible heat flux. EF is a good indicator of surface heat flux partitioning and has been widely used to measure the sign and strength of land-atmosphere interactions globally (Ukkola *et al.* 2018; Christian *et al.* 2020). In this study, we compute EF using the total cumulative latent heat flux and sensible heat flux between 0600 LST and the hour prior to convection initiation (as determined by ThOR). We also computed EF hourly using the instantaneous values of ERA5 latent and sensible heat flux and then averaged the hourly EF values between 0600 LST and the hour prior to initiation. We did not find any significant difference in the results using these two methods; therefore, the results shown here use the former method of computing EF.

This study also uses ERA5 reanalysis to characterize boundary layer height and LCL height on diurnal timescales. Specifically, we assess the average PBL height and LCL height in the six hours leading up to each initiation event. ERA5 defines the PBL height as the minimum height for the bulk Richardson number of 0.25. Although ERA5 assimilates radiosonde information, there are inherent biases in reanalysis estimates of PBL and LCL heights. However, Guo *et al.* (2021) found ERA5 estimates of PBL height had the overall lowest bias (~130 m on average) compared with three other reanalysis products. ERA5 also exhibited a strong correlation with radiosonde-derived PBL height (Guo *et al.* 2021). Likewise, Taszarek *et al.* (2021) found ERA5's finer horizontal and vertical resolutions made it more reliable than other reanalysis products for representing convective environments. In this study, we calculated the change in PBL and LCL heights from six hours to hour of convection initiation for each event.

### *2.4. Soil Moisture-Based Coupling Diagnostic*

Observation-driven analyses of soil moisture-precipitation feedbacks are inherently reliant on statistical methods of determining feedback sign and strength. However, numerous factors can confound statistical tests and make it difficult to establish or infer causality. Guillod *et al.* (2015) argued differences in the apparent sign and strength of feedbacks between studies may be due to differences in spatial and temporal effects of soil moisture on precipitation and proposed a diagnostic method that attempts to disentangle the spatial and temporal effects. We adopt the temporal soil moisture coupling diagnostic of Guillod *et al.* (2015) and, more recently Moon *et al.* (2019) to characterize the temporal sensitivity of afternoon convection initiation to underlying soil moisture. One modification we made to this method is to use the location of convection initiation – determined by the ThOR algorithm – instead of the location of maximum afternoon precipitation, as used by Guillod *et al.* (2015) and Moon *et al.* (2019), among others.

Following the notation of Moon *et al.* (2019), the temporal coupling metric $S'_{init}$ is computed as the soil moisture anomaly underlying the point of convection initiation. Soil moisture anomalies were computed as the difference between each daily SMERGE value and the average of a 30-day window centered on that calendar day. This effectively removes the strong seasonal cycle of soil moisture present throughout the central United States. Therefore, $S'_{init}$ is the daily soil moisture anomaly on the day prior to a ThOR event. This deviates from previous studies that use the soil moisture on the morning prior to the precipitation event; however, because SMERGE blends multiple satellite datasets with the Noah land surface model and is only available at the daily resolution, we were limited to using the daily soil moisture anomaly the day prior to the event. The metric is computed for all afternoon convection initiation events (1200 to 2000 LST) between May and September, 2005 – 2017 in the central United States.

The temporal coupling diagnostic only represents the sign of the sensitivity of the atmosphere to soil moisture, but not the extent or strength of this sensitivity. To better measure the strength of coupling in the study region, we compare the event samples – soil moisture conditions underlying convection initiation points – with corresponding control samples. Following Moon *et al.* (2019), the control sample is the same metric at the same locations as the initiations, but calculated based on non-initiation days from the same month for all years, 2005 – 2017. While Moon *et al.* (2019) pooled all events together in 5° x 5° boxes for their global analysis, our regional focus and relatively larger sample size allows us to examine event – control differences in 1° x 1° boxes across the study region. The difference between the soil moisture underlying initiations (i.e., event) and non-initiations (i.e., control) is compared to the distribution of the differences taken between 1,000 random samples of event and control values. The size of the random samples is equal to the size of the event sample in that grid box, and all values for event and control are pooled together for the random samples. In this way, we can measure both the sign of the coupling diagnostic (i.e., the actual event-control difference), and the anomaly of the diagnostic (i.e., the percentile of the distribution of random samples). The feedback is considered significant at any grid cell where the event-control difference is greater than the 90$^{th}$ percentile or less than the 10$^{th}$ percentile of the random samples distribution.

### *2.5. Atmosphere-Based Coupling Diagnostics*

We also compute atmosphere-based coupling diagnostics to complement the temporal soil moisture-based diagnostic and provide additional evidence of the impact of the land surface on the diurnal variation in boundary layer conditions leading to convection initiation. We use atmospheric profiles of temperature and dew point from ERA5 to compute the Convective Triggering Potential and Low-Level Humidity Index (CTP-HI, Findell *et al.* 2003). CTP-HI characterizes the suitability of the pre-convective environment for triggering land surface convection. CTP is calculated as the integrated area between the environmental temperature profile and a moist adiabat drawn from the observed temperature 100 mb above the surface to

300 mb above the surface. Practically, when the environmental profile is close to the dry (moist) adiabatic lapse rate, convection initiation is favored over dry (wet) soils. A negative CTP value indicates an atmospheric inversion, which does not favor convection, irrespective of soil conditions. The low-level humidity index is computed as the sum of the differences between temperature and dew point temperature at 50 and 100 mb above the ground surface. We calculate CTP-HI using ERA5 fields of temperature and dew point before each afternoon initiation event, at 0600 LST, to characterize the pre-convective environment.

## 3. Results

### *3.1 Sensitivity of Convection Initiation to Soil Moisture*

The temporal diagnostic of Guillod *et al.* (2015) and Moon *et al.* (2019) are used to determine the sign and strength of atmospheric sensitivity to soil moisture, associated with ThOR-identified convection initiation. Figure 1 shows the metric composite across the study region, with blue (red) shading indicating wetter (drier) soils associated with initiations than the control group. The map shows the average event – control difference for all events pooled together in the respective 1° grid cell. The diagnostic value in the grid cells with a star are considered statistically significant, meaning the value is either greater than the 90$^{th}$ percentile or less than the 10$^{th}$ percentile of the random samples' distribution.

Three subregions are identified with strong and significant differences between initiation event and control soil moisture conditions based on the temporal metric (Figure 1). Specifically, much of the central and eastern half of Texas in the southern U.S. exhibits a strong, positive temporal sensitivity relative to the control. This pattern indicates convection initiation tends to occur over wetter than normal soils in this region. In contrast, two areas farther north, in the U.S. mid-south and central plains, exhibit significant negative sensitivity. This result indicates convection initiation tends to occur over drier than normal soils in this region.

Overall, the sensitivity analysis indicates that the study region exhibits significant preferences for convection initiation over both wetter and drier than normal soils. The three sub-regions are all within the southern half of the study region, and in relatively close geographic proximity to each other.

The sensitivity metric assessed is a representation of the statistical preference of soil moisture patterns underlying convection initiation in the central U.S. While this metric metric is useful for understanding broad patterns of potential land-atmosphere coupling sign and strength, it does not provide evidence of a physical interaction between soil moisture, surface heat flux, and boundary layer modification leading to initiation. The remainder of the study seeks to confirm the plausibility of wet- or dry-soil feedbacks across the study region – as implied by the sensitivity metric – using the local land—atmosphere coupling (LoCo) process chain framework (e.g., Santanello *et al.* 2018; Lawston-Parker *et al.* 2021). Specifically, we examine changes in surface heat fluxes, low-level humidity and temperature, and PBL and LCL height leading up to convection initiation over wet and dry soils with the goal of connecting the physical processes understood to link land and atmosphere, and either confirm or refute the existence of wet- and dry-soil feedbacks in the region.

### *3.2 Sensitivity of Surface Heat Flux to Soil Moisture*

The terrestrial leg of land-atmosphere coupling is typically represented by the sensitivity of latent and sensible heat flux to changes in soil moisture (Hsu and Dirmeyer, 2021; Wakefield *et al.* 2021). Indeed, it is primarily through modification to surface heat flux partitioning that soil moisture influences boundary layer temperature and humidity. In this study, we use cumulative latent and sensible heat flux from 6 am LST to the hour prior to convection initiation, and compute EF from these accumulations. We chose 6 am LST to begin assessing EF as this approximates local sunrise time during the warm season. We then compare the EF associated with an initiation event to the average EF across all non-event days in the event calendar month at that location. For example, the EF prior to an initiation event on June 5, 2008 in a given location is compared to the average EF at that location on all non-event June days between 2005 and 2017. The EF anomaly is then computed by taking the difference between the initiation event day EF and the corresponding non-event day average EF. The resulting EF anomalies are then averaged over 1° x 1° grid cells across the study region to assess the spatial variability of EF sensitivity to underlying soil moisture anomalies. In the following analyses, "wet soils" and "dry soils" are defined by $S'_{init}$, the temporal soil moisture anomaly underlying each convection initiation event. Dry (wet) soils are those in which $S'_{init}$ is less than (greater than) 0.

The results show much of the study area exhibits higher EF than average prior to afternoon initiation over wet soils (Figure 2), associated with elevated latent heat flux relative to sensible heat flux. The magnitude of the positive EF anomaly corresponding with wet soils is strongest in the southern half of the study region, and particularly so in the same part of Texas that exhibited a significant preference for afternoon initiation over wetter than normal soils (Figure 1). The strong, positive EF anomaly in this region is physically consistent with the wet soil pathway of land-atmosphere coupling, such that abundant soil moisture favors partitioning of incoming energy to latent heating via evapotranspiration (Ford *et al.* 2014). In contrast, only a small fraction of the study area exhibits a noteworthy EF anomaly prior to afternoon initiation over dry soils (Figure 2). The mid-south region, centered over the state of Arkansas, and to a lesser extent the panhandle regions of Texas and Oklahoma, exhibit a strong preference for negative EF anomalies accompanying afternoon initiation over drier than normal soils. These two regions also exhibited significant preferences for convection initiation over drier than normal soils (Figure 1). The strong, negative EF anomaly in these regions are also physically consistent with the dry soil pathway of land-atmosphere coupling, such that limited soil moisture favors partitioning of incoming energy to sensible heating via increased near-surface air temperature (Yang *et al.* 2018). The positive EF anomalies in the Texas region and the negative EF anomalies in the mid-south region are significantly different from average EF conditions, determined at the 95% confidence level using a paired t-test.

The consistency between maps in Figures 1 and 2 provide important evidence for wet and dry soil feedbacks present in different sub-regions of the study area. Because surface heat fluxes are the conduit between soil moisture anomalies and boundary layer conditions, we would not expect strong land-atmosphere feedbacks to exist without an alignment of surface heat flux anomalies with soil moisture anomalies (i.e., higher EF over wetter soils and vice versa). However, the lack of a consistent temporal or spatial sensitivity signal (Figure 1) and lack of a strong EF anomaly (Figure 2) in the northern half of the study region suggests soil moisture feedback to afternoon initiation, while possibly present, are not strong enough to provide a consistent signal.

### *3.3 Atmospheric Pre-Conditioning*

The connection between the terrestrial and atmospheric legs of the LoCo process chain are partly determined by the degree to which the atmosphere is "pre-conditioned" to soil moisture feedbacks ahead of initiation. Observation-based analysis of land-atmosphere coupling can be confounded by the effects of synoptic scale features and atmospheric conditions that either encourage or discourage convection initiation irrespective of underlying land surface conditions

(Tuttle and Salvucci, 2017). Although it is impossible to completely account for this effect, many studies have attempted to describe atmospheric controls on or pre-conditioning to convection initiated via wet or dry soil feedbacks.

In this study, we use the CTP-HI framework to assess the atmospheric pre-conditioning ahead of initiation events across the study region. We adopt the CTP and HI thresholds set by Findell and Eltahir (2003) for denoting atmospheric conditions that (1) favor initiation via dry soil feedbacks, (2) favor initiation via wet soil feedbacks, (3) favor initiation irrespective of soil moisture conditions, and (4) are too stable for convection initiation. More recent studies have adjusted these thresholds for a wider geographic application (Wakefield *et al.* 2019). We found our results were insensitive to adjustment of CTP and HI thresholds, and therefore we chose to use the original thresholds proposed by Findell and Eltahir (2003). We group afternoon initiation events, and their corresponding soil moisture anomalies, by morning atmospheric conditions deemed favorable for initiation over either wet soils or dry soils. We then composite soil moisture anomalies underlying the initiation events in either group to assess the consistency of soil moisture conditions with atmospheric conditions purported to favor wet- or dry-soil feedbacks.

The results show the Texas region exhibits a significant preference for wetter than normal soils underlying initiation events which occur in atmospheric conditions favorable for wet soil feedbacks (Figure 3). In fact, much of the western half of the study area shows a similar pattern of wet soil convection initiation events corresponding with an atmosphere that is pre-conditioned for wet soil feedbacks. Interestingly, wet soil-primed events make up a smaller proportion of all events in the western half of the study area relative to the eastern half (supplemental Figure S2). In fact, most events in the western half of the study region are atmospheric-controlled, that is too stable for initiation over wet or dry soils.

Meanwhile, much of the eastern half of the study region shows a preference for drier than normal soils underlying events which initiation occurs in atmospheric conditions favorable for dry soil feedbacks (Figure 3). Both the mid-south and central plains regions show significant preferences for dry soils leading up to initiation in an atmosphere that is preconditioned to dry soil feedbacks. These regions also exhibited an overall significant preference for initiation over drier than normal soils, and preferential sensible heat flux partitioning leading up to these initiations. All of which are consistent with the physical pathway of dry soil feedbacks to convection initiation. The eastern half of the study region, especially the mid- to lower-Mississippi Valley experience more dry soil-primed events than wet soil-primed or atmospheric controlled events, based on CTP-HI (supplemental Figure S2).

Three subregions of the study area show signals of soil moisture, surface heat flux, and atmospheric conditions that are consistent with wet or dry soil feedbacks: Texas, mid-south, and central plains (supplemental Figure S1). Therefore, the remainder of the analysis in this study are focused on these three regions.

### *3.4* ***Boundary Layer Modification Leading to Initiation***

Atmospheric pre-conditioning to convection initiation, whether via wet or dry soil feedbacks, is an important, but incomplete part of the atmospheric leg of the LoCo process chain. To complete the process chain, the boundary layer must respond to changes in near-surface temperature and/or humidity via soil moisture-induced surface heat flux anomalies. This final step is often represented by the interplay between the PBL height and the height of critical atmospheric levels like the LCL. Theoretically, dry soils and corresponding increased surface sensible heat flux act to rapidly grow the PBL and can make it more likely parcels rising from the surface surpass the LCL and inducing cloud formation and, eventually precipitation. Meanwhile, wet soils and corresponding increased latent heat flux can act to limit LCL height, making it more likely parcels reach the LCL and initiate precipitation.

In each of the three regions denoted as having a high potential of either wet or dry soil feedbacks for initiation, we examine the sensitivity of both PBL and LCL heights to surface heat flux immediately prior to afternoon convection initiations. The results in Figure 4 show the joint distributions of evaporative fraction from 0600 LST to the hour prior to initiation and the PBL height (m) averaged between 6 hours to 1 hour prior to initiation. The distributions are divided by wet soil and dry soil initiation events, and the contoured areas represent the middle 90% and 75% of the joint distributions.

The distributions of EF differ significantly between wet and dry soil events in all three regions, which was demonstrated in Figure 2. In the Texas region (Figure 4a), the average PBL height prior to convection initiation also exhibits notable, but smaller magnitude differences between wet and dry soil events. A non-parametric Mann-Whitney test found statistically significant differences between average PBL heights leading up to initiation over wet and dry soils in the Texas region (5% confidence level). PBL height is sensitive to EF in the Texas region, such that – whether over wetter or drier than normal soils – PBL height is mostly confined to less than 1300 m when EF is greater than 0.5 (i.e., more latent than sensible heat flux). However, when pre-initiation EF is less than or equal to 0.4, PBL height increases rapidly with decreasing EF. This PBL response to differential EF is consistent with past observation- and model-based studies showing PBL growth is enhanced with strong surface sensible heat flux in many global regions (Sathyanadh *et al.* 2017; Rappin *et al.* 2022).

We tested the sensitivity of PBL growth in the Texas region to total surface flux – the sum of latent and sensible heat flux – in place of evaporative fraction (supplemental material Figure S3).

While PBL height generally increases with more available energy, the relationship is weaker and decidedly non-linear as compared to the stronger and linear relationship between PBL height and EF. The patterns in supplemental figure S3 suggest flux partitioning – as modified by soil moisture – is a larger constraint on PBL growth than total available energy in the Texas region.

While EF in the mid-south region is sensitive to soil moisture (Figure 4b), EF rarely drops below 0.5, characteristic of the humid sub-tropical climate of the region. Average PBL height leading up to initiation is somewhat sensitive to EF; however, to a lesser extent than in the Texas region. Differences between average PBL height leading up to initiations over dry and wet soils are statistically significant from a Mann-Whitney test. The largest difference between the Texas and mid-south regions is the effective range of EF, and values rarely drop below 0.50 (i.e., more sensible heat than latent heat) in the latter region. We additionally tested the sensitivity of PBL growth in the Mid-South region to total surface flux – the sum of latent and sensible heat flux – in place of evaporative fraction (supplemental material Figure S4). While the relationship between PBL height and total surface flux was stronger and more linear in the Mid-South region than in the Texas region, it was still overall weaker than the relationship between PBL height and EF.

The same can be said about the central plains Region (Figure 4c), which has significant differences in EF between wet and dry soils. However, the small difference in PBL height leading up to initiations over dry and wet soils was not statistically significant based on the Mann-Whitney test. The significant, positive relationship between EF and soil moisture in all three regions suggests the terrestrial leg of the LoCo process chain are similarly strong between the three regions. However, the inconsistent relationship between EF and PBL or LCL between regions suggests the strength of the atmospheric leg varies considerably.

Differences in LCL height leading up to initiations are less pronounced than for PBL height (Figure 5). In fact, only the Texas region exhibited statistically significant differences in LCL height ahead of initiations over dry and wet soils, from a Man-Whitney test, while differences in the mid-south and central regions were not significant. Soil moisture and EF were more strongly related to the dynamic range of LCL heights ahead of initiations, such that drier soils and lower EF generally limit the LCL height range to between 1000 and 2200 m, compared with a range of 200 to 2000 m over wetter soils and high EF. This effect was most pronounced in the Texas region, suggesting a stronger atmospheric response to surface forcing (Figure 5a) relative to the mid-south and central plains regions (Figures 5b, 5c). More generally, the results from Figures 4 and 5 suggest that soil moisture, via surface heat flux partitioning, has a larger impact on the PBL than on the LCL.

The sensitivity of diurnal PBL height to pre-initiation EF, relative to the LCL, is clear in the panels in Figures 6-8, which show the change in PBL and LCL height 7 hours leading up to convection initiation in the Texas, mid-south, and central plains regions. PBL and LCL growth are represented in the red and blue boxes, respectively. The boxes represent the middle 50% of PBL and LCL heights at each hour, the range between the whiskers represents the middle 90% of heights, and the thick, white line in each box represents that distribution's median PBL or LCL height. We separate PBL and LCL height changes by corresponding EF values. EF values less than 0.33 represent conditions with most available energy partitioned to sensible heat flux, EF values greater than 0.66 represent conditions with most available energy partitioned to latent heat flux, and EF values between 0.33 and 0.66 represent conditions with roughly similar partitioning between latent and sensible heat flux.

PBL sensitivity to EF is immediately apparent in the Texas region (Figure 6), as the median PBL height change between 7 hours prior to initiation and 1 hour prior to initiation is almost 1500 m for events with an EF less than 0.33, compared to less than 1000 m for events with an EF greater than 0.66. The strong relationship between EF and PBL height in the Texas region is not dependent on underlying soil moisture, nor is the likelihood of PBL growth reaching the LCL height, which is often a precursor for convection initiation over wet or dry soils. Because of the relatively strong PBL growth with low EF values (i.e., high sensible heating) relative to high EF, PBL growth leading up to initiation surpassed the estimated LCL height in nearly 60% of low-EF events (< 0.33), compared to 30% of high-EF events (> 0.66). While this finding highlights the strong land-atmosphere interactions in the Texas region, it also suggests that despite high EF dampening PBL heights in the region, growth is still sufficient to reach the LCL in many cases over both wet and dry soils.

Over the 13-year study period, there were almost 200 more events over wetter than normal soils than over drier soils in the Texas region, including almost 600 more wet soil events than dry soil events with EF values exceeding 0.66, which explains why the Texas region had a significant wet soil temporal sensitivity (Figure 1). Conditions prior to initiation events over wet soils in the region generally followed the LoCo process chain for wet soil feedbacks to precipitation, including preferential latent heat flux partitioning and modest changes in LCL height leading up to initiation. While PBL growth was also subdued by higher EF ahead of wet soil events, growth was still sufficient to surpass the LCL in many cases, helping with initiation. It is worth noting that, while fewer in number, events overlying drier than normal soils generally followed the LoCo process chain for dry soil feedbacks to precipitation: preferential sensible heat, lower EF, and strong PBL growth. In fact, PBL growth over dry soils – irrespective of EF values – were more effective at surpassing the LCL height in the hours leading up to initiation than PBL growth over wet soils – 45% of events versus 35% of events. Both terrestrial and atmospheric legs of the LoCo process chain are apparent in the Texas region, suggesting that both wet soil feedbacks and dry soil feedbacks are prevalent in the region, although the former more than the latter.

In the mid-south region, PBL growth is similarly strongest when EF is less than 0.33 and is subdued when EF is greater than 0.66, irrespective of underlying soil moisture conditions (Figure 7). The PBL reached the LCL in 80% of events in the mid-south region with EF less than 0.33. However, a larger proportion of events in the mid-south region followed EF values greater than 0.33 compared to the Texas region. It was under these conditions, with strong latent heating and EF values exceeding 0.66, where differences appeared between wet soil and dry soil conditions. Only 46% of wet soil events with EF values exceeding 0.66 in the mid-south region, compared to 55% of dry soil events in the same conditions. The differential outcomes between wet and dry soil events in these cases is the difference in the sensitivity of PBL growth and LCL growth to EF. Because LCL growth was less sensitive to changes in EF in the mid-south region, the likelihood of the PBL reaching the LCL is mostly based on PBL growth, which was slightly stronger over drier than normal soils than wetter than normal soils in the mid-south region (Figure 7). The limited response in LCL height to EF or soil moisture also suggests the wet soil path of the LoCo process chain may not be strong in the mid-south region, at least not as strong as the dry soil path. Namely, PBL growth caused by strong sensible heating is a more relevant forcing for soil moisture feedbacks in the mid-south region than LCL height change via surface latent heating. Even when EF was moderate to high (> 0.33), we found different responses in

PBL growth between dry and wet soils, possibly explaining why the mid-south region had more than 600 additional initiation events over dry soils than wet soils.

Patterns of PBL and LCL heights grouped by EF and soil moisture in the central region are broadly like those in the mid-south region (Figure S8). In the central region, PBL growth is strongest in accordance with low EF values. The PBL reached the LCL in 60% of events in the central region events with EF less than 0.33, compared to about 40% of events with EF values greater than 0.33. Differences between wet and dry soils in the central region are apparent, but subdued relative to the mid-south region. While PBL growth appears to be strongly dependent on EF in the central region, the limited LCL response and differences between wet and dry soils suggest a weaker atmospheric leg of the LoCo process chain in this region. Compared to the mid-south region, which had 600 more dry soil initiation events than wet soil events, the central region only saw 50 more dry soil events than wet soil events over the study period.

One important caveat to these results is our use of a seasonally variable soil moisture anomaly to determine “wet” vs “dry” soils. Such anomalies do not necessarily reflect physically wet or dry soils if convection initiation occurs primarily during a wet or dry season. The diurnal LCL height change may be more responsive to actual soil wetness conditions more so than anomalies, and by using anomalies we may be misrepresenting the actual coupling between soil moisture and LCL. Therefore, we also examined soil moisture conditions underlying convection initiation in the Texas and Mid-South regions using a physically based indicator of dryness (the “dryness index”). The dryness index is simply the difference between the SMERGE volumetric water content underlying the point of convection initiation and the volumetric water content of the wilting point at that location. Plant root uptake of soil water decreases as soil moisture approaches the wilting point, at which point transpiration – and latent heat flux – significantly declines. Because of its impact on transpiration rates, studies have found the wilting point to be an important determinant of land-atmosphere coupling (Hohenneger and Stevens, 2018; Hsu and Dirmeyer, 2022). The dryness index in the Texas and Mid-South regions generally ranges from -0.05 to 0.40 $m^3 m^{-3}$, where positive (negative) values indicate soils that are wetter (drier) than the wilting point. Because SMERGE soil moisture is derived from merging satellite retrievals with the NLDAS Noah-2 land surface model, we use the NLDAS-2 Noah soil properties dataset (Mitchell *et al.* 2004) to represent wilting point across the study region.

The median soil wetness underlying convection initiation events in Texas and Mid-South regions is between 0.12 and 0.16 $m^3 m^{-3}$ above (i.e., wetter than) the wilting point (supplemental figure S5). Approximately 2% of events in the Texas region occurred with a soil moisture value at or below the wilting point, and only 3 of over 5000 events in the Mid-South region corresponded with soils drier than the wilting point. It is important to note that root water uptake and transpiration can be constrained at soil wetness levels well above wilting point, so even with the dryness index it is challenging to precisely determine "wet" from "dry" soil to the extent that the wetness or dryness would significantly impact surface flux partitioning and LCL height. With that said, most convection initiation events in our study occurred over soils with some plant available water. Furthermore, we find no significant relationship between LCL height and dryness index, confirming the atmospheric leg of LoCo coupling in the Texas and Mid-South regions is primarily driven by PBL response to surface flux partitioning.

Lastly, to account for the potential dataset dependence of our study, all analyses – including temporal sensitivity of convection to wet or dry soils and assessment of the terrestrial and atmospheric legs of LoCo process chains – were duplicated using ERA5 soil moisture instead of SMERGE. The results of the duplicate analyses using ERA5 soil moisture (available in

Supplemental Material, Figures S6-S9) were very similar to those using SMERGE soil moisture, providing confidence that the results of this study are relatively insensitive to the land surface dataset.

## 4. Summary & Conclusions

Soil moisture plays an important role in regional hydroclimatology and can feedback to modify the boundary layer to encourage or impede convection initiation and, ultimately precipitation.

In this study, we sought to combine a climatological assessment derived from event frequency-based metrics with a process-based analysis of wet and dry soil feedbacks to convection initiation in the central U.S. We found three regions exhibited significant preferences for initiation over wet soils or dry soils. Specifically, the Texas region exhibited a significant preference for initiation over wet soils and the mid-south and central plains regions exhibited preferences for initiation over dry soils.

The terrestrial leg of feedback process chains, inferred by the relationship between soil moisture and EF, was strong in all three regions. Both dry soils and wet soils initiated strong responses in surface flux partitioning. However, the atmospheric leg of the process chains showed a more mixed response between the regions. Afternoon PBL growth was highly sensitive to EF in all three regions, mostly irrespective of soil moisture. However, LCL height was not as sensitive to soil moisture or EF as PBL in all three regions. The result was a strong and consistent boundary layer response to drier soils and low EF in all three regions, implying the presence of a healthy dry soil feedback process. The Texas region also exhibited a strong and consistent boundary layer response to wetter soils, with somewhat subdued LCL growth making it more likely that even modest PBL growth could reach the LCL. These results suggest that both wet- and dry-soil feedback processes are present in the Texas region. However, while wet soil feedbacks seem to be more frequent than dry soil feedbacks in the region, a higher proportion of events over dry soils saw PBL height surpass LCL height. Therefore, the Texas region appears to be a wet soil feedback region based solely on event frequency metrics. However, the region exhibits signs of having both wet and dry soil feedbacks, and the latter may be more efficient in generating convection than the former. Meanwhile, the mid-south and central plains regions do not exhibit signs of strong and consistent wet soil feedbacks, namely LCL height change is mostly insensitive to underlying EF and soil moisture. The lack of LCL response to surface forcing in these two regions means the likelihood of initiation is mostly dependent on PBL growth, which tends to be stronger under drier soils, even with similar EF.

This study used a large sample of events and the location of convection initiation to pinpoint climatological subsurface, surface, and boundary layer conditions leading to convection initiation. Additionally, the combination of a climatological assessment and more detailed, process-based regional assessment of soil moisture feedbacks provides a unique perspective of the strength and consistency of soil moisture-precipitation coupling in the C U.S. The findings of this study will inform a comprehensive modeling assessment of soil moisture feedbacks in the near future.

**Availability Statement:**

ThOR convection initiations data and Matlab code used to analyze sensitivity of precipitation to the temporal, spatial, and heterogeneity of soil moisture are made available via GitHub: doi:10.5281/zenodo.8006927. ERA5 reanalysis datasets used to calculate evaporative fraction, CTP-HI, and PBL height are made available via Zenodo: doi: 10.5281/zenodo/8006958.

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## Figures & Captions

**Figure 1.**. Panels show composites of (left) temporal sensitivity of initiation to soil moisture (middle) spatial sensitivity of initiation to soil moisture and (right) soil moisture heterogeneity underlying initiation. All maps show composites of event – control differences in each metric. Starred grid cells indicate differences deemed statistically significant at 95% confidence level.

**Figure 2**. Maps show average evaporative fraction (EF) anomaly prior to afternoon initiation events. EF anomalies are averaged over 1x1 degree grid cells across the study region and separated by (left) wet soil initiations and (right) dry soils initiations.

**Figure 3**. Maps show average soil moisture anomaly prior to afternoon initiation events that occur in atmospheric conditions denoted as preconditioned to (left) wet soil feedbacks and (right) dry soil feedbacks. Atmospheric preconditioning was identified using the CTP-HI framework.

**Figure 4**. Joint distributions of evaporative fraction and average PBL height (m) leading up to initiations over (red) dry soils and (blue) wet soils in (a) Texas, (b) mid-south, and (c) central plains regions. The contoured areas represent the middle 90% and middle 75% of the joint distributions.

**Figure 5**. Joint distributions of evaporative fraction and change in LCL height (m) leading up to initiations over (red) dry soils and (blue) wet soils in (a) Texas, (b) mid-south, and (c) central plains regions. The contoured areas represent the middle 90% and middle 75% of the joint distributions.

**Figure 6**. PBL and LCL height in the 7 hours prior to convection initiation in the Texas region. Blue (red) boxes show the distributions of LCL (PBL) height at each hour for all convection initiation events. Initiation events are grouped by wet soils (top panels) and dry soils (bottom panels), and by EF values (left to right).

**Figure 7**. PBL and LCL height in the 7 hours prior to convection initiation in the (a) mid-south and (b) central regions. Blue (red) boxes show the distributions of LCL (PBL) height at each hour for all convection initiation events. Initiation events are grouped by wet soils (top panels) and dry soils (bottom panels), and by EF values (left to right).

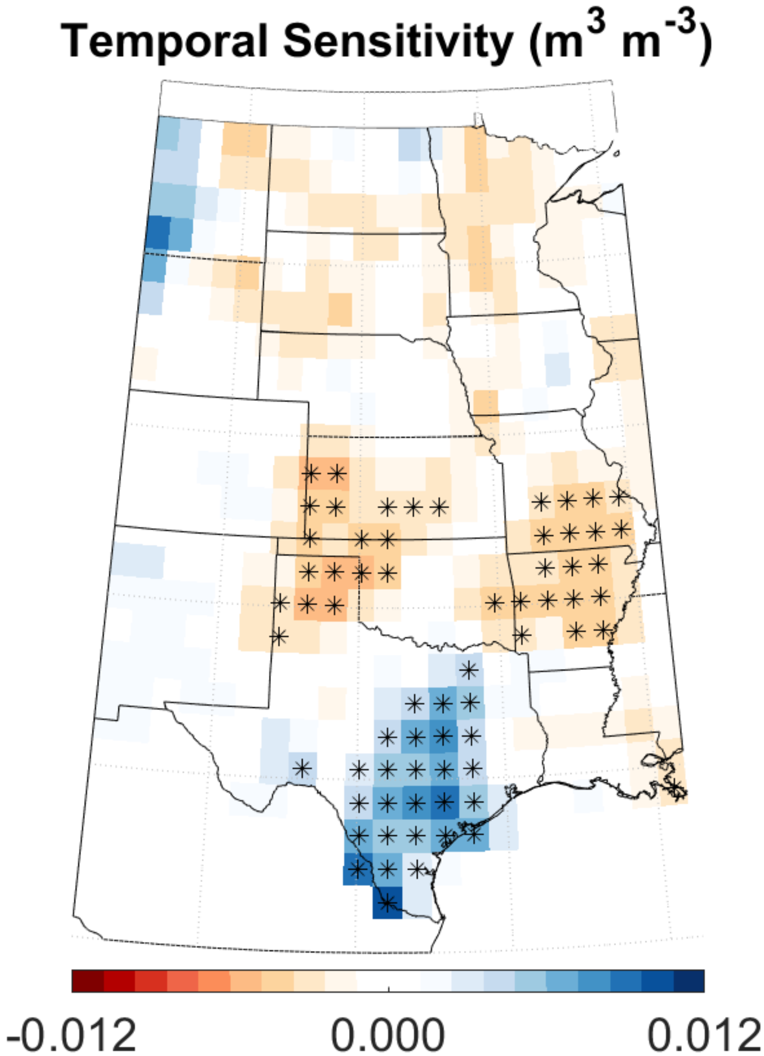



**Figure 1**. Map shows event – control composite of the temporal sensitivity of initiation to soil moisture (middle) spatial sensitivity of initiation to soil moisture and (right) soil moisture heterogeneity underlying initiation. Starred grid cells indicate differences deemed statistically significant at 95% confidence level.

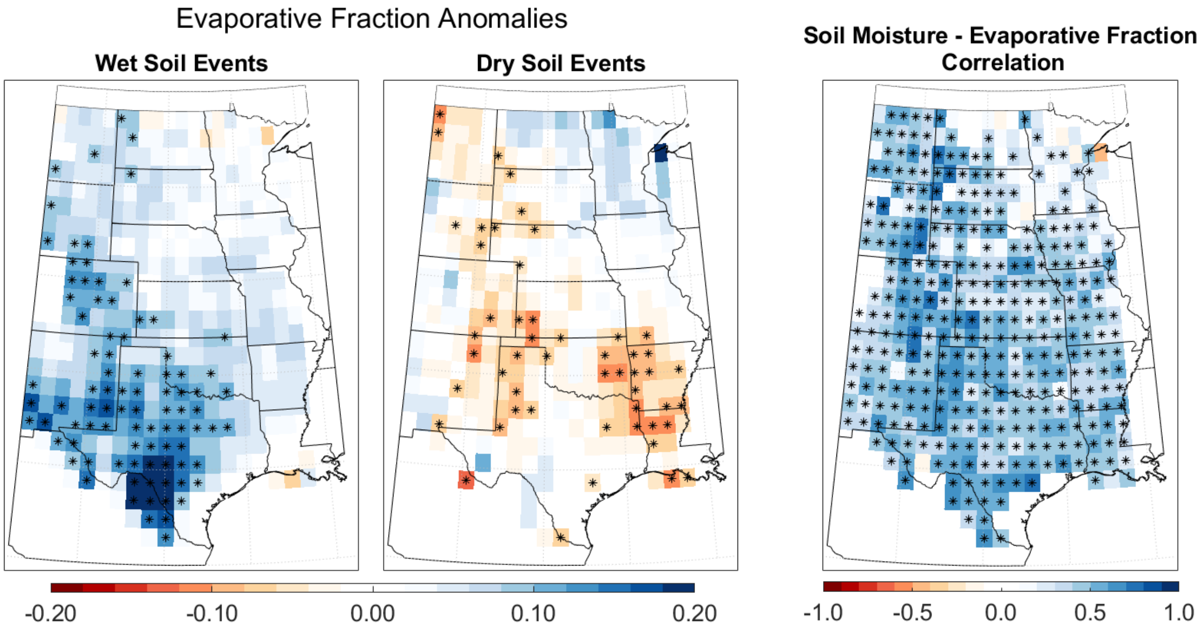



**Figure 2**. Maps show (left) average evaporative fraction (EF) anomaly prior to afternoon initiation events. EF anomalies are averaged over 1x1 degree grid cells across the study region and separated by wet soil initiations and dry soils initiations. Right map shows the correlation between soil moisture and EF. Starred grid cells indicate differences deemed statistically significant at 95% confidence level

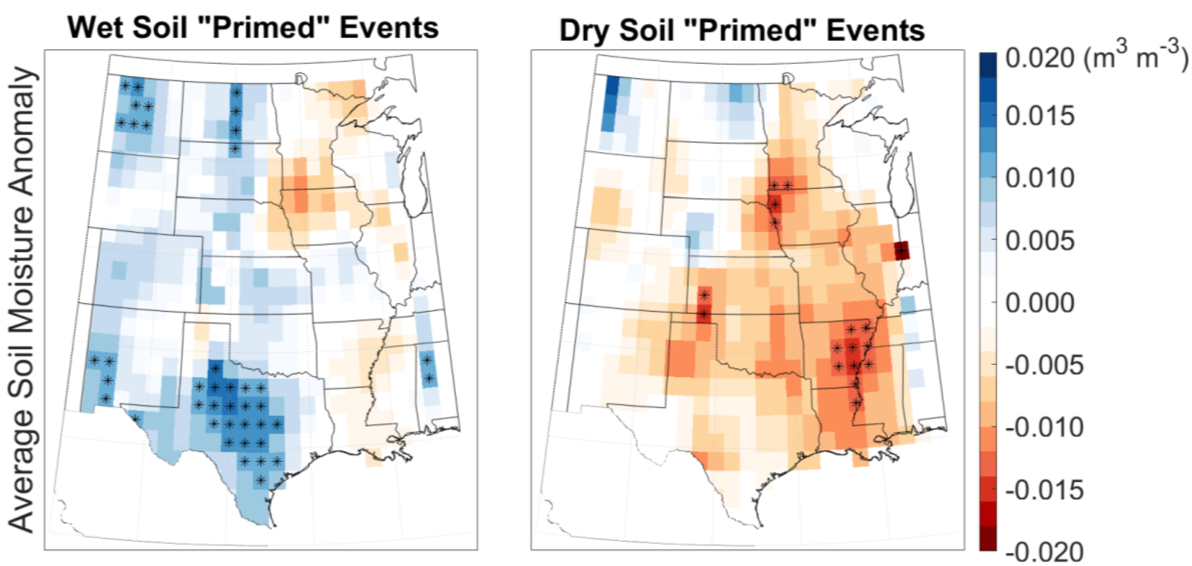
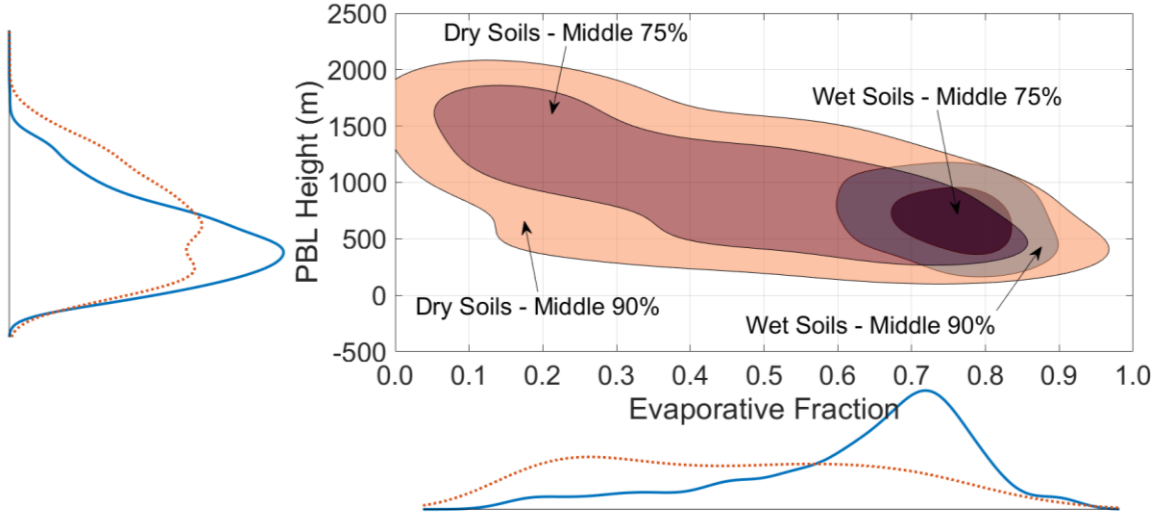



**Figure 3**. Maps show average soil moisture anomaly prior to afternoon initiation events that occur in atmospheric conditions denoted as preconditioned to (left) wet soil feedbacks and (right) dry soil feedbacks. Atmospheric preconditioning was identified using the CTP-HI framework.

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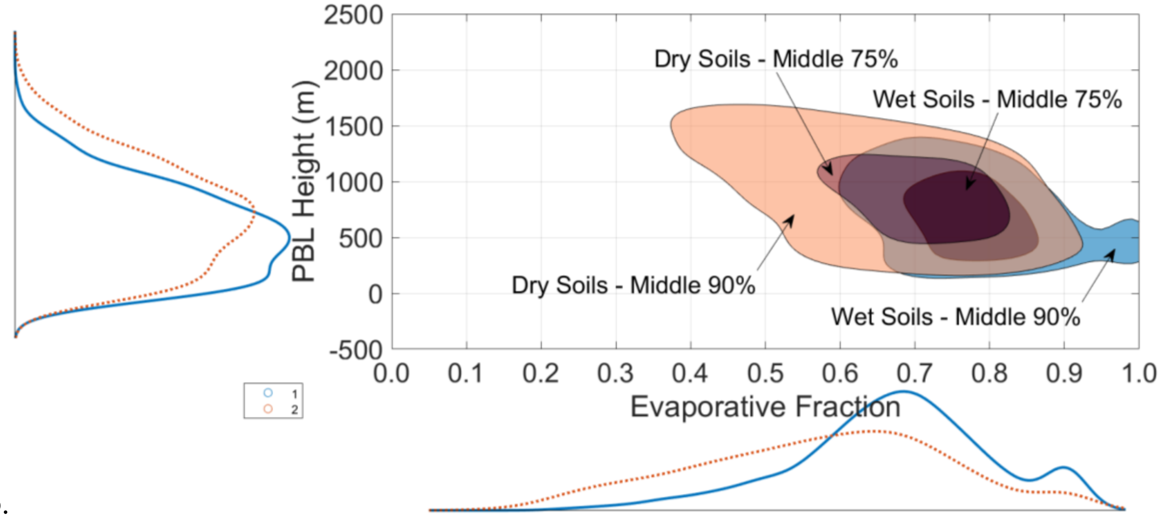


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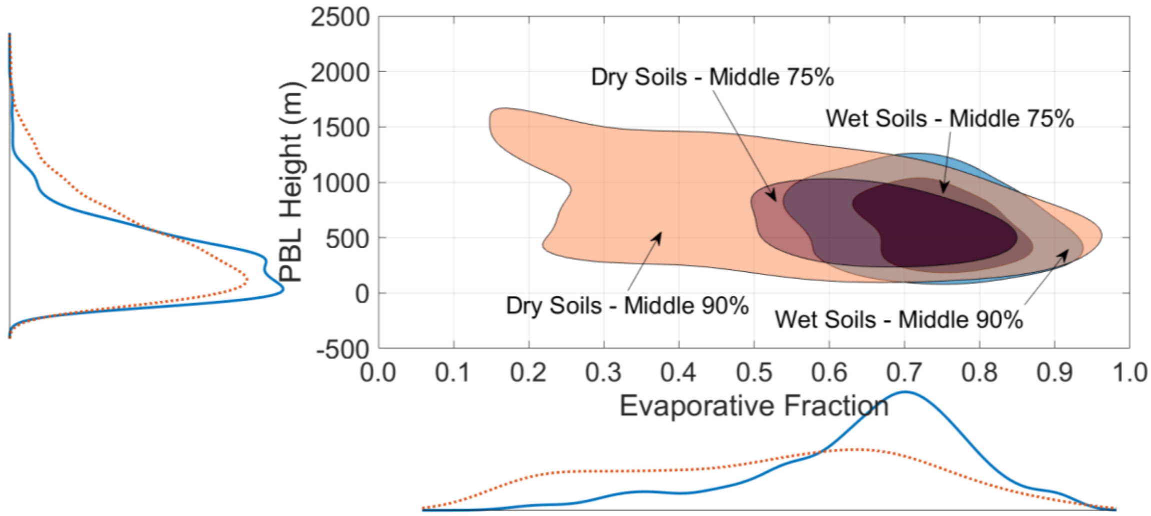
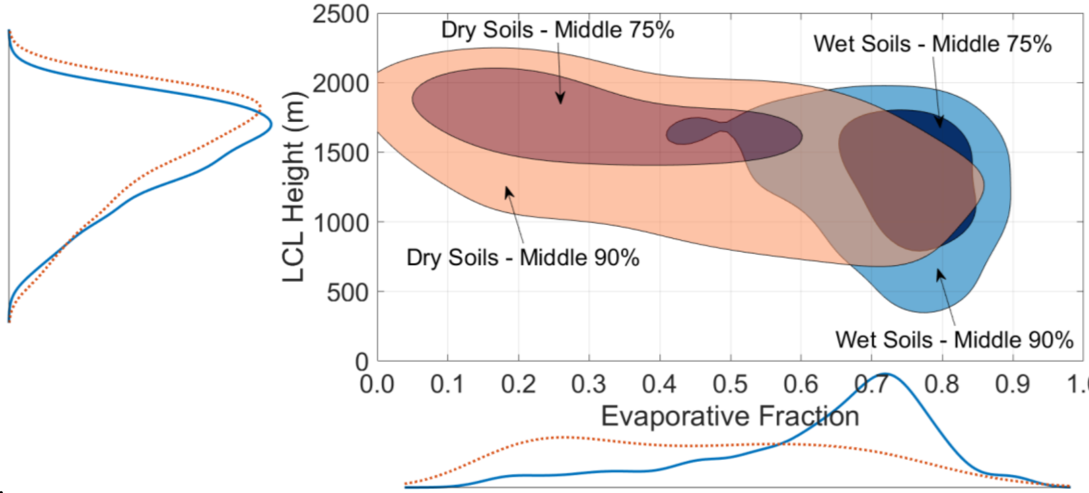



c.

**Figure 4**. Joint distributions of evaporative fraction and average PBL height (m) leading up to initiations over (red) dry soils and (blue) wet soils in (a) Texas, (b) mid-south, and (c) central plains regions. The contoured areas represent the middle 90% and middle 75% of the joint distributions.

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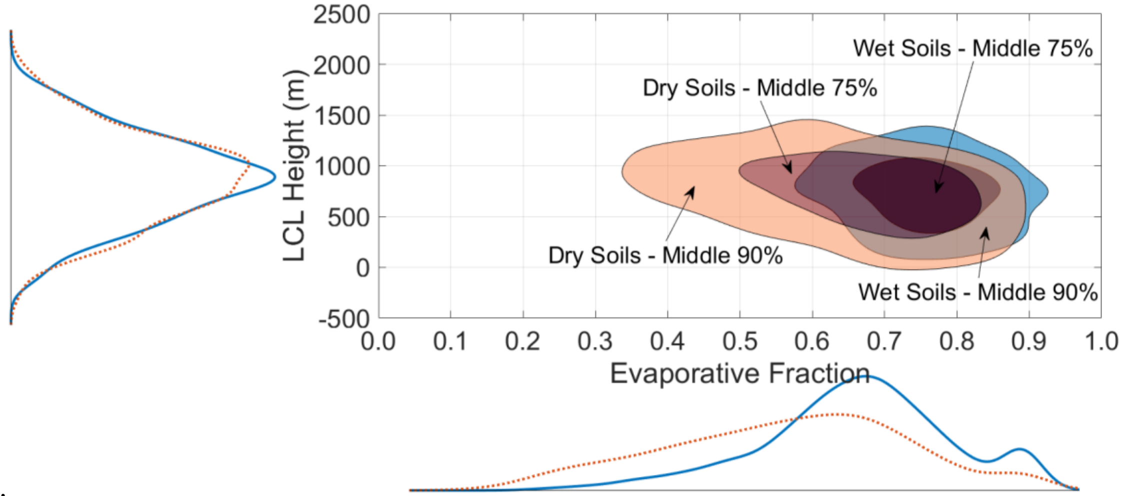


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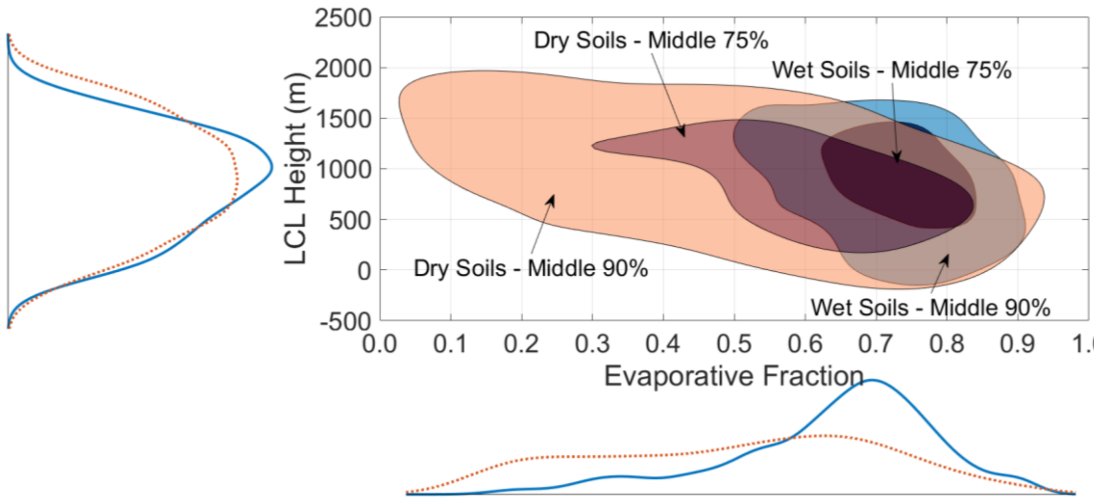



c.

**Figure 5**. Joint distributions of evaporative fraction and change in LCL height (m) leading up to initiations over (red) dry soils and (blue) wet soils in (a) Texas, (b) mid-south, and (c) central plains regions. The contoured areas represent the middle 90% and middle 75% of the joint distributions.

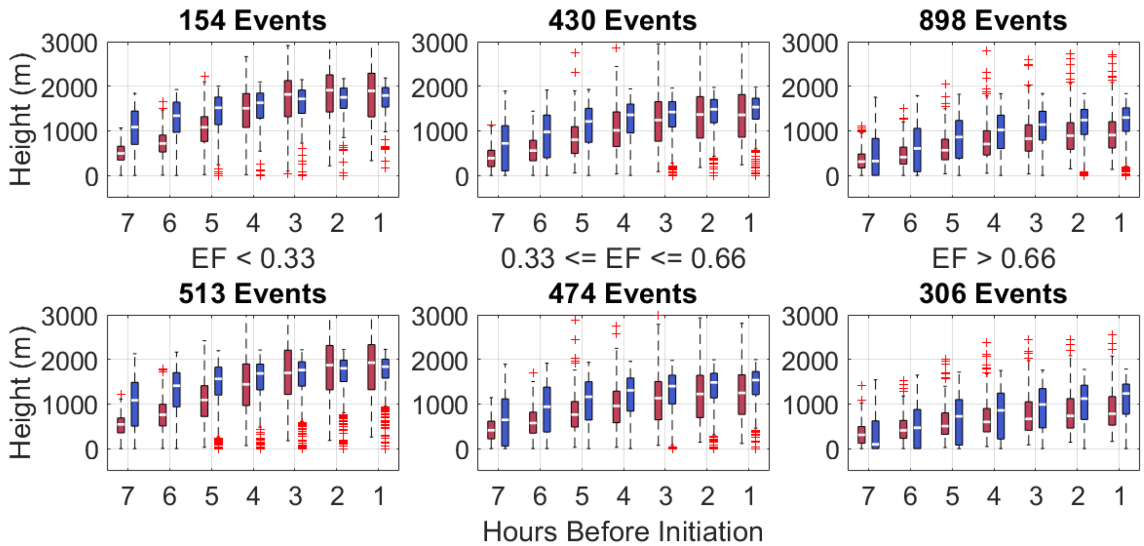
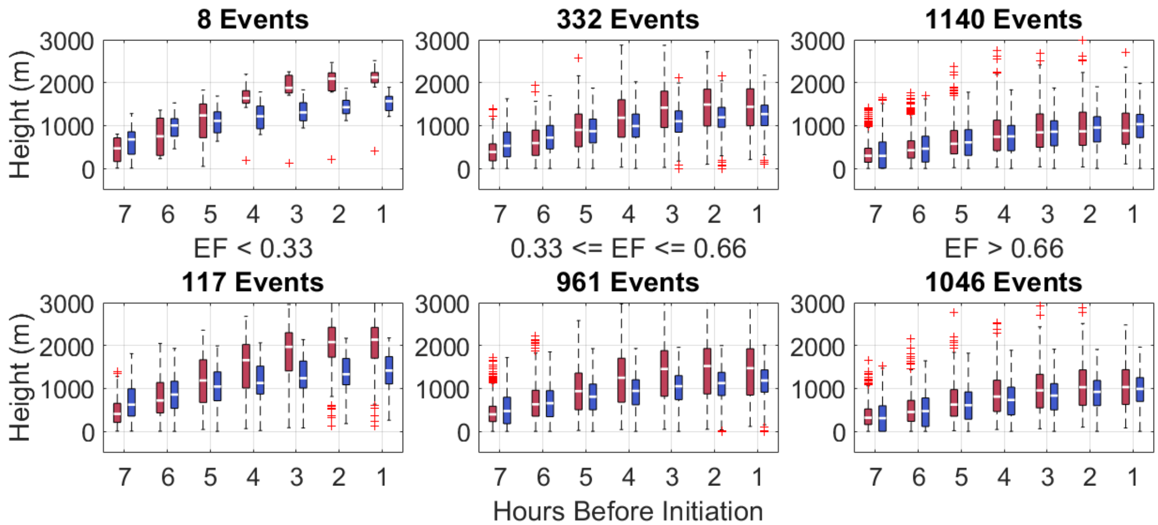
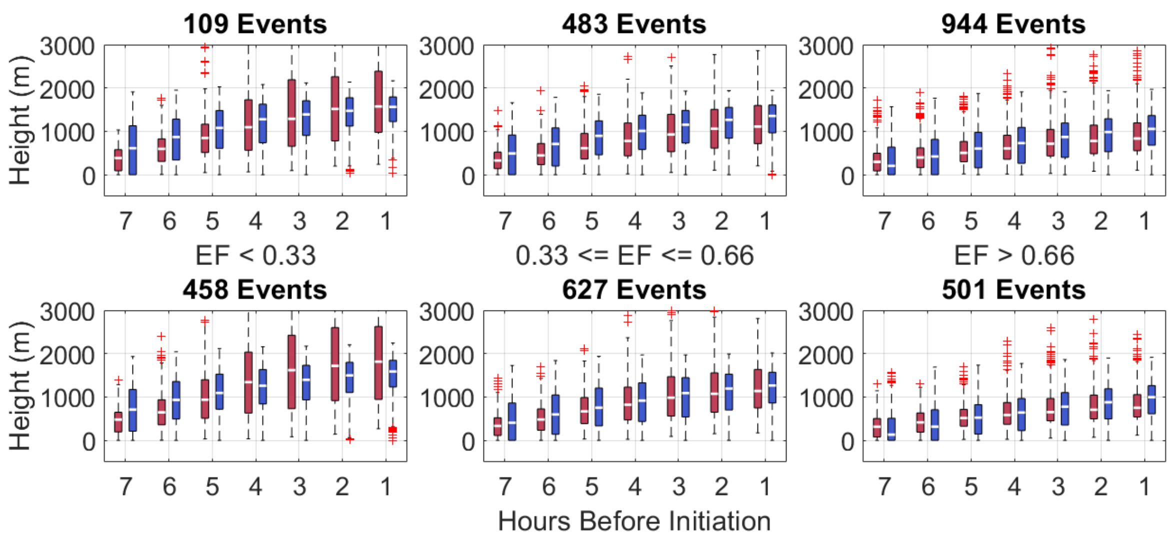



**Figure 6**. PBL and LCL height in the 7 hours prior to convection initiation in the Texas region. Blue (red) boxes show the distributions of LCL (PBL) height at each hour for all convection initiation events. Initiation events are grouped by wet soils (top panels) and dry soils (bottom panels), and by EF values (left to right).




a.




b.

**Figure 7**. PBL and LCL height in the 7 hours prior to convection initiation in the (a) mid-south and (b) central regions. Blue (red) boxes show the distributions of LCL (PBL) height at each hour for all convection initiation events. Initiation events are grouped by wet soils (top panels) and dry soils (bottom panels), and by EF values (left to right).

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