# An Analysis of the Soil Moisture Feedback on Convective and Stratiform Precipitation

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## ABSTRACT

Land–atmosphere interactions in midlatitude continental regions are particularly active during the warm season. It is still unclear whether and under what circumstances these interactions may involve positive or negative feedbacks between soil moisture conditions and rainfall occurrence. Assessing such feedbacks is crucially important to a better understanding of the role of land surface conditions on the regional dynamics of the water cycle. This work investigates the relationship between soil moisture and subsequent precipitation at the daily time scale in a midlatitude continental region. Sounding data from 16 locations across the midwestern United States are used to calculate two indices of atmospheric instability—namely, the convective available potential energy (CAPE) and the convective inhibition (CIN). These indices are used to classify rainfall as convective or stratiform. Correlation analyses and uniformity tests are then carried out separately for these two rainfall categories, to assess the dependence of rainfall occurrence on antecedent soil moisture conditions, using simulated soil moisture values. The analysis suggests that most of the positive correlation observed between soil moisture and subsequent precipitation is due to the autocorrelation of long stratiform events. The authors found both areas with positive and areas with negative feedback on convective precipitation. This behavior is likely due to the contrasting effects of soil moisture conditions on convective phenomena through changes in surface temperature and the supply of water vapor to the overlying air column. No significant correlation is found between daily rainfall intensity and antecedent simulated soil moisture conditions either for convective or stratiform rainfall.

## 1. Introduction

The land–atmosphere coupling plays an important role in the dynamics of the hydrologic cycle. This role is more important during the warm (i.e., growing) season when soil moisture can affect the energy and water exchange between the land surface and the atmosphere through the process of evapotranspiration (e.g., Betts et al. 1996; Schär et al. 1999; Betts 2004; Koster et al. 2004; Seneviratne et al. 2006). Despite the numerous studies on the impact of soil moisture conditions on land–atmosphere interactions (e.g., Brubaker and Entekhabi 1996; Eltahir 1998; Pielke et al. 1999), the lack of a conclusive climatological analysis of the causal dependence between root-zone soil moisture and subsequent rainfall prevents the assessment of the impact of these interactions on the water cycle and the rainfall regime. In fact, it is still unclear how soil moisture conditions may affect rainfall occurrence during the warm season, as different authors have provided evidence in support of contrasting hypotheses on the existence of (i) positive feedbacks (e.g., Eltahir and Pal 1996; Findell and Eltahir 1997; D'Odorico and Porporato 2004; Oglesby and Erickson 1989), (ii) negative feedbacks (e.g., Giorgi et al. 1996; Findell and Eltahir 2003b; Cook et al. 2006), and (iii) no feedbacks (e.g., Georgakakos et al. 1995; Salvucci et al. 2002) between soil moisture and precipitation.

One of the major limitations in the analysis of these feedbacks lies in the lack of a methodology to assess the

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strength and sign of any causal relation between soil moisture and precipitation, as well as the lack of records of soil moisture with fine temporal resolution. Evidence for such feedbacks is usually sought by analyzing energy and water vapor transfer between the land surface and the atmosphere (e.g., Eltahir 1998; Kochendorfer and Ramírez 2005; Brubaker and Entekhabi 1996). Positive feedbacks between soil moisture and precipitation have been explained by considering the water vapor balance of the planetary boundary layer (PBL): higher soil moisture values are associated with higher transpiration rates, that is, with a more intense transfer of moisture into the near-surface atmosphere, which, in turn, would enhance rainfall occurrence (e.g., Eltahir and Bras 1996; Dirmeyer and Brubaker 1999; Brubaker et al. 2001; Koster and Suarez 2004). Known as "precipitation recycling" (e.g., Eltahir and Bras 1996; Trenberth 1999), the precipitation contributed by moisture from local/regional transpiration would favor the emergence of a positive feedback between soil moisture and precipitation during the growing season (e.g., Lettau et al. 1979; Eltahir 1989; Rodriguez-Iturbe et al. 1991). Simulations with atmospheric general circulation models (AGCMs; Shukla and Mintz 1982; Rind 1982; Oglesby and Erickson 1989; Koster and Suarez 2004; Koster et al. 2003) have shown the importance of soil moisture dynamics to the interactions between the land surface and the atmosphere. Koster and Suarez (2003) adopted the National Aeronautics and Space Administration (NASA) Seasonal-to-Interannual Prediction Project (NSIPP) model to generate different 3-month simulations for the boreal summers in the period 1997–2001. They found a significant impact of soil moisture on summertime precipitation only in those continental regions characterized by (i) large initial soil moisture anomalies, (ii) strong sensitivity of evaporation to soil moisture, and (iii) strong sensitivity of precipitation to evaporation.

An empirical approach to the assessment of soil moisture–precipitation feedbacks was taken by Findell and Eltahir (1997), who used data from the Illinois Climate Network (Hollinger and Isard 1994) in a correlation analysis between daily soil moisture data and the total amount of rainfall measured in the following days. A similar analysis was developed by Eltahir and Pal (1996) and by D'Odorico and Porporato (2004), who investigated the relation between soil moisture and the number and size (depth) of storms in the following days. Although these correlations suggest the existence of a positive feedback during the summer period, the autocorrelation inherent to the rainfall regime may induce a bias in these statistical analyses (Findell and Eltahir 1997). While it can be argued that the autocorrelation itself may be a by-product of land–atmosphere interactions (e.g., Rodriguez-Iturbe et al. 1998), it is clear that the assessment of soil moisture–precipitation feedback remains a difficult task due to the circularity of the problem. Unfortunately, these correlation analyses cannot provide conclusive evidence of a causal relation between soil moisture and the subsequent probability of rainfall, though some correlation methods have been suggested that account for rainfall autocorrelation using "vector autoregression" (Salvucci et al. 2002). This limitation can also be addressed by combining the correlation analysis with some additional information on the processes involved in the land–atmosphere interactions in such a way that the statistical analyses are driven by our understanding of the physical processes. To this end, the present study makes use of sounding data to separate convective from stratiform precipitation events. While the former are affected by local surface conditions (e.g., soil moisture), which are known to contribute to the triggering of convection and the consequent production of precipitation, stratiform weather systems develop at larger spatial and temporal scales and exhibit a different response to local soil moisture conditions.

In this paper we focus on a monodimensional (i.e., vertical) analysis of temperature and humidity profiles, without investigating the horizontal dynamics resulting from spatial gradients of soil moisture. The information on the physical processes provided by the sounding data are used to classify convective and stratiform precipitation on the basis of atmospheric instability indexes and to carry out the correlation analysis on these two groups separately. A nonparametric statistical methodology is also applied to provide a more powerful assessment of the dependence between soil moisture and precipitation.

## 2. Data and methods

### a. Meteorological data

Meteorological data from 16 locations across the midwestern United States (Fig. 1 and Table 1) were considered. Because of its continental setting and the existence of relatively long soil moisture records, this region has already been used as a case study in other investigations of land–atmosphere interactions, including those on soil moisture–precipitation feedbacks (Pan et al. 1995; Findell and Eltahir 1997; Koster et al. 2004).

For each of the 16 stations, sounding data were acquired from the archives of the National Climatic Data Center (NCDC) (available online at http://www.ncdc.noaa.gov/oa/upperair.html). Each sounding includes vertical profiles of air temperature and dewpoint tem-

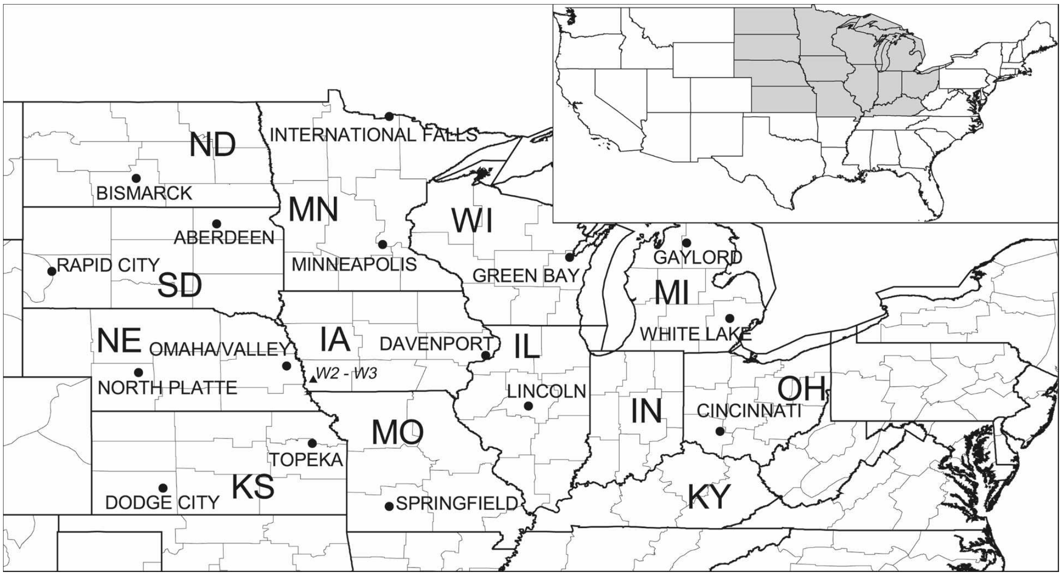

FIG. 1. Geographical setting of the considered 16 stations and of the watershed W2 and W3 in Iowa (IA); the light lines denote the climatic division borders. The region where simulated soil moisture is available is indicated with a gray shade on the inset.

perature measurements taken at different pressure levels. For most stations sounding data are available since 1971, with one to two soundings available on each day, though on some days sounding data were completely missing (23% of daily data from 1971 to 2005, on average). Daily precipitation data were taken from the NCDC archives and were available from 1948 to the present for all the 16 stations.

### b. *Soil moisture simulations*

The study of soil moisture–precipitation feedbacks requires relatively long (a few decades) soil moisture records representative of the soil water content existing over a region that is large enough [i.e., at least 500–1000 km$^2$ (e.g., Avissar and Liu 1996)] to affect the dynamics of land–atmosphere interactions. Moreover, due to the diurnal character of these dynamics (see, e.g., Betts 2004) and to the time scales typical of soil moisture variability in the root zone, soil moisture records with daily resolution are desirable for the assessment of the feedback. Because in the study region soil moisture has been measured just at a few points and with a biweekly sampling frequency (Hollinger and Isard 1994), we use a dataset of simulated soil moisture calculated by the method

TABLE 1. Characteristics of the stations considered and their convective regime.

| Station | State | Lat (°N) | Lon (°W) | POR* | Fraction of convective days in Jun–Aug (%) |
|---|---|---|---|---|---|
| Aberdeen | SD | 45.45 | 98.41 | 1971–2003 | 39 |
| Bismarck | ND | 46.77 | 100.75 | 1971–2003 | 29 |
| Cincinnati | OH | 39.42 | 83.75 | 1971–2003 | 43 |
| Davenport | IA | 41.62 | 90.58 | 1971–2003 | 46 |
| Dodge City | KS | 37.77 | 99.97 | 1971–2003 | 52 |
| Gaylord | MI | 44.90 | 84.72 | 1971–2003 | 14 |
| Green Bay | WI | 44.48 | 88.13 | 1971–2003 | 33 |
| International Falls | MN | 48.57 | 93.38 | 1971–2003 | 25 |
| Lincoln | IL | 40.15 | 89.33 | 1989–2003 | 31 |
| Minneapolis | MN | 44.85 | 93.57 | 1971–2003 | 36 |
| North Platte | NE | 41.13 | 100.68 | 1971–2003 | 42 |
| Omaha valley | NE | 41.32 | 96.37 | 1971–2003 | 50 |
| Rapid City | SD | 44.07 | 103.21 | 1971–2003 | 40 |
| Springfield | MO | 37.23 | 93.38 | 1971–2003 | 60 |
| Topeka | KS | 39.07 | 95.62 | 1971–2003 | 59 |
| White Lake | MI | 42.70 | 83.47 | 1971–2003 | 33 |

* Period of record.

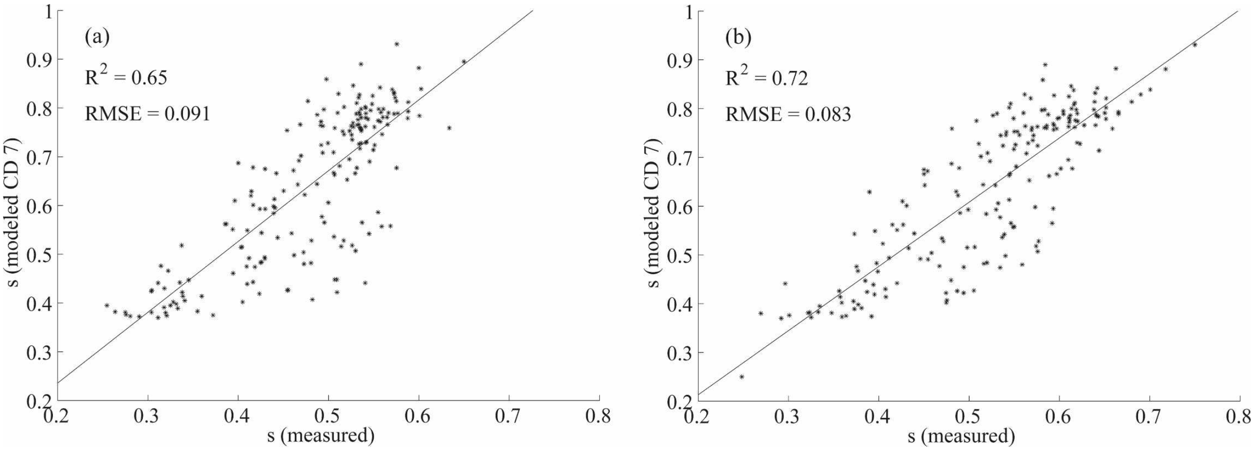

FIG. 2. Comparison of soil saturation values $s$ obtained from simulations for Iowa, Climatic Division 7, and measurements in two watersheds in Iowa: (a) W3 and (b) W2. Measurements were collected during the months from April to October 1972–94 and averaged over the top 50 cm of soil.

presented in Kunkel (1990) for the midwestern region of the United States. These data comprise daily estimates of soil moisture at the climate division (CD) scale (see http://www.ncdc.noaa.gov/oa/documentlibrary/normals/usmap.pdf) for the period 1949–2003. More specifically, the soil moisture values were calculated with a multilayer (nine layers for the top 2 m of soil column) model of the soil water balance (Kunkel 1990), which makes use of a database of average soil properties for row-cropped areas in each climate division (Hollinger 1995). This model uses the Crop Estimation through Resource and Environmental Synthesis (CERES)-Maize corn development and simulation model (Jones and Kiniry 1986) to compute daily evapotranspiration rates as a function of the hydrometeorological conditions (i.e., measured values of daily precipitation, minimum and maximum air temperature, cloud cover, air humidity, and wind speed). Figure 1 shows (gray shade on inset) the states where these simulated data of soil moisture were available.

In this study, the soil water content is expressed in terms of relative soil moisture (or soil saturation, $s = \theta/\rho$, where $\theta$ is the volumetric water content and $\rho$ the porosity, with $0 < s < 1$), averaged through the typical depth of the root zone (top 50 cm; e.g., D'Odorico and Porporato 2004), that is, through the soil thickness that is effective in the interactions between the land surface and the atmosphere.

A comparison between simulated and measured soil moisture values was carried out to assess whether the adopted data were consistent with the few existing point measurements. For this comparison, soil moisture data from two watersheds located in Iowa, CD 7 (W2 and W3, 41.2°N, 95.6°W) provided by the Global Soil Moisture Data Bank (http://climate.envsci.rutgers.edu/soil_moisture/; Robock et al. 2000) were used. Soil moisture values were measured at three sites within each of the two watersheds for a 23-yr-long period (1972–94). Measurements were taken twice a month (April–October) for 13 consecutive layers down to a 2.4-m depth, using gravimetric techniques for the shallower part and neutron probes for the deeper portion of the soil profile (Robock et al. 2000). Depth-averaged (top 50 cm) soil moisture data were averaged over the three sites within each watershed and compared with the simulated values of average soil moisture (Kunkel 1990) in the top 50 cm of Iowa CD 7. Figure 2 shows an overall good linear fit ($R^2$ values of 0.65 and 0.72) between measured and calculated values of soil moisture, especially if one considers that local (measured) values of soil moisture are compared with the (modeled) spatial averages over the climate division. Root-mean-square errors (RMSE) for the linear fit between modeled and observed values are also indicated in Fig. 2. A similar comparison could be carried out using the soil moisture observations from Illinois (Hollinger and Isard 1994). However, these observations were made at field sites with grass cover, which is not representative of the dominant land cover (crops) in these climate divisions.

### c. *Research methods*

The goal of this study is to assess whether any significant relationship exists between soil moisture and the probability of occurrence of subsequent precipitation. The first technique used to assess this dependence is linear regression of precipitation probability against soil saturation. To carry out this regression, the soil moisture data were partitioned into $J$ nonoverlapping bins. For each bin $j$ and day $t$, the probability ($P$) of the "triggering of precipitation," that is, the occurrence of precipitation on day $t + 1$, is calculated as the number of rainy days preceded by a day with soil moisture value in the $j$th bin, divided by the total number of days with soil moisture in the $j$th bin.

The use of a 1-day lag in the assessment of the impact of soil moisture on precipitation is motivated by the need to prevent the results from being affected by the dependence of soil moisture on precipitation (i.e., precipitation values need to be subsequent to soil moisture values) and by the fact that the dynamics of the PBL essentially develops on a daily scale basis (see, e.g., Betts 2004). Thus, the soil moisture conditions that most likely affect the interactions with the atmosphere are those of the previous day. Moreover, in the study region the time scales typical of soil moisture dry-down after rain are likely to be of just a few days, depending on the depth of the soil layer under question (50 cm in this study). Soil moisture classes were chosen in a way that they contain the same number of daily values of soil moisture. Eight classes were used in this study, chosen as a compromise between having enough points in each bin to calculate the probability $P$ and having enough classes to detect any dependence of $P$ on soil moisture. The relation between $P$ and soil moisture was evaluated by fitting a line to the calculated values of the probability of rainfall occurrence ($P$) for each bin by means of the linear least squares method. It is worth noting that this study, by considering just the probability of rain on day $t + 1$ for a given range of soil moisture on day $t$ without consideration of precipitation on other days, focuses on the evaluation of the land–atmosphere interactions based on the probability of triggering of precipitation events, and it does not carry out any test to assess their persistence.

The relation between precipitation and soil moisture can be better disentangled by considering an alternative graphical representation of the same variables. We start from the same information used in the previous analyses, the sample $\{s_j\}$, $j = 1, 2, \ldots, N$ of soil moisture values on all days, whether followed by a rainy day or not. First the set of all soil moisture values, $\{s_j\}$, is ordered from smallest to largest, $(j) = 1, 2, \ldots, N$, yielding the set $\{s_{(j)}\}$; the corresponding cumulative distribution function (CDF) is computed as $F(s_{(j)}) = j/N$. Then the subset of $\{s_{(j)}\}$ containing soil moisture values on days preceding rainy days is selected and denoted $\{s_{(i)}\}$, $i = 1, 2, \ldots n$. The CDF corresponding to $\{s_{(i)}\}$ is computed as $i/n$. Those values of the CDF of all soil moisture values $F(s_{(j)})$ corresponding to $\{s_{(i)}\}$ are plotted on the horizontal axis and $i/n$ on the vertical axis (as in Figs. 5 and 6), allowing a comparison between the two distributions. If the subset $\{s_{(i)}\}$ of soil moisture values on days before rainy days were "uniformly" sampled from the complete set of soil moisture values $\{s_{(j)}\}$, the distributions would be the same and the plot would lie along the bisector between (0, 0) and (1, 1) except for random variation. If certain values of soil moisture are instead more likely to occur before rainy days, then the line will deviate significantly from the bisector. If soil moisture is likely to be high before rainy days (indicating positive feedback), then the $F(s_{(j)})$ values sampled will be concentrated among the larger values and thus the line will deviate to the lower right of the bisector, while if soil moisture is likely to be low before rainy days (indicating negative feedback), then the line will deviate to the upper left. A similar graphical representation is sometimes used in a completely different framework, that is, as a verification tool of the reliability of probabilistic predictions. We refer to Laio and Tamea (2007) for further details on the modality of interpretations of these diagrams.

A more objective quantification of the strength of the feedback can be obtained by considering that the graphical method can be accompanied by suitable statistical tests. As suggested above, under the null hypothesis of no soil moisture–precipitation feedback, there is no difference between the smaller sample containing the $s_i$ values in days preceding rainfall, and the larger one containing all $N$ soil moisture measurements. As a consequence, the $s_i$ values have distribution $F(s)$, which in turn implies that the $F(s_i)$ values constitute a random sample of size $n$ from a uniform distribution (e.g., Laio and Tamea 2007). Two uniformity tests can therefore be applied to the $F(s_i)$ values to quantify the significance of any eventual feedback. The first one is based on a statistic ($\alpha_K$) developed by Kolmogorov in 1933 (see Kendall and Stuart 1977, 476–481), which evaluates the maximum distance between the empirical curve and the bisector (see, e.g., Fig. 5). The second one is a more powerful tool referred to as a Cramér–Von Mises test (see, e.g., Laio 2004), based on a statistic ($\alpha_{\mathrm{CVM}}$) that measures the squared distance between the empirical curve and the bisector. These uniformity tests are better suited at detecting the existence of a possible feedback between soil moisture and precipitation than the correlation analyses we have discussed. In fact, 1) soil moisture data are analyzed without requiring ad hoc binning and averaging within an assigned number of bins; 2) the analysis is robust for time spans as short as one month, thus allowing identification of possible intraseasonal variations or individual months when the feedback is stronger; and 3) the method is nonparametric in that no a priori linear dependence is assumed to exist between soil moisture and the probability of rainfall occurrence.

### *d. Classification of rainfall events*

The separation between convective and stratiform precipitation was carried out using a combination of two indices of atmospheric instability found in the literature. The convective available potential energy (CAPE) index is used here to quantify the degree of atmospheric conditional instability and the ability to generate convective rainfall. We use the formulation of CAPE found in Moncrieff and Miller (1976):

$$\mathrm{CAPE} = \int_{\mathrm{LFC}}^{\mathrm{LNB}} (T_{\mathrm{vp}} - T_{\mathrm{va}}) R_d \, d\ln p, \tag{1}$$

where LFC is the level of free convection, LNB is the level of natural buoyancy, $T_{\mathrm{vp}}$ and $T_{\mathrm{va}}$ are the virtual temperatures of the air parcel and the environment, respectively, $R_d$ is the gas constant for dry air, and $p$ is the air pressure.

CAPE comprises the integrated effect of the positive buoyancy of an air mass that rises through the atmosphere according to the parcel theory. It is noteworthy that CAPE values calculated using the same sounding data may vary with the calculation method, the pressure level of the considered air parcel, and whether a correction for virtual temperature is applied (see Doswell and Rasmussen 1994). The criterion used here is based on a standard irreversible (or pseudoadiabatic) process (e.g., Williams and Renno 1993) with correction for virtual temperature. The initial level of the air parcel was chosen as the highest pressure level (lowest elevation) where both dewpoint and air temperature were available, with a lower threshold set to 800 hPa. Soundings that did not comply with those requirements were discarded.

The second index used to classify the rainfall was the convective inhibition (CIN). The definition is the same as CAPE but with a different integration interval:

$$\mathrm{CIN} = \int_{\mathrm{SFC}}^{\mathrm{LFC}} (T_{\mathrm{vp}} - T_{\mathrm{va}}) R_d \, d\ln p, \tag{2}$$

where "SFC" means surface. CIN accounts for the presence of a capping inversion between the surface and the level of free convection, which induces a negative buoyancy force. This effect may prevent near-surface air parcels from becoming unstable. Combining the two indices, convective days are then identified as those in which CAPE $\geq$ 400 kJ kg$^{-1}$ and CIN $\geq -5$ kJ kg$^{-1}$, as in Findell and Eltahir (2003a). Rainfall occurrences are partitioned into only two classes, with stratiform rainfall being defined as those occurring on nonconvective days.

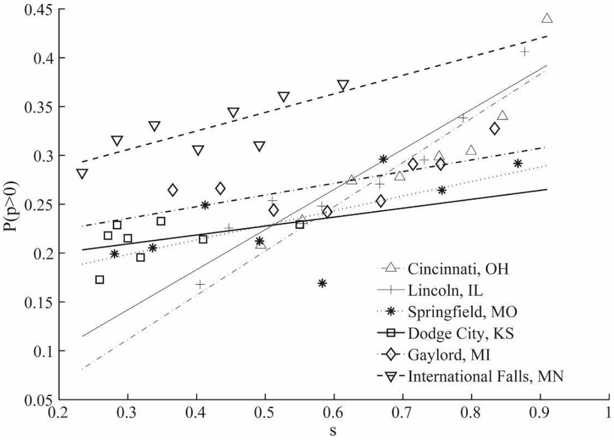

FIG. 3. Linear fits for soil moisture ($s$) and probability of precipitation on the following day $P(p > 0)$ considering the whole rainfall dataset, for six stations for the period June–August.

## 3. Results and discussion

### *a. Relation between probability of rainfall occurrence and soil moisture*

We applied the methods described in section 2c to the 16 stations. We focused on the warm season (i.e., June–August), as it includes most (72%, averaged over all the stations) of the days with convective precipitation that occur throughout the year. Figure 3 shows the relation between soil moisture and the probability of precipitation on the following day for all days, whether convective or not, for the June–August period for 6 out of the 16 stations. Among these 16 linear regressions only 4 were not significant at the 10% level, and all of them showed a positive slope ranging between 0.05 and 0.52. These results are in agreement with previous findings (Findell and Eltahir 1997; D'Odorico and Porporato 2004) supporting the existence of a positive feedback between soil moisture and subsequent precipitation.

Such a positive dependence may result either from (i) autocorrelation of precipitation due to the persistence of large-scale forcings and the consequent occurrence of (stratiform) events longer than one day, or (ii) the actual existence of an effective feedback between soil moisture and subsequent precipitation (Findell and Eltahir 1997). The feedback is expected to exist in the warm season, when the coupling between the land surface and the atmosphere is stronger and the conditions are favorable for the formation of convective systems (e.g., Koster et al. 2003; Koster and Suarez 2004).

The autocorrelation of precipitation is clearly a confounding factor, which may prevent the correct assessment of soil moisture–rainfall feedback. Thus, a better understanding of this feedback requires a classification of rainfall events as convective or stratiform. Stratiform rainfall is typically produced by large-scale, long-lived weather systems, which are not controlled by local surface conditions (e.g., soil moisture) for time scales as short as one day. Thus, any dependence between soil moisture and the occurrence of stratiform rainfall in the following day is likely to be induced by the autocorrelation effect. Conversely, convective rainfall typically occurs in short events and is affected by local surface conditions.

We have used the atmospheric instability indices described before (in section 2d) to investigate the regime of convective precipitation for all the 16 stations. A well-defined "convective season" was observed for each station in the course of the warm season. In fact, the annual distribution of the probability, $P_c$, of convective precipitation was always "unimodal" with a peak between June and August. Table 1 shows the percentage of convective precipitation days out of the total for the period between June and August. The intraseasonal analysis shows little variations of the likelihood of convective rainfall occurrences within the warm season, with the values for July being only slightly larger than those for June and August. Table 1 shows that convective precipitation plays an important role in the summer rainfall regime, as it contributes about 40% of the total days with rainfall, computed as an average for all the stations. With its mean value of 10.6 mm $\text{day}^{-1}$ on days with rain, the intensity of convective rainfall was on average significantly higher than that of stratiform rain at 7.9 mm $\text{day}^{-1}$. The mean number of consecutive days with convective precipitation was 1.20, while stratiform precipitation had a mean duration of 1.46 days. This result is in agreement with the common notion that convective instability is associated with short and intense events. This difference between the duration of convective and stratiform precipitation would likely become stronger if finer-resolution data were used (note that these values were computed from daily data), since convective events are known for their capability to develop and cease in a few hours. In fact, because of the daily time scale typical of the PBL dynamics, each convective day should be considered as a different event.

Regression analyses such as those shown in Fig. 3 were also carried out on convective and stratiform precipitation separately. The results are shown in Fig. 4 for the case of Cincinnati, Ohio. At all stations the dependence between soil moisture and probability of precipitation on the following day is mostly because of stratiform precipitation. In fact, similar slope ($\beta$) and $R^2$ values are found when a line is fitted to soil moisture and rainfall data using either total rainfall or stratiform rainfall events only (e.g., for the case in Fig. 4, $\beta_{\text{total}} = 0.45$, $R^2_{\text{total}} = 0.86$ and $\beta_{\text{stratiform}} = 0.34$, $R^2_{\text{stratiform}} = 0.87$ for all rainfall occurrences and stratiform rainfall, respectively). The dependence of convective precipitation on antecedent soil moisture condition was instead found to be weaker, but still positive and significantly correlated ($\beta_{\text{convective}} = 0.12$; $R^2_{\text{convective}} = 0.76$). Because the positive dependence found between the occurrence of days with stratiform rain and the antecedent soil moisture conditions is greatly affected by the autocorrelation and relatively long duration of stratiform rainfall events (defined as a sequence of consecutive stratiform days with rain), we repeated this correlation analysis using only the first day of each stratiform event. The results of this analysis are shown in Fig. 4 (circles fitted by the dotted line). On the other hand, due to the daily nature of the boundary layer dynamics, consecutive days of convective precipitation are assumed to be associated with separate convective storms. It is found that the triggering of stratiform events (Fig. 4, circles) are only weakly related to surface conditions, suggesting that the positive linear relationship between soil moisture and daily stratiform precipitation (Fig. 4, squares) does not result from a feedback in land–atmosphere interactions but from the persistence of stratiform events and the consequent autocorrelation of stratiform precipitation. Thus, the triggering of stratiform precipitation remains independent of the existing surface conditions. As this analysis is focused at evaluating the probability of triggering of precipitation, we make the implicit assumption that

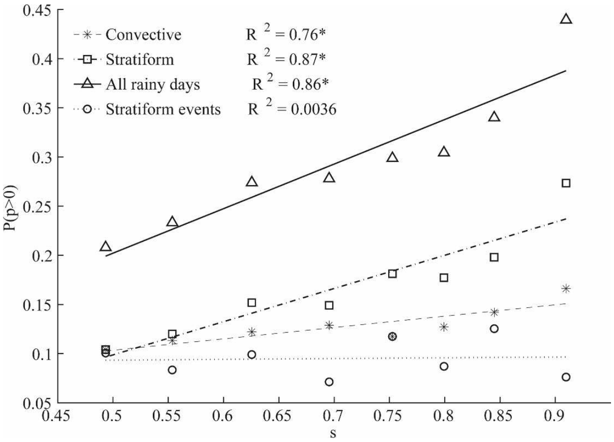

FIG. 4. Linear fits between soil moisture ($s$) and the probability of precipitation on the following day $P(p > 0)$ for Cincinnati, OH, over the period June–August under four different conditions. Significant linear regressions at the 10% level are marked with an asterisk.

TABLE 2. Significance level (%) for Kolmogorov ($\alpha_K$) and Cramér–Von Mises ($\alpha_{CVM}$) test statistics, and corresponding slope $\beta_c$ of the linear fit, for convective precipitation between June and August. Significant linear regressions at the 10% level are marked with an asterisk.

| Station | $\alpha_{CVM}$ (%) | $\alpha_K$ (%) | $\beta_c$ | Feedback |
|---|---|---|---|---|
| Aberdeen | 15.9 | 23.3 | −0.070 | Slightly negative |
| Bismarck | 42.8 | 47.9 | 0.004 | None |
| Cincinnati | 4.24 | 13.7 | 0.115* | Positive |
| Davenport | 61.8 | 53.8 | −0.028 | None |
| Dodge City | 60.5 | 71 | −0.053 | None |
| Gaylord | 2.79 | 0.971 | −0.058 | Negative |
| Green Bay | 23.1 | 20.6 | −0.030 | Slightly negative |
| International Falls | 1.32 | 0.325 | −0.070 | Negative |
| Lincoln | 0.291 | 0.908 | 0.178* | Positive |
| Minneapolis | 65.9 | 72.5 | 0.001 | None |
| North Platte | 41.6 | 34.9 | 0.055 | None |
| Omaha valley | 19.7 | 26.3 | −0.067* | Slightly negative |
| Rapid City | 14 | 19.2 | 0.041 | Slightly positive |
| Springfield | 67.1 | 88.2 | −0.007 | None |
| Topeka | 36.8 | 46.2 | 0.036 | None |
| White Lake | 22.6 | 18 | −0.026 | Slightly negative |

there is no soil moisture effect on the persistence of stratiform rainfall.

Results from the other locations are mostly in agreement with the results for Cincinnati shown in Fig. 4 for total and stratiform rainfall, but they show clear differences in the relation between convective events and surface soil moisture. The dependence between the frequency of convective rainfall and antecedent soil moisture led to both positive and negative values of the regression slope, with a number of stations exhibiting nonsignificant fits, due to either low values of slope $\beta_c$ (see Table 2) or to clear departures from the linear dependence. These results suggest that even in the warm (convective) season, the positive relationship found between soil moisture and subsequent precipitation considering all days is mostly contributed by the persistence of large-scale rainfall events, while the feedback between land surface and precipitation is usually weaker and more difficult to detect.

Consequently, we applied the uniformity tests to each station and each class of rainfall for the warm period, in order to assess the significance of the obtained feedback, giving particular focus to convective precipitation. Figure 5 shows the results obtained with these tests for the station of Cincinnati between June and August. The four empirical curves in Fig. 5 refer to (a) all the rainy days, (b) convective days, (c) stratiform days, and (d) stratiform events (i.e., considering only the first day of each event) and correspond to the four cases analyzed by the regression and presented in Fig. 4. The two dashed lines in each graph indicate the $\alpha_K = 5\%$ significance level of the Kolmogorov statistics. Table 2 reports the significance level for each of the 16 stations analyzed between June and August obtained with the two statistical tests on convective rainfall. It also includes the slopes of the regression lines obtained with the linear fits (described at the beginning of this section) on the same class of rainfall, together with an overall evaluation of the soil moisture–convective precipitation feedback in the warm season. We adopted a classification that defines as positively (or negatively) correlated those stations where $\alpha_{CVM} < 10\%$, while a slightly positive (or negative) feedback was defined by the condition $10\% < \alpha_{CVM} < 25\%$. The outcome of this analysis allows us to identify three main regions with similar characteristics: a positive feedback zone in the southeastern area of the study region, a negative feedback zone in the northern area, and a central/western region where no clear feedback was detected. Plotted in Fig. 6 are the results of the uniformity test on convective precipitation for six stations (the same reported in Fig. 3), using two stations from each region.

The application of the uniformity tests during convective days was then repeated separately on each of the three months of the warm season (June–August). These monthly results are consistent with the general picture obtained for the warm season as a whole, though they show a significant variability within the warm season. Two clear examples of this phenomenon are those of Green Bay, Wisconsin, and Minneapolis, Minnesota, which are located along the boundary among the zones with negative, positive, and no feedbacks. These two locations are characterized by a strong positive feedback ($\alpha_{CVM} = 2.02\%$ and $\alpha_{CVM} = 2.96\%$, respectively) for the month of June, while the same analysis for June–August shows no feedback for Minneapolis and a slightly negative feedback for Green Bay.

It is noteworthy that the geographic layout of regions with different feedbacks (i.e., positive, negative, or no feedback) emerging from the results of our analyses is partly in agreement with the study by Findell and Eltahir (2003b), who proposed a subdivision of the United States into homogeneous regions with similar feedback characteristics, based on indices of atmospheric instability calculated for the same season (June–August). In particular, the region where we found no significant feedback (i.e., central–western region of the studied domain) is classified (Findell and Eltahir 2003b) either as 1) "Atmospheric controlled region" or 2) "Transitional region"; that is, no prevailing correlations can be seen in that 1) soil moisture does not affect the rainfall triggering or 2) both positive and

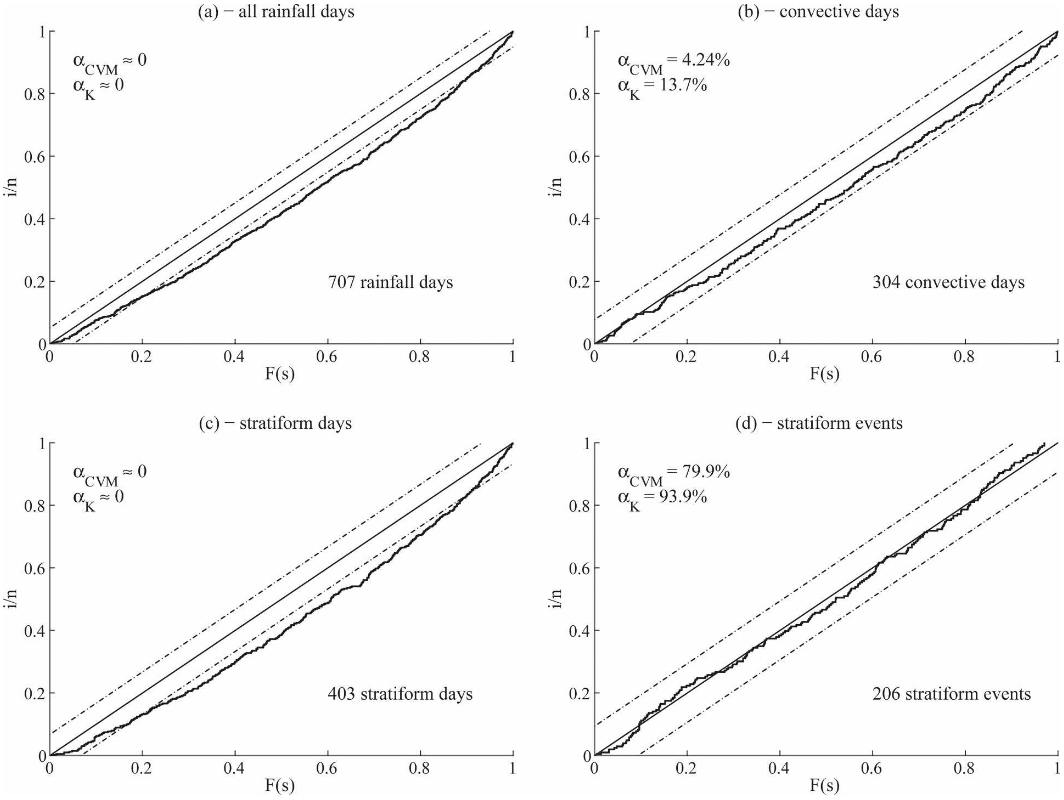

FIG. 5. Probability plots of the empirical distribution of soil moisture on days before different types of rain events with respect to the cumulative distribution function of soil moisture, $F(s)$, for Cincinnati, OH, between June and August: (a) all rainy days, (b) convective days with rain, (c) nonconvective (stratiform) days with rain, and (d) stratiform events (the first of consecutive stratiform days with rain). The thin continuous line is the bisector of the diagram, and the dashed lines are Kolmogorov bands at a 5% level (see text for details). The significance of the feedback is measured by $\alpha_{CVM}$, the Cramér–Von Mises statistic, and $\alpha_K$, the Kolmogorov statistic.

negative feedbacks exist to a similar extent. The remaining region was classified by these authors as "Wet soil advantage region" (i.e., having positive feedback). This region includes the zone where we found convective rain to be negatively correlated with antecedent soil moisture. Nevertheless, these authors stressed the weakness of the positive feedback signal in this region, due to the coexistence of processes contributing both to negative and positive correlation. Such weakness decreases moving southward, where the evidence of a positive feedback becomes clearer. In this sense, our study confirms the hypothesis of a weaker feedback in the northern region in that it is characterized by reduced energy levels and vapor fluxes, which results in a lower percentage of convective events (see Table 1, last column).

### b. *Relation between rainfall intensity and soil moisture*

To assess the existence of a relationship between the rainfall intensity and surface conditions, we first related the average values of daily precipitation on days with rain to the soil saturation on the previous day. We found that at all of the 16 stations no significant dependence exists, in agreement with the results obtained by Eltahir and Pal (1996) and D'Odorico and Porporato (2004) using the biweekly soil moisture measurements from the Illinois Climate Network. The same analysis was then repeated separately on convective and stratiform precipitation for different periods of the year. Neither stratiform nor convective events were found to be significantly correlated to antecedent soil moisture at any of these stations. Figure 7 shows the results obtained for Cincinnati, Ohio, for the period between June and August: the data points were partitioned into eight nonoverlapping soil moisture classes having about the same number of values. The mean value of daily rainfall intensity is plotted for each class along with a dispersion bar ranging between the 5% and 95% values of their empirical cumulative distribution. In both cases (i.e., convective and stratiform) points are considerably scattered around the linear fit, and the $R^2$ values are

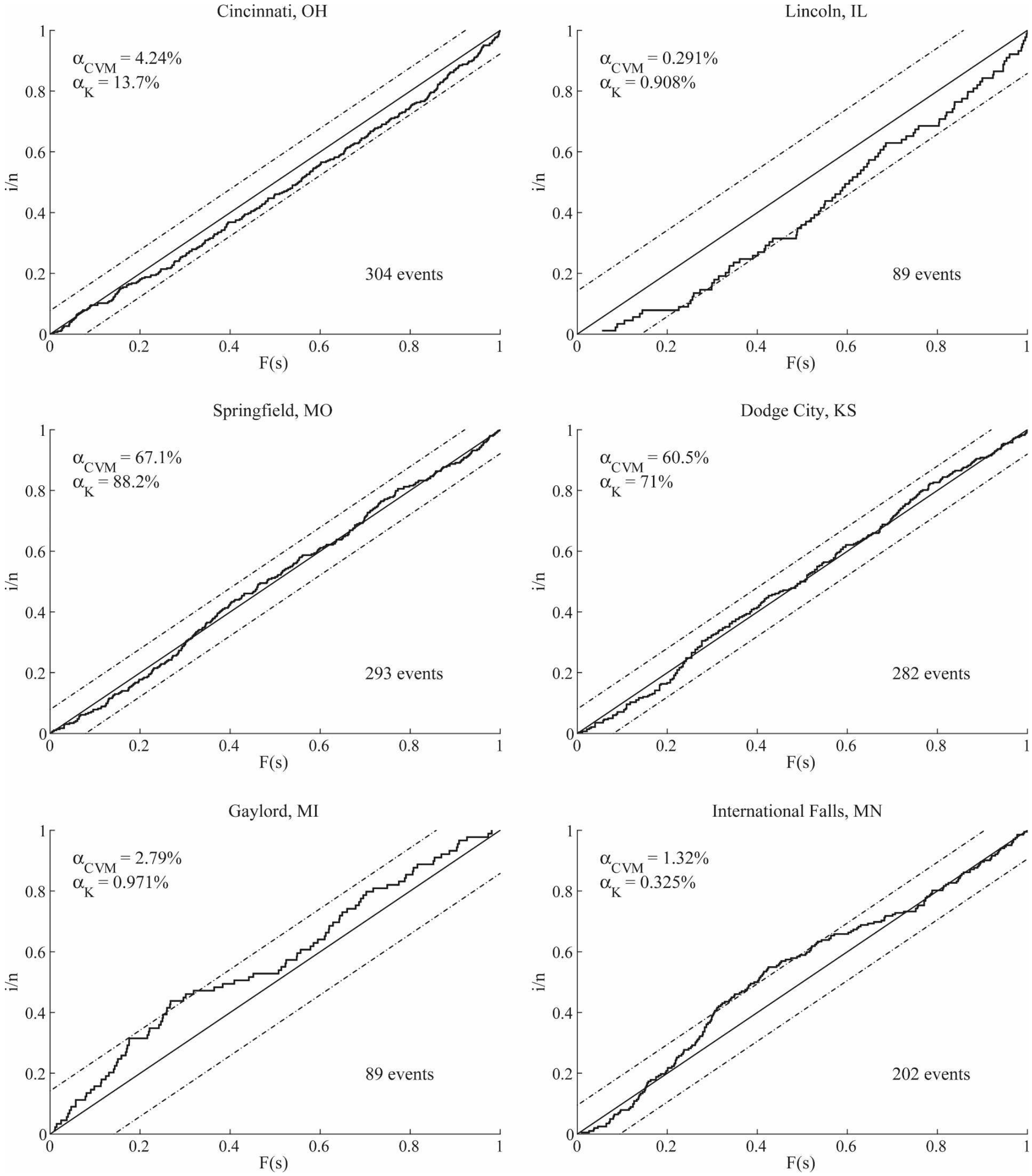

FIG. 6. Probability plots of the empirical distribution of soil moisture on days before convective precipitation with respect to the cumulative distribution function of soil moisture, $F(s)$, for six stations over the period June–August. (top) Two stations with positive feedback; (middle) two stations with no feedback; (bottom) two stations with negative feedback. The plots are as in Fig. 5

approximately zero. Thus, while a complex feedback behavior is evident in the dependence between soil moisture and the occurrence of precipitation, no dependence of daily precipitation intensity is found on soil moisture of the previous day.

## 4. Conclusions

This study investigates the conditions underlying the dependence between (simulated) soil moisture and subsequent (observed) rainfall occurrence and proposes a process-based methodology to avoid circularity in the testing of the significance of this dependence. To this end, atmospheric sounding data at 16 stations in the midwestern United States were used to classify rainfall events either as stratiform or convective. The information on the physics of these two types of precipitation, in conjunction to statistical analyses, is used to assess whether the dependence of precipitation on antecedent soil moisture results from a feedback mechanism. The

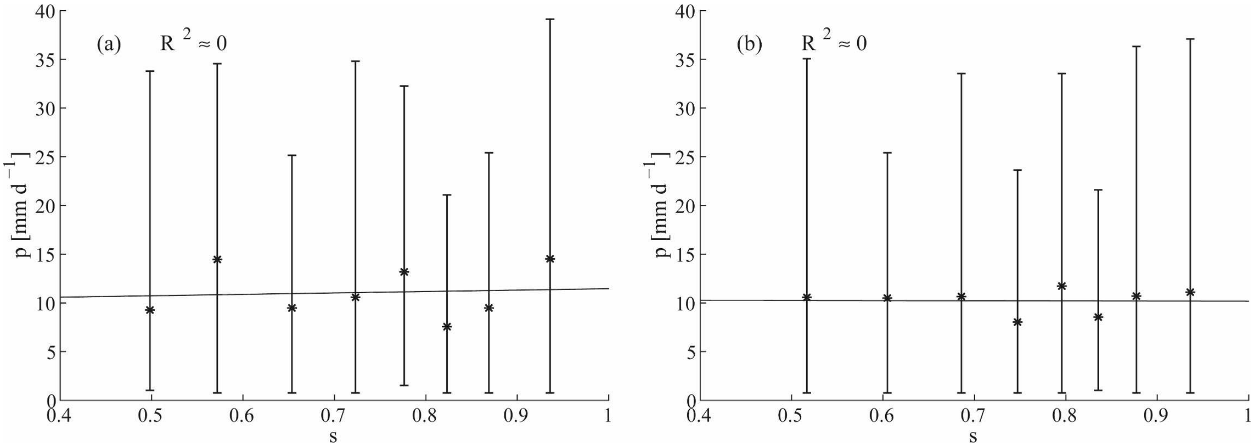

FIG. 7. Relationship between soil moisture ($s$) and rainfall intensity on the following day for (a) convective and (b) stratiform precipitation for Cincinnati, OH, over the period June–August.

data available include more than 30 yr of daily precipitation, sounding, and soil moisture data.

The results suggest that the positive relationship observed between soil moisture and the probability of occurrence of subsequent rainfall, considering all rainfall days, is mostly due to the autocorrelation of large-scale events. When this effect is removed, a relatively weak feedback is detected for some regions between soil moisture and the frequency of occurrence of convective precipitation. This feedback may be either positive or negative depending on the geographic and climatological setting.

Two main contrasting physical mechanisms may be invoked to explain such a dependence. On the one hand, high soil moisture values induce a decrease in the albedo and the Bowen ratio, thus favoring energy inflow from the soil surface and convective instability, and hence a positive feedback between soil moisture and the triggering of convective rain (Eltahir 1998). On the other hand, high soil moisture values are associated with surface cooling and the possible stabilization of the planetary boundary layer, thereby leading to subsidence (Cook et al. 2006). This effect would prevent the triggering of convective rainfall. Both effects may occur during the warm season; which one of them occurs on any given day depends on the net contributions of energy that act on the atmosphere. This leads to a complex local climatology in which the feedback between soil moisture and subsequent rainfall occurrence is difficult to detect. Presumably, a significant feedback can be detected only when one of these two mechanisms is dominant and stronger than the other.

No significant relation was detected between soil moisture and the average daily intensity of subsequent rainfall, for days characterized by nonzero rainfall. The same result was found also when convective and stratiform rainfall events were considered separately.

In conclusion, the present study suggests that soil moisture conditions do affect the triggering of rainfall events, but such a variable alone cannot provide an unambiguous dependence on the probability of subsequent precipitation. A more accurate description (and prediction) of the soil moisture–precipitation feedbacks can be presumably achieved by including the effects of one or more additional suitable variables describing the incoming energy fluxes (e.g., solar radiation, air temperature, surface temperature, etc.).

This study contributes to a better understanding of soil moisture–rainfall feedbacks and integrates process-based understanding of the physical processes into a statistical, nonparametric methodology. It shows how a major confounding factor in the assessment of these feedbacks comes from the rainfall autocorrelation. It is probably because of these confounding effects that no unanimous consensus has been reached so far on the existence/nonexistence of soil moisture–rainfall feedbacks in the midwestern United States.

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## REFERENCES

Avissar, R., and Y. Liu, 1996: Three-dimensional numerical study of shallow convective clouds and precipitation induced by land surface forcing. *J. Geophys. Res.,* **101,** 7499–7518.

Betts, A. K., 2004: Understanding hydrometeorology using global models. *Bull. Amer. Meteor. Soc.,* **85,** 1673–1688.

——, J. H. Ball, A. C. M. Beljaars, M. J. Miller, and P. A. Viterbo, 1996: The land surface-atmosphere interaction: A review based on observational and global modeling perspectives. *J. Geophys. Res.,* **101D,** 7209–7226.

Brubaker, K. L., and D. Entekhabi, 1996: Analysis of feedback mechanisms in land-atmosphere interaction. *Water Resour. Res.,* **32,** 1343–1357.

——, P. A. Dirmeyer, A. Sudradjat, B. S. Levy, and F. Bernal, 2001: A 36-yr climatological description of the evaporative sources of warm-season precipitation in the Mississippi River basin. *J. Hydrometeor.,* **2,** 537–557.

Cook, B. I., G. Bonan, and S. Levis, 2006: Soil moisture feedbacks to precipitation in southern Africa. *J. Climate,* **19,** 4198–4206.

Dirmeyer, P. A., and K. L. Brubaker, 1999: Contrasting evaporative moisture sources during the drought of 1988 and the flood of 1993. *J. Geophys. Res.,* **104D,** 19 383–19 397.

D'Odorico, P., and A. Porporato, 2004: Preferential states in soil moisture and climate dynamics. *Proc. Natl. Acad. Sci. USA,* **101,** 8848–8851.

Doswell, C. A., III, and E. N. Rasmussen, 1994: The effect of neglecting the virtual temperature correction on CAPE calculations. *Wea. Forecasting,* **9,** 625–629.

Eltahir, E. A. B., 1989: A feedback mechanism in annual rainfall, central Sudan. *J. Hydrol.,* **110,** 323–334.

——, 1998: A soil moisture-rainfall feedback mechanism. 1. Theory and observations. *Water Resour. Res.,* **34,** 765–776.

——, and R. L. Bras, 1996: Precipitation recycling. *Rev. Geophys.,* **34,** 367–378.

——, and J. S. Pal, 1996: Relationship between surface conditions and subsequent rainfall in convective storms. *J. Geophys. Res.,* **101D,** 26 237–26 246.

Findell, K. L., and E. A. B. Eltahir, 1997: An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois. *Water Resour. Res.,* **33,** 725–736.

——, and ——, 2003a: Atmospheric controls on soil moisture–boundary layer interactions. Part I: Framework development. *J. Hydrometeor.,* **4,** 552–569.

——, and ——, 2003b: Atmospheric controls on soil moisture–boundary layer interactions. Part II: Feedbacks within the continental United States. *J. Hydrometeor.,* **4,** 570–583.

Georgakakos, K. P., D. H. Bae, and D. R. Cayan, 1995: Hydroclimatology of continental watersheds. 1. Temporal analyses. *Water Resour. Res.,* **31,** 655–676.

Giorgi, F., L. O. Mearns, C. Shields, and L. Mayer, 1996: A regional model study of the importance of local versus remote controls of the 1988 drought and the 1993 flood over the central United States. *J. Climate,* **9,** 1150–1162.

Hollinger, S. E., 1995: *Midwestern Climate Center Soils Atlas and Database.* Illinois State Water Survey, 36 pp.

——, and S. A. Isard, 1994: A soil moisture climatology of Illinois. *J. Climate,* **7,** 822–833.

Jones, C., and J. Kiniry, 1986: *Ceres-N Maize: A Simulation Model of Maize Growth and Development.* Texas A&M University Press, 194 pp.

Kendall, M. G., and A. Stuart, 1977: *Inference and Relationship.* Vol. 2. *The Advanced Theory of Statistics,* 4th ed. Griffin, 748 pp.

Kochendorfer, J. P., and J. A. Ramírez, 2005: The impact of land–atmosphere interactions on the temporal variability of soil moisture at the regional scale. *J. Hydrometeor.,* **6,** 53–67.

Koster, R. D., and M. J. Suarez, 2003: Impact of land surface initialization on seasonal precipitation and temperature prediction. *J. Hydrometeor.,* **4,** 408–423.

——, and ——, 2004: Suggestions in the observational record of land–atmosphere feedback operating at seasonal time scales. *J. Hydrometeor.,* **5,** 567–572.

——, ——, R. W. Higgins, and H. M. Van den Dool, 2003: Observational evidence that soil moisture variations affect precipitation. *Geophys. Res. Lett.,* **30,** 1241, doi:10.1029/2002GL016571.

——, and Coauthors, 2004: Regions of strong coupling between soil moisture and precipitation. *Science,* **305,** 1138–1140.

Kunkel, K. E., 1990: Operational soil moisture estimation for the midwestern United States. *J. Appl. Meteor.,* **29,** 1158–1166.

Laio, F., 2004: Cramer–Von Mises and Anderson–Darling goodness of fit tests for extreme value distributions with unknown parameters. *Water Resour. Res.,* **40,** W09308, doi:10.1029/2004WR003204.

——, and S. Tamea, 2007: Verification tools for probabilistic forecasts of continuous hydrological variables. *Hydrol. Earth. Syst. Sci.,* **11,** 1267–1277.

Lettau, H., K. Lettau, and L. C. B. Molion, 1979: Amazonia's hydrologic cycle and the role of atmospheric recycling in assessing deforestation effects. *Mon. Wea. Rev.,* **107,** 227–238.

Moncrieff, M. W., and M. J. Miller, 1976: The dynamics and simulation of tropical cumulonimbus and squall lines. *Quart. J. Roy. Meteor. Soc.,* **102,** 373–394.

Oglesby, R. J., and D. J. Erickson III, 1989: Soil moisture and the persistence of North American drought. *J. Climate,* **2,** 1362–1380.

Pan, Z., M. Seagal, R. Turner, and E. Takle, 1995: Model simulation of impacts of transient surface wetness on summer rainfall in the United States Midwest during drought and flood years. *Mon. Wea. Rev.,* **123,** 1575–1581.

Pielke, R. A., Sr., G. E. Liston, J. L. Eastman, L. Lu, and M. Coughenour, 1999: Seasonal weather predictions as an initial value problem. *J. Geophys. Res.,* **104D,** 19 463–19 479.

Rind, D., 1982: The influence of ground moisture conditions in North America on summer climate as modeled in the GISS GCM. *Mon. Wea. Rev.,* **110,** 1487–1494.

Robock, A., K. Y. Vinnikov, G. Srinivasan, J. K. Entin, S. E. Hollinger, N. A. Speranskaya, S. Liu, and A. Namkhai, 2000: The Global Soil Moisture Data Bank. *Bull. Amer. Meteor. Soc.,* **81,** 1281–1299.

Rodriguez-Iturbe, I., D. Entekhabi, and R. L. Bras, 1991: Nonlinear dynamics of soil moisture at climate scales. 1. Stochastic analysis. *Water Resour. Res.,* **27,** 1899–1906.

——, P. D'Odorico, and A. Rinaldo, 1998: Possible self-organizing dynamics for land–atmosphere interactions. *J. Geophys. Res.,* **103D,** 23 071–23 077.

Salvucci, G. D., J. A. Saleem, and R. Kaufmann, 2002: Investigating soil moisture feedbacks on precipitation with tests of Granger causality. *Adv. Water Resour.,* **25,** 1305–1312.

Schär, C., D. Lüthi, U. Beyerle, and E. Heise, 1999: The soil–precipitation feedback: A process study with a regional climate model. *J. Climate,* **12,** 722–741.

Seneviratne, S. I., D. Lüthi, M. Litschi, and C. Schär, 2006: Land–atmosphere coupling and climate change in Europe. *Nature,* **443,** 205–209.

Shukla, J., and Y. Mintz, 1982: Influence of land-surface evapotranspiration on the earth's climate. *Science,* **215,** 1498–1501.

Trenberth, K. E., 1999: Atmospheric moisture recycling: Role of advection and local evaporation. *J. Climate,* **12,** 1368–1381.

Williams, E. R., and N. Renno, 1993: An analysis of the conditional instability of the tropical atmosphere. *Mon. Wea. Rev.,* **121,** 21–36.