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Analysis of the pathways relating soil moisture and subsequent rainfall in Illinois

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Abstract. This study is a continuation of an earlier work [*Findell and Eltahir*, 1997] on the soil moisture-rainfall feedback using a data set of biweekly neutron probe measurements of soil moisture at up to 19 stations throughout Illinois. Analyses in this earlier work showed a positive correlation between initial soil saturation and subsequent rainfall from early June to mid-August. This correlation was more significant than the serial correlation within precipitation, suggesting the likelihood of a physical mechanism linking soil moisture to subsequent rainfall. This paper probes the nature of such a physical pathway linking soil moisture to subsequent rainfall. The pathway is divided into two stages: soil moisture and near-surface air, and near-surface air and rainfall. An analysis of the connections between an average daily soil saturation for the whole state of Illinois with statewide average near-surface air conditions did not yield the anticipated positive correlation between soil moisture and moist static energy (MSE). It is not clear if this is due to limitations of the data or of the theory. Other factors, such as clouds, could potentially be masking the impacts of soil moisture on the energy of the near-surface air. There was evidence, however, that moisture availability at the surface has a very strong impact on the wet-bulb depression of near-surface air, particularly from mid-May to the end of August, showing good correspondence to the period of significant soil moisture-rainfall association. The final set of analyses performed used hourly boundary layer and rainfall data. A link between high MSE and high rainfall was noted during some summer months, and a link between low wet-bulb depression and high rainfall was evident for all of the months analyzed (April through September). These analyses suggest that the significant but weak correlation between soil moisture and rainfall during Illinois summers is at least partially due to soil moisture controls on the wet-bulb depression of near-surface air.

1. Introduction

Although the last few decades have seen a vast improvement in scientific understanding of the land-atmosphere system, much work remains to be completed. The work presented in this paper is part of a concerted effort to advance our understanding of the role of soil moisture conditions in the dynamics of land-atmosphere interactions. These processes are fundamental to many environmental and societal concerns, including the behavior and predictability of floods and droughts and the impacts of changing climatic conditions on regional water resources, agriculture, and ecosystems. Soil moisture conditions and behavior are clearly closely coupled with the conditions and behavior of vegetative cover. Understanding the impacts of soil moisture on atmospheric dynamics will also help in understanding the impacts of land-surface changes, such as deforestation and desertification.

A problem that has received considerable attention in recent years is the long-term impacts of increased concentrations of atmospheric CO_2 [e.g., *Wetherald and Manabe*, 1995; *Rind et. al.*, 1990; *Manabe and Wetherald*, 1987; *Mitchell and Warrilow*, 1987). At the center of this problem are interactions between the soil moisture conditions and the atmosphere. Typically, models show that a doubling of CO_2 concentration leads to higher temperatures, which cause a larger fraction of the wintertime precipitation to be in the form of rain, which in turn leads to increased soil moisture in the winters. The summers also see higher temperatures, but these are accompanied by increases in evaporative demand which tend to outpace any increase in precipitation rates, leading to extensive drying of the soil in some regions. Clearly soil moisture-rainfall interactions are a critical part of this problem. The springtime transition from these warmer, wetter winters to warmer, dryer summers is of crucial importance. *Findell and Eltahir* [1997] (hereinafter referred to as FE97) showed that a soil moisture anomaly that appears in winter or early spring in the mid-latitudes is much more likely to be quickly corrected (brought back to normal conditions) than a late-spring anomaly.

In FE97, Findell and Eltahir presented evidence for the existence of a physical mechanism that maintains a positive feedback between soil saturation levels and subsequent rainfall during Illinois summers. The positive correlation between soil saturation and subsequent rainfall was greater than the serial correlation of rainfall, indicating that rainfall alone cannot explain the relationship (see Figure 1). This result was significant because of the use of a long-term data set of directly observed soil moisture measurements. Such measurements are quite labor and cost intensive and are therefore rarely taken over large areas and long time spans.

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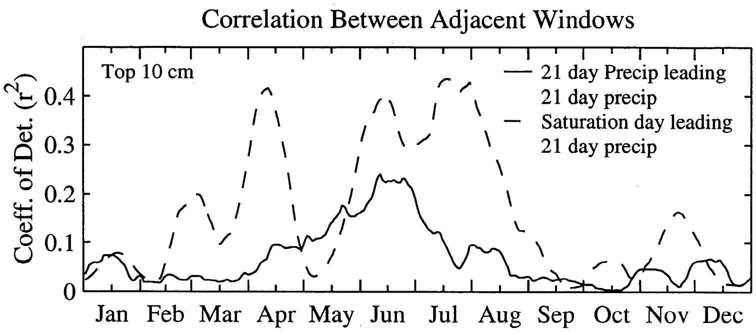


Figure 1. Comparison of smoothed lines of the correlation between adjacent precipitation windows (solid line) and of the correlation between soil saturation (top 10 cm) and subsequent precipitation (dashed line) [from *Findell and Eltahir*, 1997].

This follow-up study was initiated to investigate the possible pathways of the physical mechanism discussed by FE97. After theory and background presented in section 2 and the data set descriptions of section 3, section 4 will present the two steps of the investigated pathway: soil moisture/near-surface air connections, and near-surface air/rainfall connections. Section 5 presents the conclusions and areas of future research.

2. Background and Theory

As scientific understanding of the hydrologic cycle and the climate system has improved over the last three or four decades, soil moisture has come to be recognized as a critical element in these systems. Its importance is now considered by many to be second only to sea surface temperature (SST) in determining the memory of the coupled land-atmosphere-ocean system. Like SST, soil moisture controls the partitioning of energy into sensible and latent heat at the surface of the Earth. However, while SST changes are slow, generally occurring on seasonal timescales, land surface conditions can change dramatically at shorter timescales in response to variability in precipitation and solar forcing. The large heat capacity of water slows any such fast response by the ocean. Similarly, soil moisture acts like a reservoir of water, which damps out high-frequency fluctuations and increases the memory of the land-surface system. Furthermore, while water is always available for evaporation over the oceans, moisture availability is often a limiting factor for evaporation over land surfaces.

The albedo and Bowen ratio of any land surface are both strong functions of soil moisture. These two parameters have significant impact on the energy balance and water balance of the land surface, as depicted in the flow chart of Figure 2 [after *Eltahir*, 1998]. The following subsections describe in detail how, through both the albedo and the Bowen ratio pathways, wet soils tend to enhance net radiation at the surface. This enhancement of R_{net} increases the moist static energy and lowers the wet-bulb depression in the boundary layer and thereby increases the potential for moist convection. Any simplified schematic such as Figure 2 can in no way depict all levels of the complexity of interaction within the land-atmosphere system. It is intended to be an outline to mark the main pathways for transmission of information between elements of the coupled system and thereby shed light on potential feedback mechanisms. Figure 2 and the following discussion provide the theoretical context for the analyses presented in section 4.

2.1. Radiative Controls on the Land-Atmosphere System

Net radiation at the surface, R_{net}, is the sum of incoming short wave solar radiation, reflected solar radiation (negative in sign), outgoing long wave terrestrial radiation (also negative), and incoming long wave radiation returned to the surface by backscattering from radiatively active molecules in the atmosphere, particularly water vapor. Some of this net radiation is consumed as heat flux into ground G (usually of the order of 15% or less, depending on the land cover). The remainder and typically the greater percentage, of R_{net} is transferred to the air, partly as sensible heat flux H and partly as latent heat flux λE, where λ is the latent heat of vaporization and E is the evaporation rate. The energy balance equation is given by $R_{net} - G = H + \lambda E$. The turbulent sensible and latent heat fluxes both increase the moist static energy (MSE) of the boundary layer [*Betts et al.*, 1996; *Carlson and Ludlam*, 1968] and mix the lower levels of troposphere, so quantities like mixing ratio and potential temperature are nearly constant throughout this mixed layer. MSE is very closely related to the moist entropy and the equivalent potential temperature θ_E [*Emanuel*, 1994], and the terms moist static energy and boundary layer entropy (BLE) are used almost interchangeably.

With an increase in energy available at the surface in wet soil conditions, $H + \lambda E$ should also increase, assuming negligible changes in G. This, in turn, should cause an increase in the MSE contributed to the boundary layer from the land surface.

2.2. Bowen Ratio Dependence on Soil Moisture

Though the total flux of moist static energy into the boundary layer is dependent on the total available radiation, the depth of the BL is dependent on the partitioning of this available energy. Soil moisture plays a role in this process by its effect on the Bowen ratio β: i.e., by its effect on the partitioning of sensible and latent heat fluxes ($\beta = H/\lambda E$). Typical values of β are of the order of 0.07 over open oceans, where the sea surface temperature responds little to the diurnal cycle of solar forcing [*Betts et al.*, 1996], to many hundreds over dry land surfaces, where all of the energy transfer occurs as sensi-

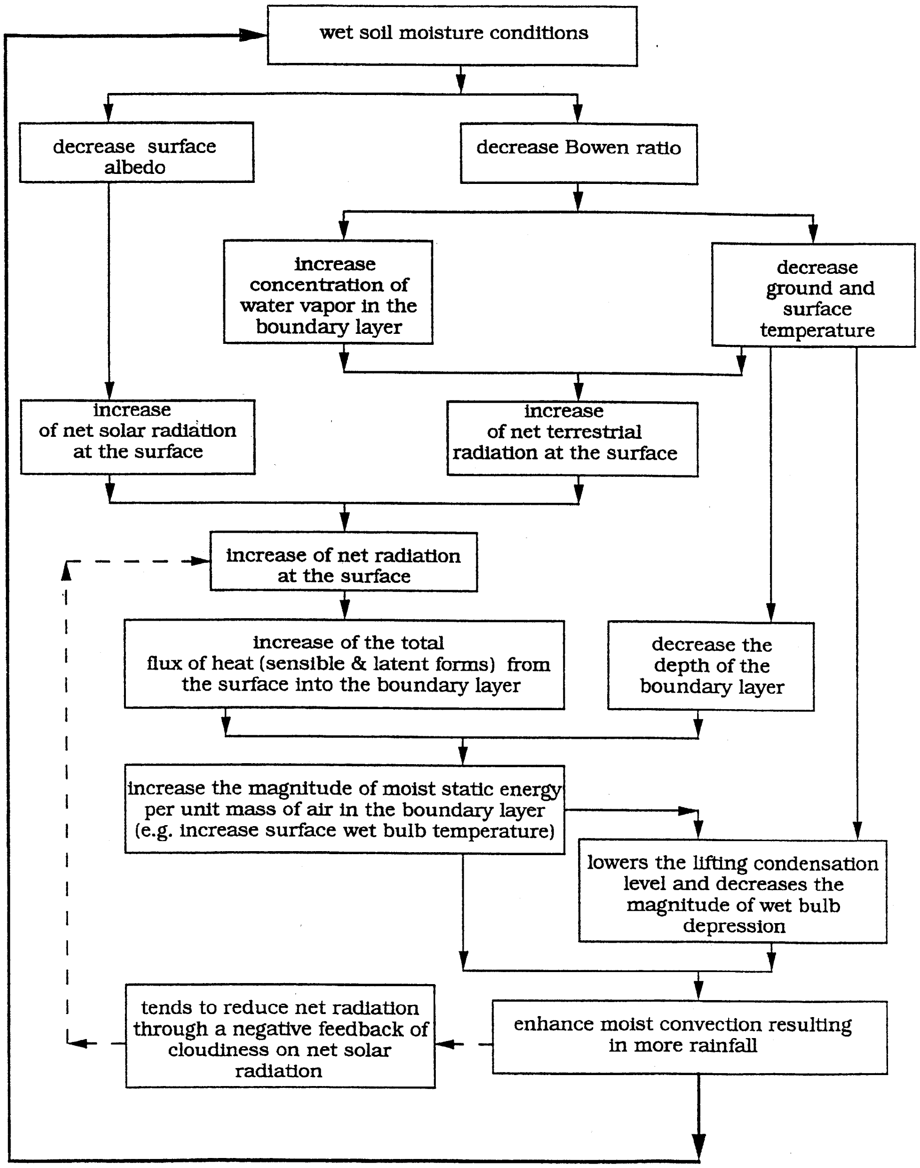


Figure 2. Pathways for soil moisture-rainfall feedbacks [from *Eltahir* 1998].

ble heating (e.g., dry lake bed example in the work of *Wallace and Hobbs* [1977, p. 345]). Sensible heat flux is largely responsible for the turbulent mixing of near-surface air, so when sensible heat flux increases, the boundary layer grows more rapidly. However, the increase of the moist static energy (MSE) in this mixed layer is proportional to the sum of the latent and sensible heat fluxes. For a given amount of available energy, R_{net} - G, a larger Bowen ratio means more sensible heating of the air, a deeper boundary layer, and therefore less MSE per unit depth. Wet soils should lead to a smaller Bowen ratio and, by the same reasoning, more MSE per unit depth, as shown on the right-hand side of Figure 2.

The basic sketch above of the role of soil moisture in BL processes suggests that increased soil moisture should lead to increased moist static energy (MSE) in the mixed layer [*Betts et al.*, 1996]. Increased MSE, in turn, has been shown to be correlated with increased precipitation [e.g., *Williams and Renno*, 1993; *Eltahir and Pal*, 1996; *Zawadzki and Ro*, 1978; *Zawadzki et al.*, 1981], as indicated at the bottom of the Figure 2 flow chart. However, locally controlled convection, which is the focus of each of these studies, is only one of many rainfall production mechanisms. The convective rainfall discussed here, and in FE97, is expected to be important in midlatitude regimes, such as the state of Illinois, only during the summer months. Even in the midlatitude summers, the impact of soil moisture anomalies is reduced when synoptic winds are strong [*Carlson and Ludlam*, 1968; *Entekhabi et al.*, 1996].

2.3. Radiative Feedbacks

Much of the literature on soil moisture-rainfall feedback mechanisms focuses on the control that soil moisture has on the Bowen ratio of the land surface [e.g., *Betts and Ball*, 1995, 1998]. The work of *Eltahir* [1998], *Zheng and Eltahir* [1998], and *Schär et al.* [1999], however, also consider radiative feedbacks triggered by the effects that soil moisture has on albedo α as well as the Bowen ratio. The modeling studies of *Zheng and Eltahir* [1998] and *Schär et al.* [1999] support the theory presented by *Eltahir* [1998], where it is argued that wet soil conditions over large areas increase net radiation at the land surface. The left-hand side of the flow chart in Figure 2 outlines these feedback mechanisms.

Wet soil conditions decrease the surface albedo, which leads to increased absorption of solar radiation [$R_{solar} = S_{in}(1-\alpha)$] at the land surface. As discussed earlier, wet soil conditions decrease the ratio of sensible heating to latent heating at the land surface (the Bowen ratio). Thus wet soils lead to lower surface temperature, which leads to reduced outward flux of long wave terrestrial radiation, $R_{terr,out}$. In addition, the increased evapotranspiration that accompanies wet soils leads to an increase in water vapor content of the boundary layer. This increase in greenhouse gas content leads to enhanced downward flux of terrestrial radiation, $R_{terr,in}$. Thus the net terrestrial radiation at the land surface should increase: $R_{terr} = R_{terr,in} - R_{terr,out}$. For a given input of solar radiation, S_{in}, then each of the terms in the radiative balance equation should increase with wet soils:

$$R_{net} = S_{in}(1-\alpha) + R_{terr,in} - R_{terr,out}.$$

Zheng and Eltahir [1998] show that without the effects of soil moisture on surface radiative fluxes, the impact of soil moisture anomalies on rainfall would be much less significant than otherwise.

A complicating factor in this course of events is clouds (depicted by the dashed lines in Figure 2). On rainy days when cloud cover is high, incoming solar radiation is greatly reduced because of the blocking effect of the clouds. *Betts and Ball* [1995] report that during the summer of 1987, rainy or heavy overcast days at the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) site in Kansas averaged 8/10 cloud cover, while days they characterized as dry averaged only 3/10 cloud cover. As a result, net radiation was greatly reduced on rainy days, when the decrease in S_{in} was the dominant effect. The mechanism described above, however, is argued by *Eltahir* [1998] to be important before the initiation of rainfall and heavy overcast. The modeling study of *Schär et al.* [1999] supports this hypothesis. In soil moisture perturbation experiments over Europe, they showed that the effect of decreased solar radiation associated with higher soil moisture was half the magnitude of increased terrestrial radiation associated with higher soil moisture.

2.4. Wet-Bulb Depression

This theoretical framework suggests that the energetic state of BL air will clearly reflect the moisture condition of the underlying soils. However, as discussed in the results and conclusions, another important consideration is the initial condition of the lower troposphere. The flow chart in Figure 2 depicts the ways that the land surface contributes energy and moisture to the BL, but convection is determined by the absolute conditions of the BL. These are strongly dependent on the local conditions during the previous day and on the amount of large-scale advection, as well as the land surface effects discussed here. Future research will include these two other aspects of soil moisture-boundary layer interactions.

The wet-bulb depression, $T_{dpr} = T - T_w$, is an excellent measure of the absolute condition of near-surface air, where T_w is the wet-bulb temperature. T_{dpr} can be most simply thought of as a measure of the saturation of the air, and it is closely related to the pressure level at which a parcel reaches saturation: small T_{dpr} means low cloud base and a small difference between pressure at the surface and pressure at the lifting condensation level (P_{LCL}). *Betts and Ball* [1995, 1998] found that FIFE data had to be carefully filtered by soil temperature to uncover clear soil moisture-T_w links, while no such filter was needed to link soil moisture and P_{LCL}. The far right-hand side of Figure 2 shows the dependence of T_{dpr} on soil moisture conditions. Wet soils tend to decrease the surface temperature T and increase the surface humidity q. This humidity increase means an increase in wet-bulb temperature T_w. Therefore wet soils lead to a compounded decrease in T_{dpr}. This variable then should show a more significant response to soil moisture conditions than either T or T_w.

Another important aspect of the stronger signal shown by T_{dpr} is the daily constraint on near-surface conditions. Except when soil conditions are very dry, surface air is close to saturation at dawn, bringing T_{dpr} close to zero at the beginning of each day. This constraint will render advection far less important in T_{dpr} analyses than in T or T_w analyses, where there are no such constraints on the magnitude of the variable. Since T_w is a measure of moist static energy, T_{dpr} should show a more significant response to soil moisture conditions than MSE. Section 4 shows that the Illinois data are consistent with this hypothesis.

3. Data Sets

3.1. Soil Moisture Data

The soil moisture data used in this study is the same as that used by FE97: the reader is referred to that paper and to *Hollinger and Isard* [1994] for more details on the Illinois State Water Survey (ISWS) network of soil moisture stations. The Illinois Climate Network (ICN) includes 19 stations, with biweekly observations at 11 depth intervals (top 10 cm, 20 cm intervals between 10 and 190 cm (10-30 cm, 30-50 cm, etc.), and a 10 cm interval between 1.9 and 2 m below the surface). Station locations are shown in Figure 3. These data were converted to soil saturations by dividing by the porosity measured at each site. Since it is the large-scale soil saturation that is of interest for this study, the statewide average soil saturation for a given day was determined by averaging all the station-specific values for the preceding 3 week period. Since the soil moisture measurements were taken twice monthly, a 2 week period at a station could possibly have no sampling events, while a 3 week period should always have at least one sampling event from each station. The analyses presented here use this time series of daily statewide average soil saturation in the top 10 cm.

3.2. NCDC Surface Airways Data

Surface meteorological data were obtained from the National Climatic Data Center (NCDC) Surface Airways Hourly Data Set TD-3280. Only eight stations are located within Illinois. These eight are supplemented by five additional stations: Paducah, Kentucky, just over the Ohio River at the southern tip of the state; Milwaukee, Wisconsin, approximately 60 km north of the northeastern corner of Illinois, and three additional stations in western Indiana, 40, 100, and 110 km east of Illinois. See Figures 3 and 4 for station locations.

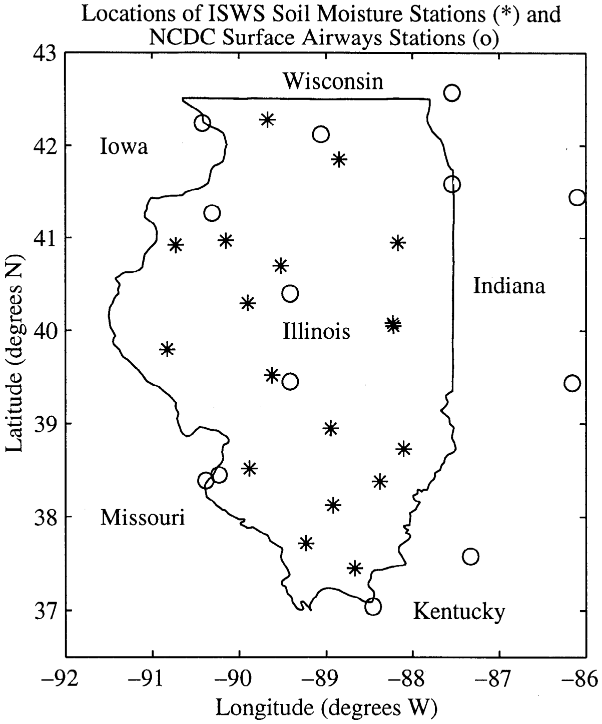


Figure 3. Locations of Illinois State Water Survey (ISWS) soil moisture stations (asterisks) and National Climatic Data Center (NCDC) surface airways stations (circles). Solid line is the Illinois state boundary.

Given the paucity of data within the approximately 300 km by 650 km control volume of Illinois, the inclusion of this supplemental information was deemed beneficial to the statistical validity of the analysis. The Kentucky station is only nominally outside of Illinois, and the other four are in the predominately downwind direction of Illinois, and can therefore be an indicator of the influence of soil saturation on boundary layer air as it is advected out of our study area. The averaging of data both within and downwind of the soil moisture study area is intended to address two of the difficulties of working with real data: the complications of advection, and the limitations of data collection and availability.

Surface parameters obtained from the NCDC hourly data set include temperature T, wet-bulb temperature T_w, pressure P, and relative humidity f. From these quantities, wet-bulb depression $T_{dpr} = T - T_w$, potential temperature θ, virtual potential temperature θ_v, equivalent potential temperature θ_E, wet-bulb potential temperature θ_w, temperature of the lifting condensation level (LCL) T_{LCL}, pressure depth to the LCL $P_{LCL} - P_s$, and mixing ratio w were calculated at each station for each hour. The hourly values of each of these variables were then averaged at all 13 stations. The daily minimum, mean, and maximum of each of these 12 variables was then determined, and these 36 quantities were then used in an analysis with the daily soil saturation time series described in section 3.1. The variables are divided into three classes of consistent behavior: measures of relative humidity (f, $P_{LCL} - P_s$, and T_{dpr}), measures of buoyancy (T, θ, and θ_v), and measures of moist static energy (T_w, θ_w, and θ_E). Since the behavior of variables within each class is very similar, only T_{dpr}, T_w, and θ results will be discussed.

3.3. EarthInfo NCDC Hourly Rainfall Data

The hourly rainfall data used in this analysis was obtained through EarthInfo, Inc. This data set is a subset of the National Climatic Data Center (NCDC) TD-3240 file, with hourly precipitation records for many stations throughout the United States beginning in 1948. Within Illinois, there were 82 stations with consistent hourly rainfall records. The locations of these stations are shown with the surface airway stations in Figure 4.

4. Results and Discussion

4.1. Analysis of the Relationship Between Soil Moisture and Rainfall

Previous analyses of 14 years of soil moisture and rainfall data from the Illinois State Water Survey indicate a small but significant physical link between soil saturation and subsequent rainfall during Illinois summers (FE97). As shown in Figure 1 (reprinted from FE97), this correlation is greater than the serial correlation of rainfall over the state. This result supports the beginning and end of the Figure 2 flow chart. The remainder of this study attempts to ascertain if directly observed data support the details of the pathways between the top and the bottom of the figure.

4.2. Analysis of the Relationship Between Soil Moisture and Near-Surface Air

Analyses showed that during the summer months, soil saturation has a negative correlation with daily wet-bulb depression T_{dpr}, but is poorly correlated with measures of the moist static energy (MSE) (e.g., wet-bulb temperature T_w) or

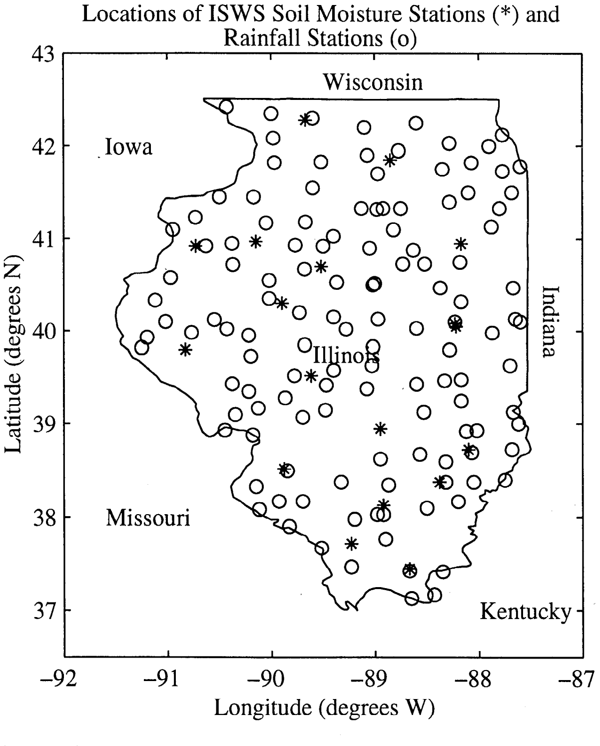


Figure 4. Locations of NCDC surface airways hourly data stations (circles) and hourly rainfall stations (asterisks). Solid line is Illinois state boundary.

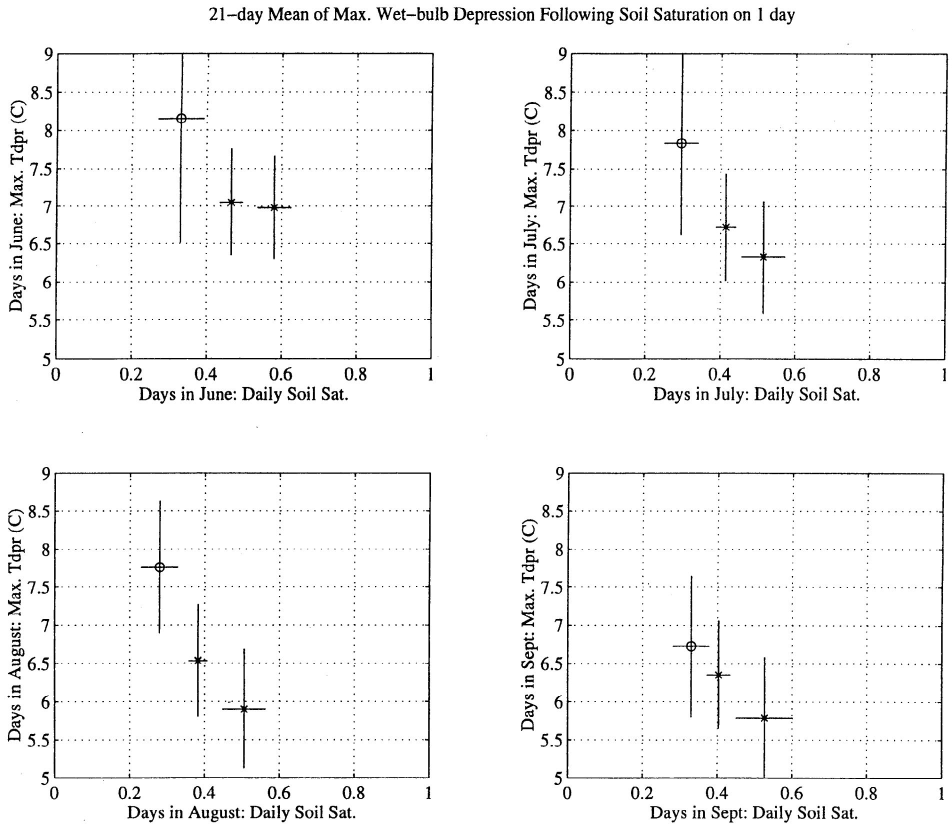


Figure 5. Correlation between dry, normal, and wet soil saturation conditions in the top 10 cm with wet-bulb depression. Error bars are ± 1 standard deviation.

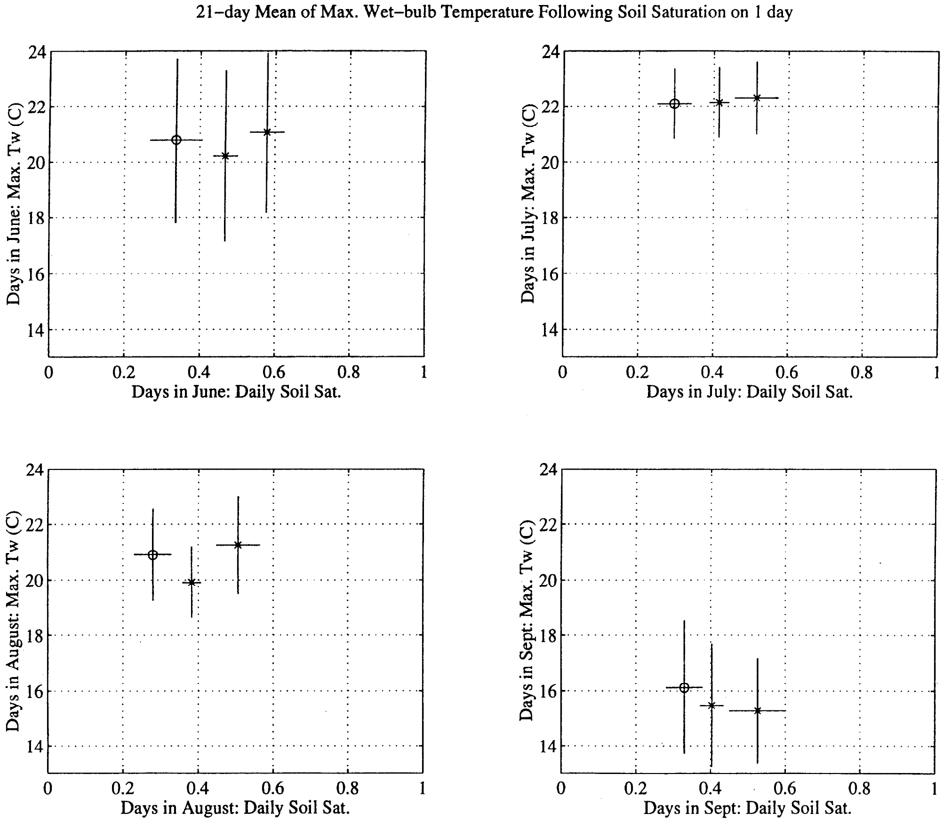
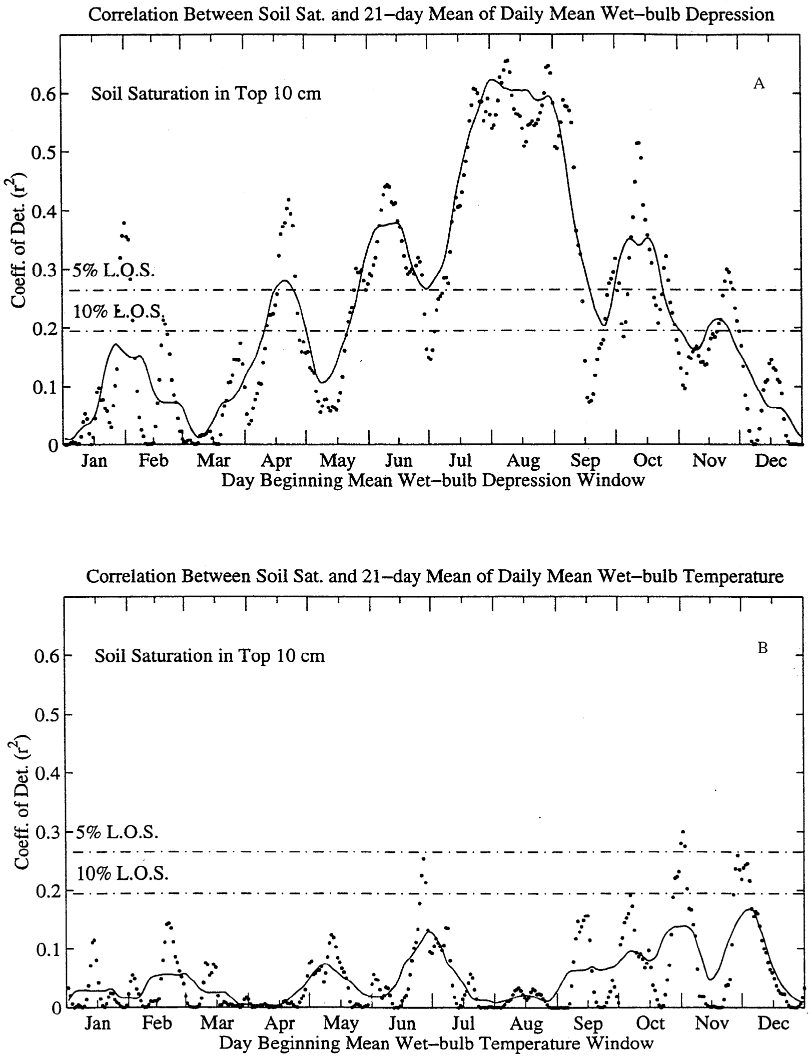


Figure 6. Correlation between dry, normal, and wet soil saturation conditions in the top 10 cm with wet-bulb temperature. Error bars are ± 1 standard deviation.


Correlation Between Soil Sat. and 21–day Mean of Daily Mean Wet–bulb Depression

Correlation Between Soil Sat. and 21–day Mean of Daily Mean Wet–bulb Temperature

Figure 7. Temporal correlation between soil saturation on 1 day and subsequent 21 day mean of (A) wet-bulb depression and (B) wet-bulb temperature. Dots are daily values; solid line is 21 day average; dashed-dotted lines are 5% and 10% level of significance lines for the daily values.

the buoyancy (e.g., potential temperature θ) of near-surface air. Figure 5 shows this relationship between T_{dpr} and soil saturation in the top 10 cm. The daily maximum T_{dpr} was averaged over a 21 day period following an initial soil saturation condition. The data were binned according to dry, normal, and wet initial soil conditions. These analysis techniques were similar to those applied by FE97: the reader is referred to that work for an explanation of the 21 day averaging window. Results did not change significantly with the selection of different length windows. Figure 6 shows a similar depiction of the T_w-soil saturation relationship.

Figure 7a shows that the correlation between soil saturation and T_{dpr} is significant during the summer months, in correspondence to the time period that the soil moisture-rainfall feedback is also significant. No such significance is present at any time period with wet-bulb temperature (Figure 7b) or with potential temperature (not shown). The wet-bulb depression result is consistent with the farthest right pathway of Figure 2, but the wet-bulb temperature result is not consistent with the expectation shown in Figure 2. As discussed earlier, T_{dpr} is expected to show a more dramatic response to soil moisture conditions than T_w, but the theory depicted in Figure 2 suggests that we should see some response in T_w.

4.3. Analysis of the Relationship Between Near-Surface Air and Rainfall

To corroborate the aforementioned studies that demonstrated a positive correlation between surface conditions and precipitation, the final stage of these analyses included hourly near-surface air measurements and rainfall in the subsequent hour (excluding hours where rainfall had already begun). A link between high MSE and high probability of initiation of rainfall was noted for June and August, but no such link was observed during July or September (T_w results are shown in Figure 8). The buoyancy measures T, θ, and θ_v showed poor association with rainfall during all months. This may be due to the competing factors of increased soil moisture leading to increased moist static energy in the boundary layer, which is expected to lead to more convective rainfall, and decreased sensible heat flux, which decreases the likelihood of boundary

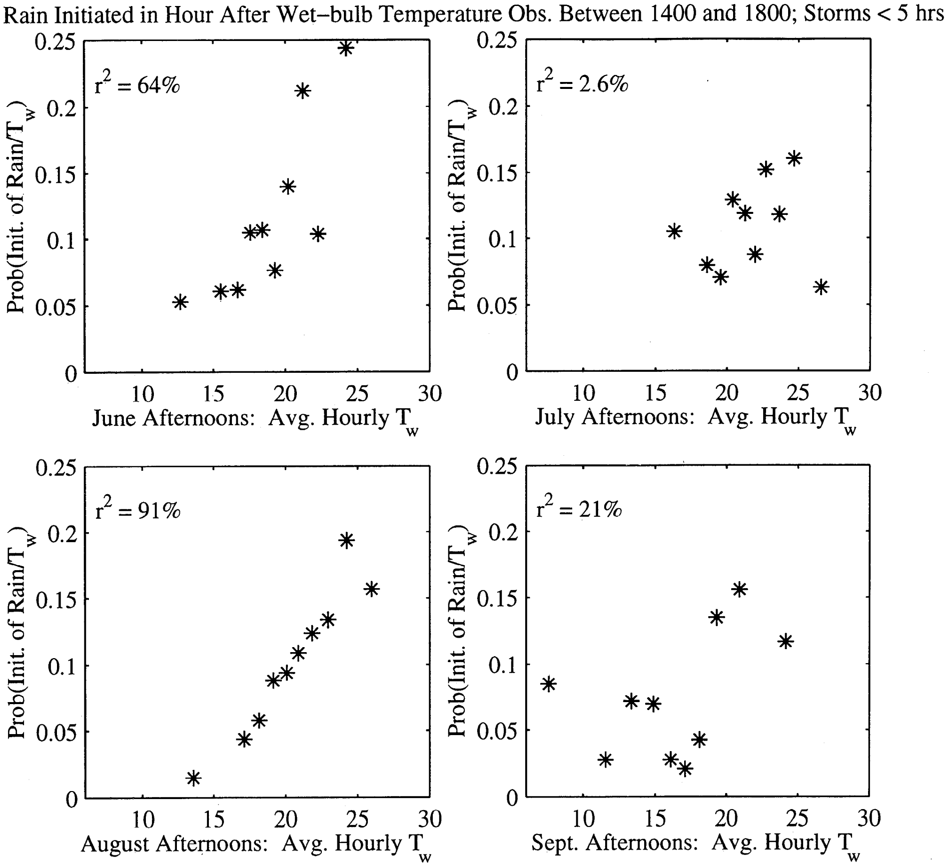


Figure 8. Probability of initiation of rainfall in the hour after an observation of wet-bulb temperature. T_w observations were divided into 10 bins with equal numbers of occurrences (thus error bars within each bin are negligible).

layer growth overtaking the level of free convection and initiating convection. However, a link between low wet-bulb depression and high probability of initiation of rainfall was evident for all of the months analyzed (April through September; Figure 9 shows June-September). Some filtering of the data was performed to remove large-scale synoptic rainfall events. Figures 8 and 9 tally T_w and T_{dpr} in the hour before the initiation of rainfall events that lasted less than 5 hours. The results did not change significantly when this duration was varied between 3 and 8 hours. These analyses then suggest that the significant but weak correlation between soil moisture and rainfall during Illinois summers is due not to soil moisture controls on the boundary layer entropy but rather to soil moisture controls on the wet-bulb depression of near-surface air. These results are consistent with the bottom right-hand portion of Figure 2.

5. Summary and Conclusions

This study of the soil moisture-rainfall feedback focused on the state of Illinois, an area of approximately 300 by 650 km centered around 40°N and 89°W. The Illinois State Water Survey extensive data set of biweekly neutron probe measurements of soil moisture at up to 19 stations, beginning in 1981, motivated the study. Most previous investigations of this feedback mechanism have used inferred or modeled soil moisture time series, rather than directly observed data. Though these data are not of ideal spatial or temporal resolution, this is the largest long-term record of directly observed soil moisture currently available and can provide much-needed validation of modeling results, which often use simulated or nonrealistic soil moisture conditions.

The work of *Findell and Eltahir* [1997] showed results of a linear correlation analysis between initial soil moisture and rainfall in the subsequent three weeks: a positive correlation between these two variables is present from early June to mid-August. This correlation is more significant than the serial correlation within precipitation time series, suggesting the likelihood of a physical mechanism linking soil moisture to subsequent rainfall during Illinois summers.

This result prompted further investigation into the nature of such a physical pathway linking soil moisture to subsequent rainfall. Figure 2 presents multiple pathways for such a feedback, and many of these pathways are investigated in this work. Theory and previous studies indicated the likelihood of a positive impact of soil moisture on the moist static energy (MSE) of the boundary layer, and a positive impact of MSE on rainfall. To explore these possibilities, hourly data of surface air conditions and precipitation since 1981 (corresponding to the soil moisture data set) were obtained for 13 and 82 stations, respectively. These time series were processed to obtain hourly near-surface air conditions and precipitation depths, averaged over the whole state of Illinois.

An analysis of the connections between an average daily

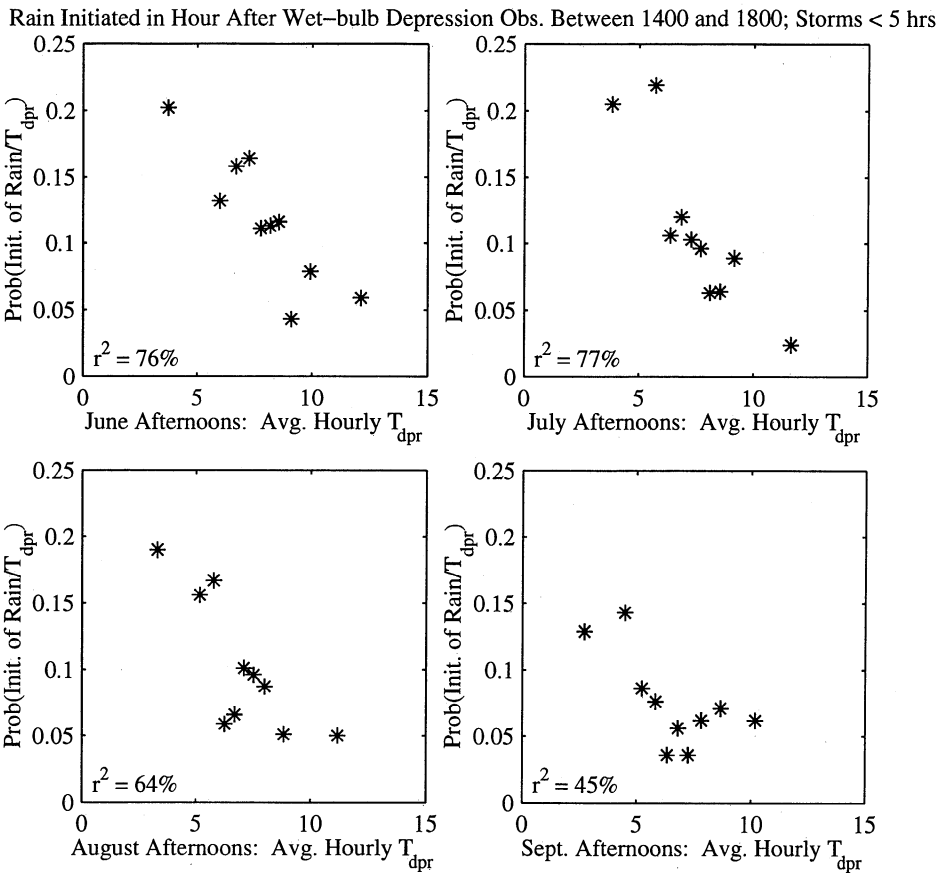


Figure 9. Probability of initiation of rainfall in the hour after an observation of wet-bulb depression. T_{dpr} observations were divided into 10 bins with equal numbers of occurrences (thus error bars within each bin are negligible).

soil saturation time series for the whole state of Illinois with these statewide average near-surface conditions did not yield the expected result of a positive correlation between soil moisture and moist static energy, as quantified by T_w, θ_w, or θ_E. This result is at odds with the sketch of feedback mechanisms given in Figure 2. It is not clear if this is due to limitations of the data or of the theory. The impact of variable incoming solar radiation was not accounted for in these analyses and may be relevant to this result, but two other possible factors may also be playing a role. First, the observations from the surface may not be representative of conditions in the entire boundary layer, while the theory relates soil conditions to boundary layer conditions. Second, data used in this study may not be robust enough to describe either the surface air conditions or the soil conditions over the entire state of Illinois at a daily timescale. Though one of the important aspects of this study is the use of directly observed soil moisture data, these data are still quite limited in both space and time and may not accurately represent conditions in the state as a whole. When more extensive data sets are available, particularly data on incoming solar radiation, it may be instructive to revisit this analysis.

Though the anticipated soil moisture-MSE link was not observed, there was evidence that moisture availability (or lack thereof) at the surface has a very strong impact on the wet-bulb depression of near-surface air. This impact was particularly strong from mid-May to the end of August, showing good correspondence to the period of significant soil moisture-rainfall association found in FE97.

The final set of analyses performed included an investigation of the hourly near-surface air and rainfall data. Data from the 82 hourly rainfall stations were averaged to compare statewide hourly rainfall to statewide hourly boundary layer conditions. A positive correlation between MSE and rainfall was noted for June and August but not for July and September. Most significant was a consistently observed link between low wet-bulb depression T_{dpr} and high rainfall rates, even after filtering out large-scale events. These analyses then suggest that the significant but weak correlation between soil moisture and rainfall during Illinois summers is due not to soil moisture controls on the boundary layer entropy but rather to soil moisture controls on the wet-bulb depression of near-surface air.

The spatial and temporal limitations of the soil moisture data set, the spatial limitations of the surface conditions data set, and the lack of both radiation data and vertical profiles of temperature and humidity throughout the boundary layer restrict the potential for more detailed investigations of the energetics of the different environments corresponding to dry, normal, and wet soil moisture conditions. Despite these limitations, these analyses show that during the summer in Illinois, soil moisture significantly impacts subsequent rainfall through its impact on the wet-bulb depression of near-surface air. Current work focuses on boundary layer processes, using radiosonde data from the Flatland experiment [*Angevine et al.*, 1998] and modeling studies with MM5 (the Penn State-NCAR Mesoscale Model, Version 5). In addition, we are updating the analyses of FE97 as more data become available and will publish updated results after we have obtained a significant addition of data.

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