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An analysis of the soil moisture-rainfall feedback, based on direct observations from Illinois

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Abstract. Many global and regional climate modeling studies have demonstrated the importance of the initial soil water condition in their simulations of regional rainfall distribution. However, none of these modeling studies has been tested against directly observed data. This study tests the hypothesis that soil saturation is positively correlated with subsequent precipitation by analyzing a 14-year soil moisture data set from the state of Illinois. The linear correlation between an initial soil saturation condition and subsequent rainfall is significant during the summer months, reaching a peak of $r^2 > 0.4$ in mid-June. This result is consistent with the hypothesis that knowledge of late spring/early summer soil moisture conditions can aid in the prediction of drought or flood years, but it does not necessarily prove that feedback from anomalous soil moisture reservoirs is the cause of anomalous summer conditions. Further analyses indicate that from early June to mid-August, persistence in rainfall cannot fully account for the observed correlations, suggesting the likelihood of a physical feedback mechanism linking early summer soil saturation with subsequent precipitation. However, spatial and temporal data limitations restrict the potential for drawing strong new conclusions from the Illinois study.

1. Introduction

It has long been recognized that soil moisture plays an important role in regional climate systems through its affect on the surface albedo and on the partitioning between sensible and latent heat fluxes. Early work by *Namias* [1952, 1960] showed that spring precipitation and soil moisture can impact summer precipitation in the interiors of continents. More recently, many researchers have noted the negative correlation between soil moisture states and mean and maximum temperatures [*Karl*, 1986; *Georgakakos et al*., 1995; *Huang et al*., 1996] and stressed the potential increase in surface heating and decrease in local evaporative contributions to atmospheric humidity that anomalously low soil moisture states can affect [*Rind*, 1982; *Trenberth et al*., 1988; *Oglesby*, 1991]. Recent work by *Eltahir and Pal* [1996] suggests a link between rainfall and surface wet bulb temperature during convective rainfall storms like those often found during the summer months in the midwestern United States. Wet bulb temperature is an indicator of surface conditions, including, among other variables, soil moisture.

Many recent studies involving general circulation models (GCMs) have offered support to *Namias*' [1952, 1960] hypothesis, showing that changes in the soil moisture regime at the end of spring/beginning of summer can significantly impact summer precipitation over continental land masses [*Shukla and Mintz*, 1982; *Rind*, 1982; *Yeh et al*., 1984; *Oglesby and Erickson*, 1989; *Oglesby*, 1991; *Pan et al*., 1995]. These GCMs, however, have all been rather broad-brush, making global or continental-scale soil moisture changes. Regional climate studies [e.g., *Georgakakos et al*., 1995; *Huang et al*., 1996] have also been used to test this hypothesis regarding the feedback from soil moisture to the atmosphere. Owing to a lack of adequate long-term data on soil moisture, none of these models has been tested against any directly observed soil moisture data sets.

This study attempts to fill this gap by analyzing the relationship between precipitation and soil moisture using the Illinois Climate Network (ICN) data set: a 14-year record of soil moisture values measured biweekly at 19 stations across the state of Illinois, as shown in Figure 1 [*Hollinger and Isard*, 1994]. Though this data set is somewhat limited in both temporal and spatial extent, it is the largest available data set of its kind, and its analysis should prove worthwhile. If, as many GCM and regional studies results suggest, spring soil moisture does indeed affect summer precipitation, the data should support this hypothesis.

To make this data analysis comparable to modeling studies, the framework for the analysis is posed as an initial value problem. We are interested in how precipitation responds to an initial soil moisture condition. In contrast to a computer model, it is difficult to isolate the causal relationship between these two variables when dealing with real data. Nevertheless, the 14 years of data are more than has previously been available for this kind of analysis and could provide some insight into the coupled land-atmosphere system. Furthermore, this analysis, based on actual observations, should provide a testing framework for future numerical experiments involving soil water and precipitation.

The next two sections present a literature review of some of the important contributions made to this topic. Section 4 sketches out the sources and details of the rainfall and soil moisture data. Sections 5 and 6 show some of the results and begin a discussion, while the final conclusions are spelled out in section 7.

2. Literature Review: GCM Results

In the above mentioned study by *Shukla and Mintz* [1982], two global scenarios are tested: a wet-soil case, where evapotranspiration is at all times equal to the potential evapotranspiration, and a dry-soil case, where there is no evapotranspi-

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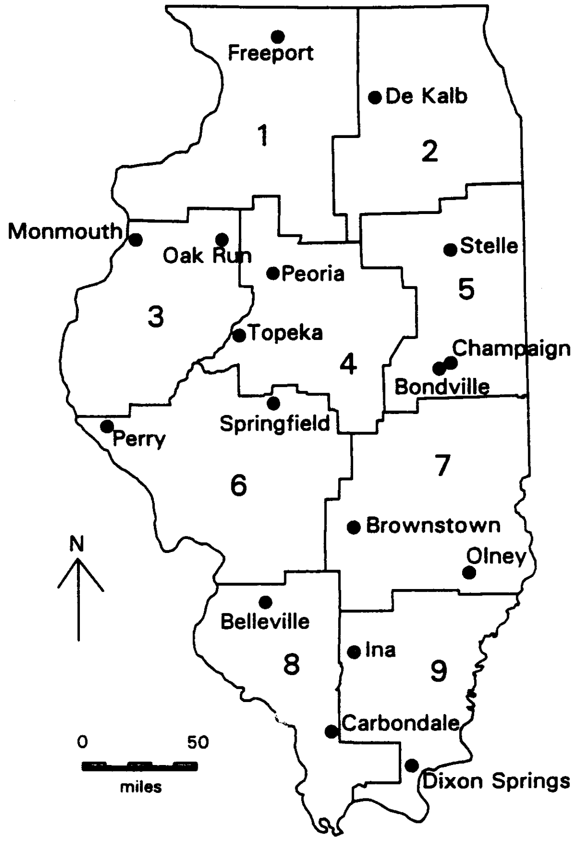

Figure 1. Locations of Illinois Climate Network (ICN) soil moisture measurement stations [from *Hollinger and Isard*, 1994] (Reprinted with permission from the American Meteorological Society, Boston, Massachusetts).

ration. Over almost the entire globe, precipitation in the dry-soil case was much less than precipitation in the wet-soil case, while surface temperatures in the dry-soil case were much higher than in the wet-soil case.

The importance of the timing of soil moisture anomalies in their affect on other climatic variables is stressed by *Oglesby*'s [1991, p. 893] study of North American droughts. Reduced soil moisture profiles are introduced into two model runs, one beginning on March 1 and one beginning on May 1. In the May 1 run, most of the initial soil moisture anomaly is maintained throughout the summer, except along the east coast of the continent, showing that "through positive feedbacks, reduced soil moisture can be a self-perpetuating condition." The March 1 run, however, shows that the anomalous condition can, in fact, correct itself. The anomaly is apparent at 20 days only over the central United States, and at 50 days, virtually all of North America is at a normal, moist state. He explains these different behaviors by noting that during winter or early spring, when the March 1 anomaly is introduced, solar insolation is generally less than in late spring and summer. The two primary direct effects of reduced soil moisture content, reduced local evaporation and increased surface heating, are thus expected to be less important in this earlier season, and the anomalous condition can be corrected prior to the onset of the new climatic regime.

Rind [1982] finds similar results in his GCM study of North America. By comparing runs which have initially reduced soil moisture levels across the entire United States to control runs, which have normal soil moisture levels on June 1, Rind found significant temperature increases and precipitation decreases across most of the United States. The effects were most noticeable in June and least noticeable in August and most consistent in the interior of the continent, where the oceans had the least influence.

Yeh et al. [1984] conducted a series of numerical experiments which tested, among other things, the importance of the latitude of soil moisture anomalies. In each of the three latitudinal bands studied, namely 30°N–60°N, 0°–30°N, and 15°S–15°N, initial saturation of the soil caused both an increase in local precipitation and cooling of the surface due to increased evaporation. Each of the simulations was run during the driest period for the latitudinal band: July 1 to November 30 for the northernmost region and January 1 to May 31 for the other two.

Several studies have focused on the causes of the 1988 U.S. summer drought, studying both sea surface temperatures (SSTs) and soil moisture states. *Trenberth et al.* [1988] found that large-scale circulation patterns caused by SSTs in the Pacific were the likely primary cause but that the low soil moisture conditions at the beginning of and throughout the season probably contributed to the severity and persistence of the drought. *Atlas et al.* [1993], on the other hand, found that tropical SST anomalies reduced the precipitation in the Great Plains but did not significantly increase the surface temperatures. Simulations with reduced soil moisture levels, however, both increased surface temperatures and decreased precipitation, accurately approximating the actual 1988 scenario. *Oglesby and Erickson* [1989, p. 1375] used the National Center for Atmospheric Research (NCAR) community circulation model (CCM1) general circulation model to demonstrate that reduced spring soil moisture, like that of 1988, can "amplify or prolong summertime drought over North America."

3. Literature Review: Results of Regional Climate Studies

Perhaps of more relevance to this analysis of data from Illinois are results from regional scale climate and/or hydrologic models. *Pan et al.* [1995] focused their study on the flood of 1993 as well as the drought of 1988. They tested the hypothesis that surface moisture availability provides an additional feedback mechanism, helping to maintain extreme wet or dry conditions. Models of a portion of the midwestern United States showed that when all other climatic variables were simulated as observed in each of the 2 years of interest, extreme changes in the surface moisture conditions (i.e., 99% of saturation simulated with the temperature, wind, and other boundary conditions observed in 1988; 1% of saturation with the boundary conditions of 1993) significantly altered the total summer precipitation.

The study of *Giorgi et al.* [1996] led to the opposite conclusion, however. They found that local recycling effects were not important in the development of extreme climatic regimes and that, contrary to the aforementioned studies, a dry soil initial condition provides for increased sensible heat flux, which contributes greater buoyancy to the air, enhancing convective systems and producing more precipitation. This cycle, then, supports a negative feedback mechanism between initial soil condition and precipitation.

Similarly, *Georgakakos et al.* [1995] found no evidence of soil water feedback to local precipitation in their study of two

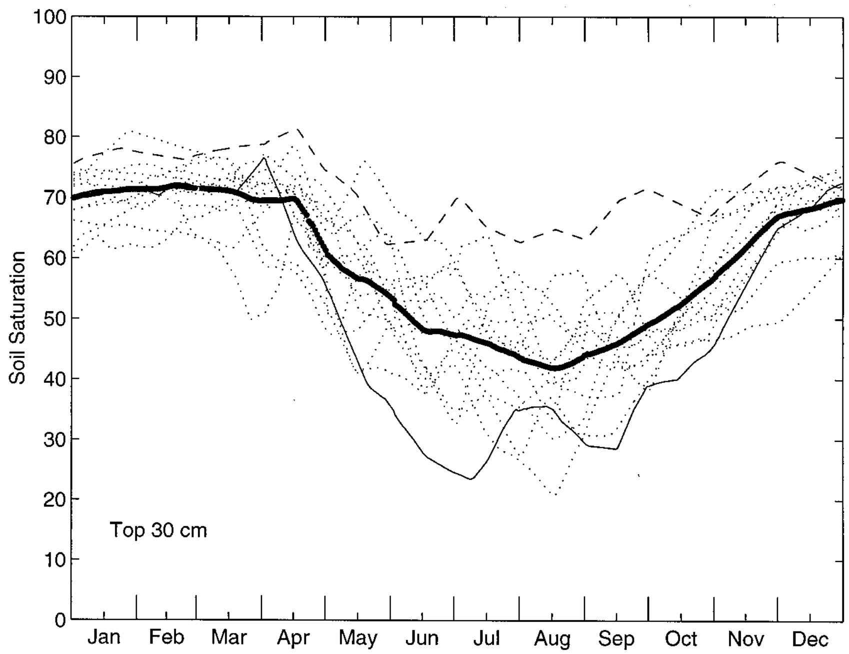

Figure 2. Annual average soil saturation cycles for top 30 cm for each year, 1981–1994. Dashed line is 1988 (extreme drought); solid line is 1993 (extreme flood); all other years are drawn with dotted lines. Thick dotted line is average of all 14 years.

2000-km^2 basins in Iowa and Oklahoma. Using daily precipitation and potential evapotranspiration as input, they were able to accurately simulate observed daily discharge over a 40-year period in each of the basins. One of the primary forcings to the river discharge was an estimated soil moisture time series: the accuracy of their streamflow series (correlation with observations better than 0.8) suggests that their soil moisture series is good. Though soil moisture was not shown to affect precipitation, there were significant cross correlations between upper soil water leading daily maximum temperature, especially during periods of extreme (high or low) soil water content.

Huang et al. [1996] created a 62-year (1931–1993) time series of monthly soil moisture data for the entire United States using a one-layer soil moisture model. They found that soil moisture is a better predictor of future monthly temperature than is antecedent precipitation, particularly in the interior of the continent during summer.

On the smaller end of the spatial and temporal scales, *Chang and Wetzel* [1991] were able to model the effects of the spatial variability of vegetation and soil moisture on the development of individual storm events. Given the absence of real soil data, they estimated soil moisture from an antecedent precipitation index. The Illinois data set is not of high enough spatial or temporal resolution to be adequately compared to the results of Chang and Wetzel.

In each of the studies mentioned above, the researchers were trying to discern the impact of soil water conditions on future climate through the use of numerical models. We would like to see what real data can tell us about this connection.

4. Data

Though each of these studies provides analyses of the links between summer rainfall and spring soil moisture, all of them used indirect means to quantify soil moisture. Since 1981, scientists from the Illinois State Water Survey have been taking direct soil moisture measurements with a neutron probe at eight grass-covered sites around their state [*Hollinger and Isard*, 1994]. Seven additional sites were added in 1982, two more were on-line by 1986, and by 1992 the total was up to 19. The locations of the first 17 stations are shown in Figure 1 (pre-1992). Biweekly measurements were taken in the top 10 cm, in 20-cm intervals between 10 and 190 cm (10–30 cm, 30–50 cm, etc.), and in the 10-cm interval between 1.9 and 2 m below the surface.

Many researchers [*Owe and Chang*, 1988; *Shukla and Mintz*, 1982] have noted the difficulty in obtaining a parameter that represents the soil moisture condition over a whole, large area. Though this data set is a very extensive collection, both temporally and spatially, we must consider the relevance of the parameter measured to this study. According to the hypothesis presented here, the initial soil water condition can provide some positive feedback to the convective regime during the summer months in Illinois. The parameter of interest, then, is the amount of soil water available for evapotranspiration. The rate at which soil water can be removed is a property of the unsaturated hydraulic conductivity of the soil. *Eagleson* [1978] stresses that in exfiltration processes (interstorm drying of the soil as well as extraction by plant roots) it is not the moisture content, θ, but rather the soil saturation, θ/n, where n is porosity, that is the controlling parameter. Therefore soil saturation is used as an indicator of the overall soil water condition at each site. Note that this is used as a qualitative indicator of the soil condition, not as an exact measure of the mass of water in the soil: the data are by no means complete enough to offer that level of detail. The soil moisture data, then, were first converted to soil saturations by dividing by the porosity (measurements were made at each of the 19 sites).

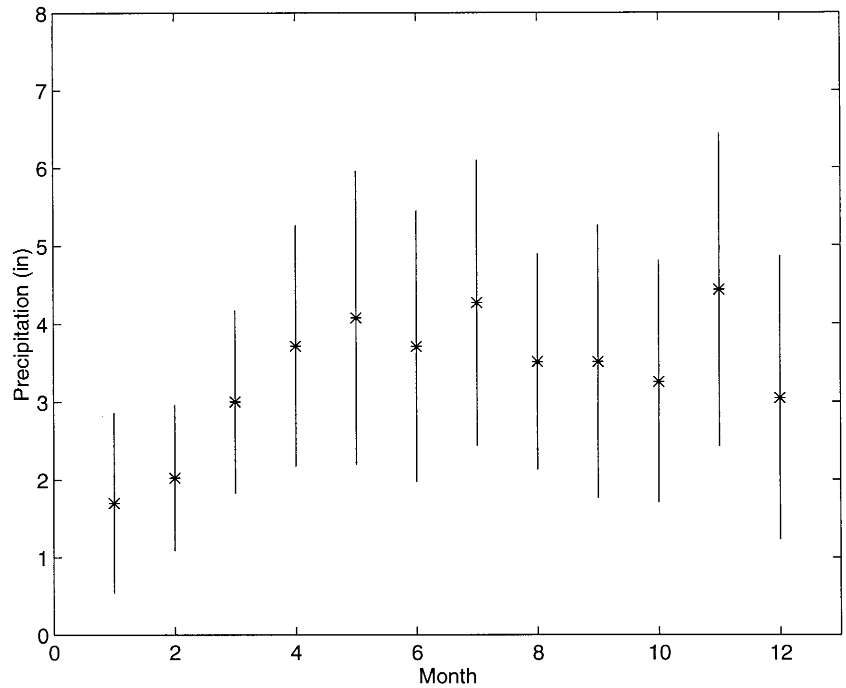

Figure 3. Average total monthly precipitation over Illinois, 1981–1994. Stars indicate means of the 14 years; lines extend to plus or minus 1 standard deviation.

Though the sampling frequency (approximately every 2 weeks) is much greater than for most soil moisture field studies, 14 days is significantly longer than a normal wetting and drying cycle during a midwestern summer. However, in this study we are not interested in the ability to predict a storm event or exactly describe the soil water condition at every moment in time. Rather, we are concerned with the mean climatic behavior over monthly or seasonal timescales rather than the predictability of erratic weather systems. It is also important to note that the sampling schedule was not set in response to particular storm or drought events (S. E. Hollinger, personal communication, 1996). The samples obtained, then, are like random realizations of the ensemble of soil moisture condition at all times throughout the entire state. The assumption implicit in this analysis is that there are enough observations distributed in time and space to give an adequate representation of the trends of the mean soil water condition in the state. An ideal data set for this analysis would have soil moisture sampled multiple times per day at many sites all over the state. Though this data set is not, by this standard, ideal, it is far more complete than any other data set known to date, and much useful information can be gleaned from it.

Simple linear interpolation was used to develop a daily time series of soil saturation for each depth interval at each site. Though each of the site-specific time series may miss important events, given no better knowledge of the soil conditions between observations, linear interpolation makes the most of the directly observed information that is available. Furthermore, since it is the large-scale soil saturation that is of interest (the soil moisture that can contribute to atmospheric humidity within the region) the statewide average soil saturation was determined by averaging all the station-specific values for each day within this 14-year time series. Although having only 19 stations is not ideal, the ICN is more comprehensive than any other soil moisture data set currently available.

An important consideration in any study related to soil moisture is the relevant depth of soil to analyze. The root zone depth is dependent on vegetation type and health and can be extremely variable. Estimates for root zone depth usually are in the range of 10 cm to a few meters. Because the depth of soil from which moisture is available for evaporation is not constant, the analysis was initially performed for average saturations in all of the available surface soil layers: 0–10, 0–30, 0–50, 0–70, 0–90, 0–110, 0–130, 0–150, 0–170, 0–190 cm, and the top 2 m. The average saturation for the layer of interest was calculated by an appropriately weighted average of saturation within each 10- or 20-cm sample interval. Figure 2 shows the average soil saturation for each of the 14 years for the top 30 cm, highlighting 1988, a substantial drought year, and 1993, a substantial flood year. Other depth intervals are not shown, due to space constraints.

Measures of daily precipitation were available at 129 stations within the state. In the work of *Kunkel et al.* [1990], data from these stations were bulked into nine crop reporting zones; here, however, we have determined the statewide average daily precipitation by averaging daily values at all 129 stations. This time series of the statewide average daily rainfall was used in all the analyses discussed below. Figure 3 shows the average total monthly rainfall during the 14 years for which we have soil moisture observations (1981–1994).

5. Results and Discussion: The Interplay Between Soil Saturation and Subsequent Precipitation Throughout the Year

To relate this data analysis with the modeling discussed in sections 2 and 3, we compared an initial soil condition to

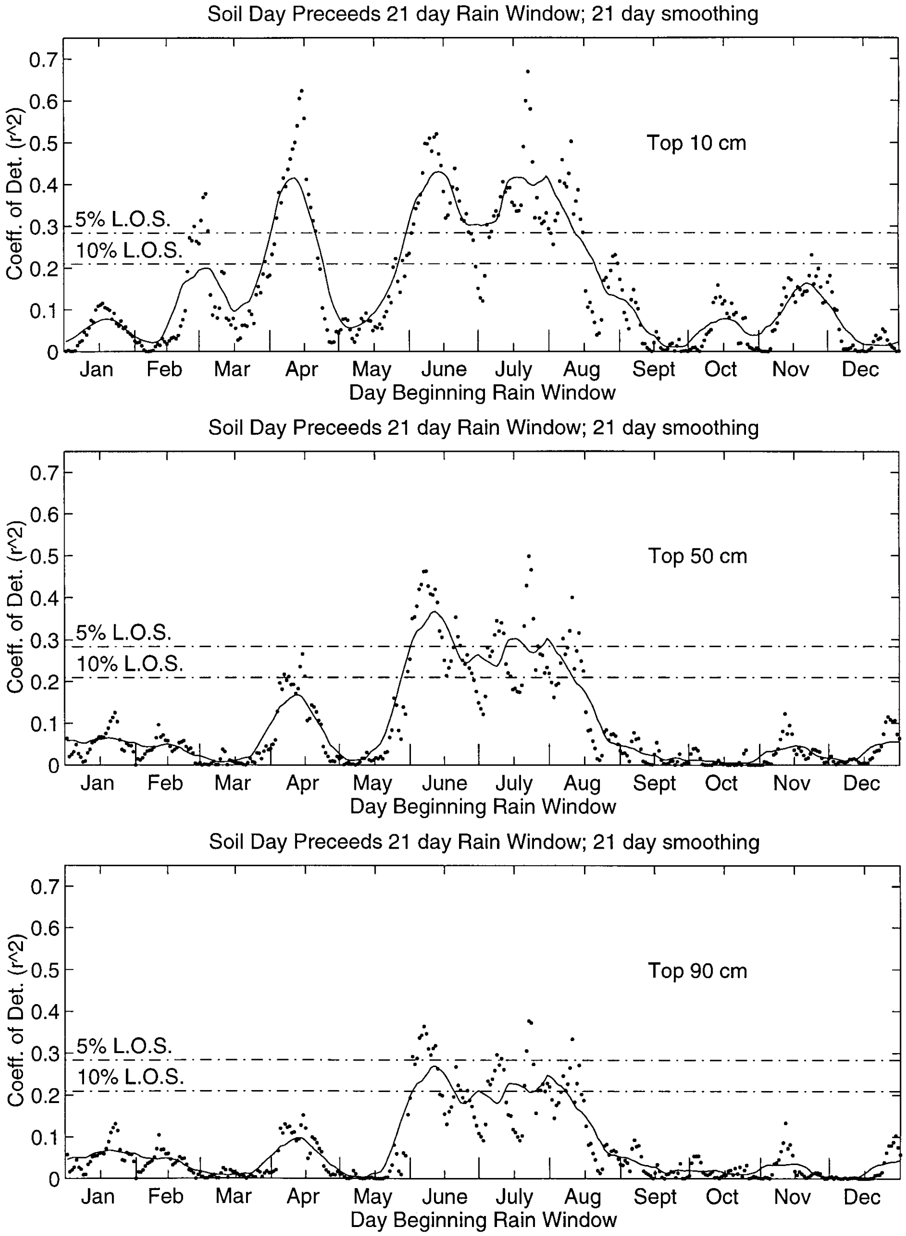

Figure 4. Correlation between initial soil saturation and precipitation in the subsequent 21 days for (a) top 10 cm, (b) top 50 cm, and (c) top 90 cm. Solid line is 21-day moving average. Level of significance lines refer to the daily values (not the smoothed line).

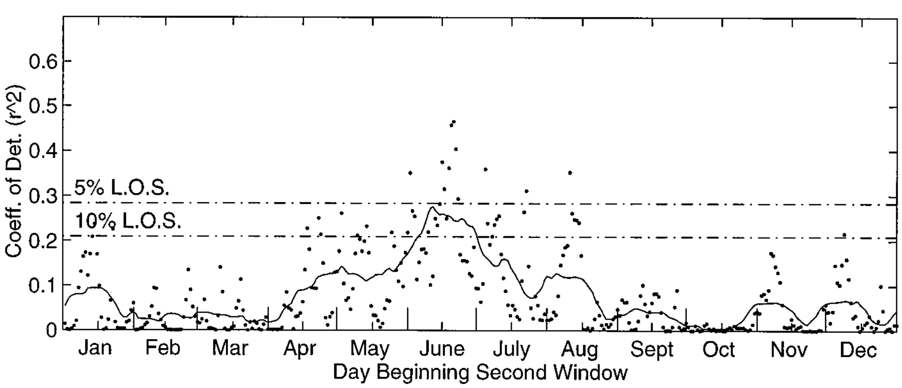

Figure 5. Correlation between adjacent 21-day precipitation windows; 21-day smoothing. Solid line is 21-day moving average. Level of significance lines refer to the daily values (not the smoothed line).

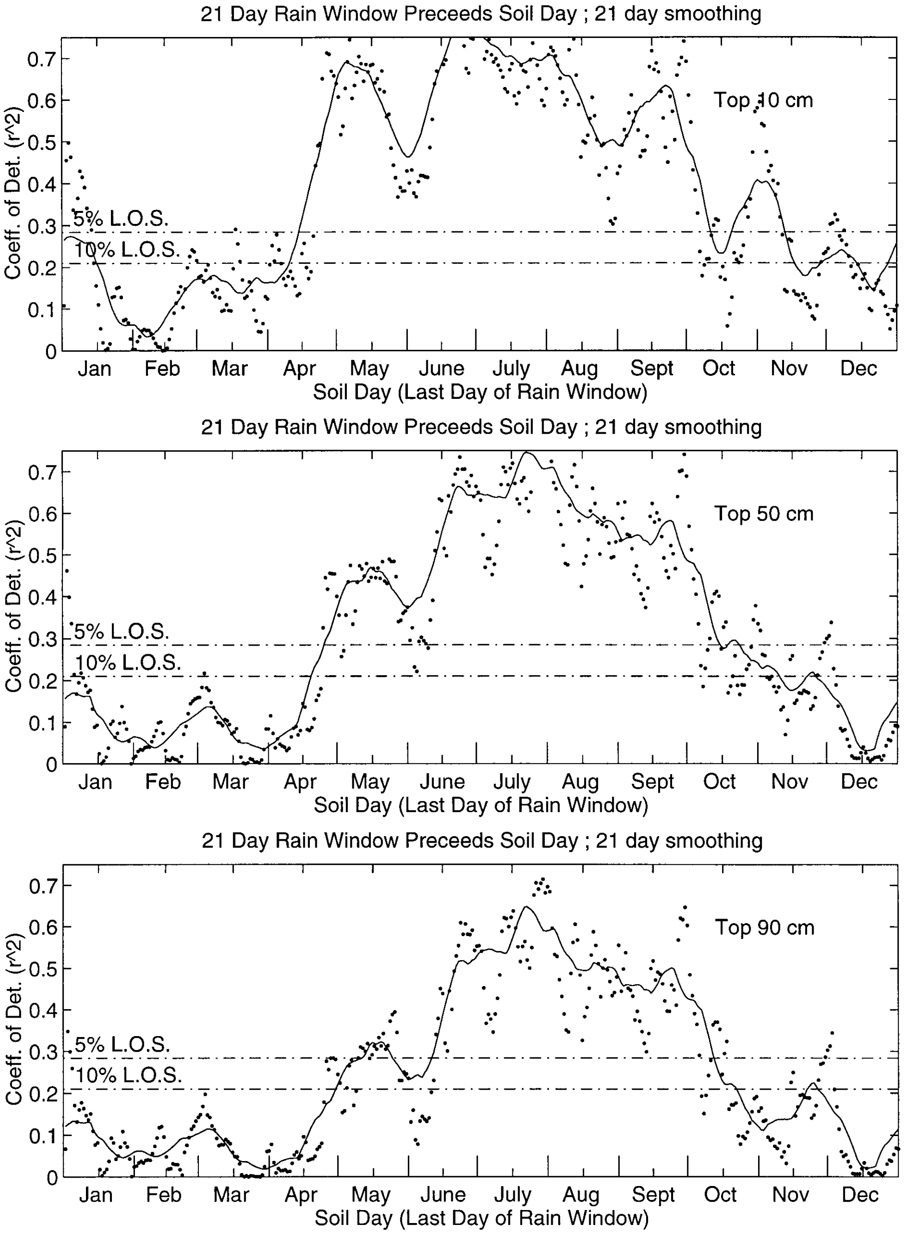

Figure 6. Correlation between 21-day total precipitation and soil saturation at the end of the 21 days for (a) top 10 cm, (b) top 50 cm, and (c) top 90 cm. Solid line is 21-day moving average. Level of significance lines refer to the daily values (not the smoothed line).

subsequent precipitation, much like a modeler would test for precipitation sensitivity to soil water. To this end, for a given day, for example, April 1, we looked at the average soil saturation within the state for each of the available 14 years. We then calculated the total precipitation in the subsequent 21 days for each of the 14 years, in this case, April 2–23. Twenty-one days is time enough for the soil to go through a few wetting and drying cycles, and for the atmosphere to go through a few convective storm cycles, so our results will be indicative not of a single weather event, but of a short climatic period. A linear regression was then performed on these two 14-year series, and the coefficient of determination r^2 was recorded as an indicator of the percentage of rainfall variability that can be explained by the soil water initial condition. This analysis was performed for all 365 days of the year. The dots in Figure 4 show that the r^2 values reach as high as 0.7 for the top 10 cm. Even after a 21-day smoothing, more than 40% of the variability in rainfall can be explained by a simple linear correlation between initial soil saturation and subsequent rainfall. Analysis of each of the 11 depth intervals (not all shown here) showed that this correlation was damped at greater depths.

The level of significance lines of Figure 4 are computed using an F distribution for the r^2. (The 5% level of significance line for an F distribution with 1 and 12 degrees of freedom in the numerator and denominator, respectively, is 4.75. This yields an r^2 of 0.2836. The 10% line is at $F(1, 12) = 3.18$, which yields an r^2 of 0.2095. See *Johnston* [1984] for details.) These lines apply to the daily measurements, not to the smoothed lines. From the Central Limit Theorem, we know that the significance lines for the smoothed data will be lower since the

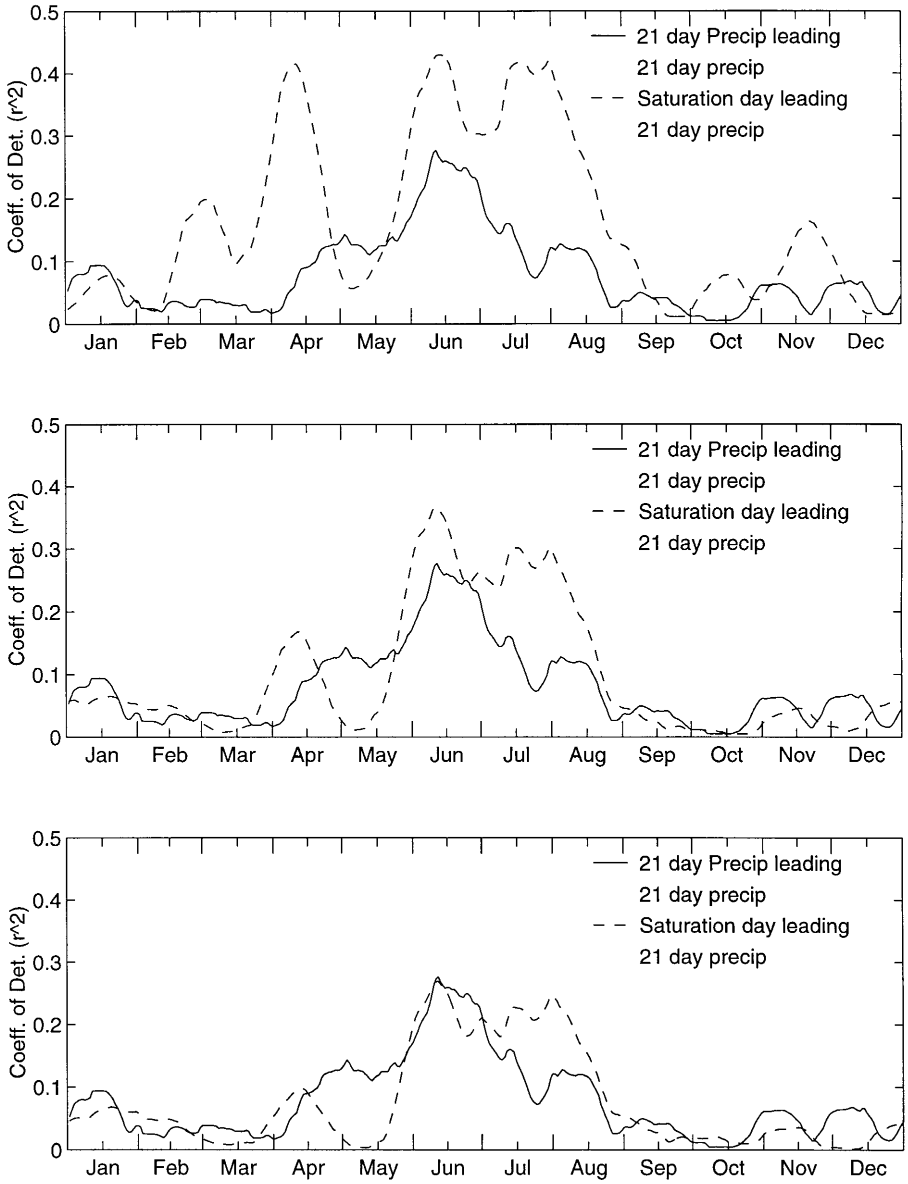

Figure 7. Comparison of smoothed lines of the correlation between adjacent precipitation windows (top) top 10 cm, (middle) top 50 cm, and (bottom) top 90 cm) (solid line, from Figure 5) and of the correlation between soil saturation and subsequent precipitation (dashed line, from Figure 4).

variability will go down as the inverse of the length of the averaging window. All Figures 4a–4c show the daily r^2 is stronger during the summer than the rest of the year, though there is a local peak during April, as well. At the shallower depths the linear correlation stays above the 10% level of significance line from the end of May to early August and for much of April. During the rest of the year the correlation between soil moisture and subsequent precipitation is not significant.

We find three possible explanations for these results showing that there is a significant linear relation between soil saturation and subsequent precipitation conditions during this summer period. First, it is possible that the relationship is due to a persistent large-scale atmospheric forcing that sustains or enhances a persistence in rainfall between adjacent time periods, and through the correlation between concurrent rainfall and soil saturation, results in the observed correlation between soil saturation and subsequent rainfall. Second, the correlation could be a reflection of a feedback process in which initial soil moisture affects rainfall, which then affects soil moisture, etc. Finally, we must consider a combination of these two mechanisms.

If large-scale atmospheric processes drive the system at hand, persistence in atmospheric conditions would first be reflected in rainfall persistence, as shown in Figure 5. Here persistence in rainfall is measured by the correlation between the total precipitation in adjacent 21-day windows. Figure 6 then shows the correlation between a 21-day rainfall window and soil saturation at the end of the window. If precipitation forces soil saturation at the end of a given window (Figure 6), and if precipitation is also linearly correlated with precipitation in the next time window (Figure 5), soil saturation may, merely as a direct consequence of this rainfall forcing, also be significantly correlated with subsequent precipitation (Figure 4). In this case, we would expect the rainfall persistence to be greater

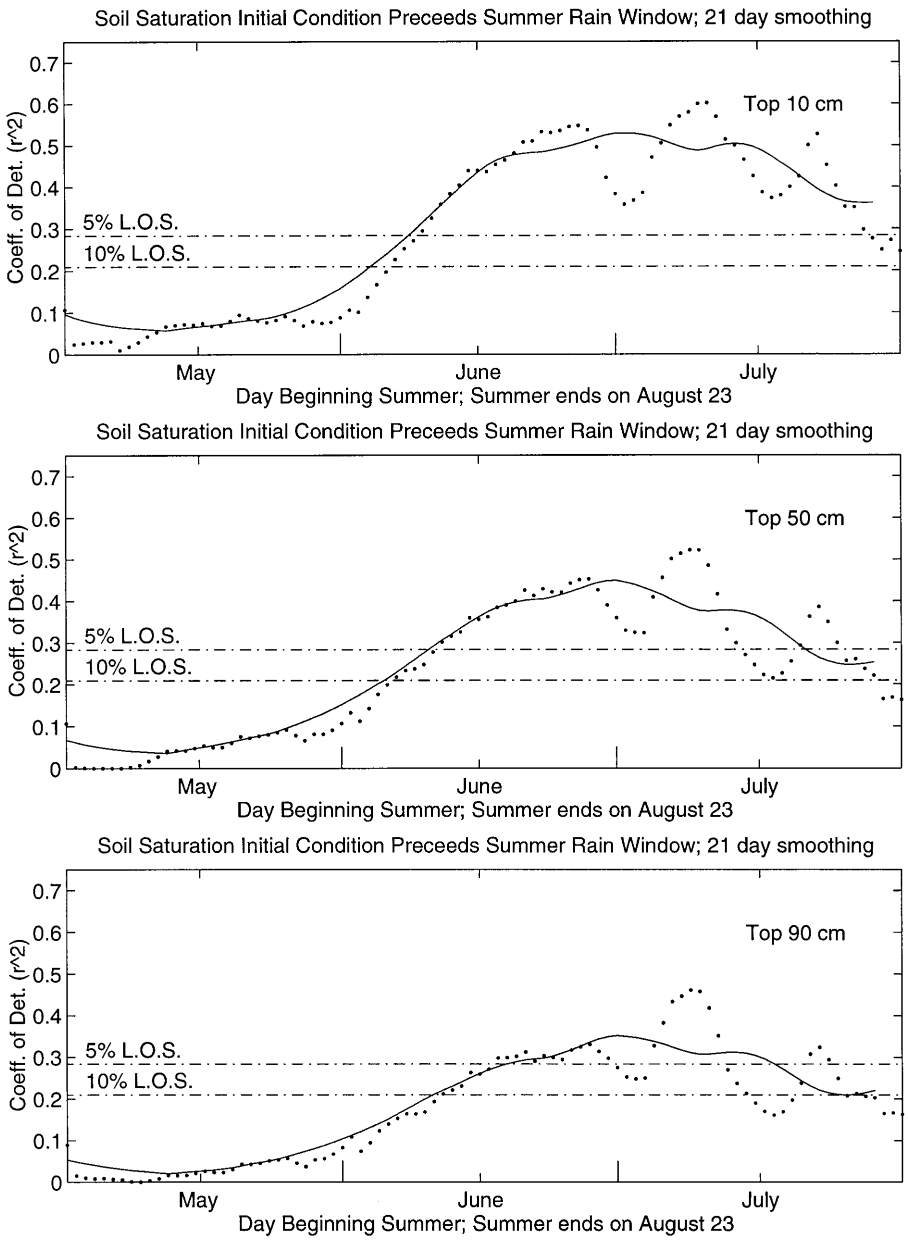

Figure 8. Correlation between initial soil saturation and precipitation in the rest of the summer (through August 23) for (a) top 10 cm, (b) top 50 cm, and (c) top 90 cm. Solid line is 21-day moving average. Level of significance lines refer to the daily values (not the smoothed line).

than the correlation between soil saturation and subsequent precipitation.

In a scenario in which soil moisture is a driving force affecting rainfall we would expect the state of the soil moisture reservoir to affect rainfall directly. In this case, the correlation between soil saturation and subsequent rainfall should outweigh the correlation between rainfall in adjacent windows.

Figures 7a–7c are plots of the smoothed lines of Figures 4a–4c superimposed on the smoothed precipitation persistence line of Figure 5. From this figure we can see that for autumn and winter the correlation between rainfall and prior soil moisture is comparable to the correlation between serial precipitation windows. This suggests that persistence due to large-scale atmospheric forcing can account for much of the observed linear correlation between soil moisture and subsequent rainfall during these seasons. Throughout June, July, and August, and for a portion of the spring, however, rainfall is better correlated with prior soil moisture than with prior rainfall. This suggests that during the summer, feedback from soil moisture is the more likely physical explanation. At no point, however, can we rule out the possibility that a combination of the two given explanations is responsible for the observations. These results are consistent with the GCMs discussed earlier and with the regional study of *Pan et al.* [1995].

6. Results and Discussion: Focus on Spring and Summer Connections

Given the results of the analysis for the entire year, it seems pertinent to focus on the summer months. An analysis similar to the one described above was performed, comparing the correlation between an initial soil condition and total precipi-

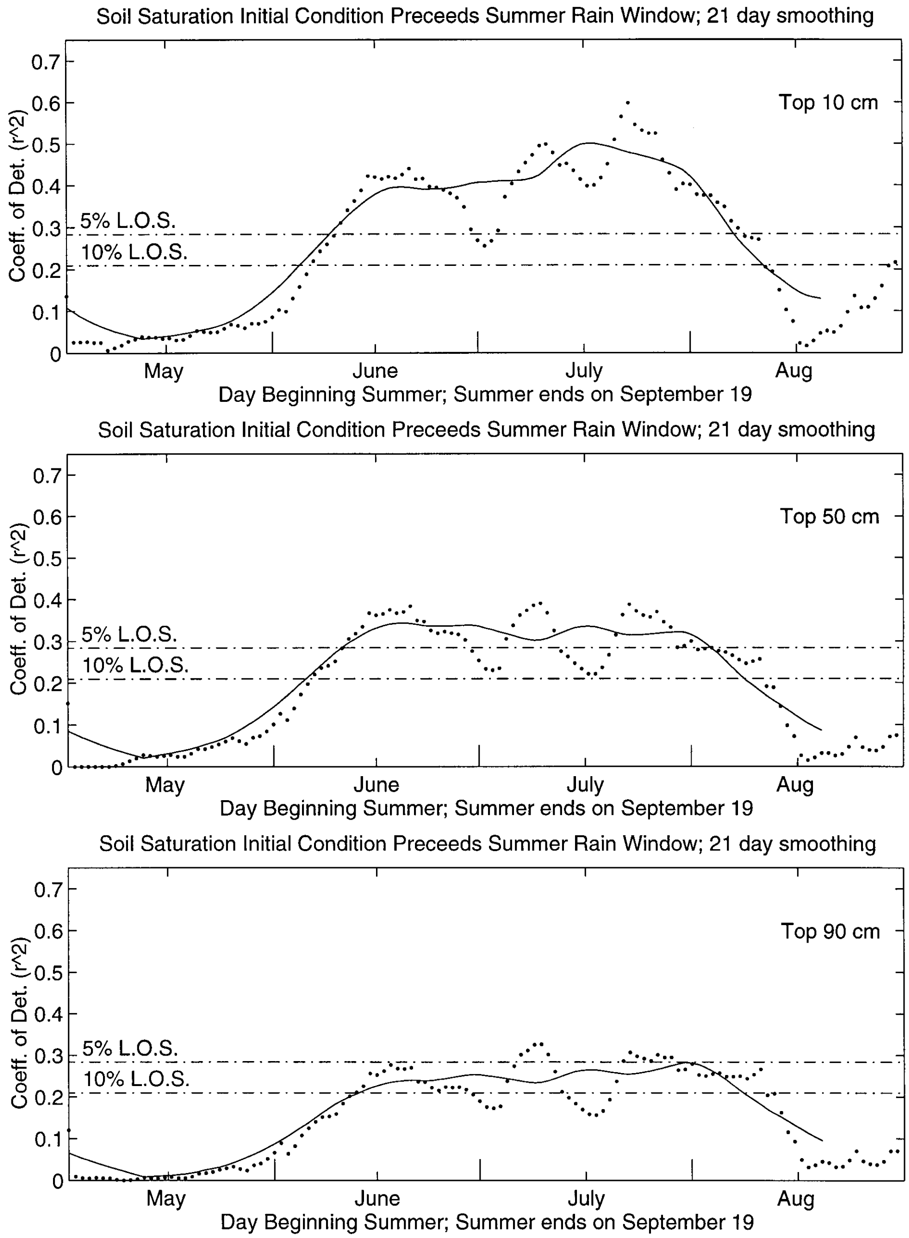

Figure 9. Correlation between initial soil saturation and precipitation in the rest of the summer (through September 19) for (a) top 10 cm, (b) top 50 cm, and (c) top 90 cm. Solid line is 21-day moving average. Level of significance lines refer to the daily values (not the smoothed line).

tation during the rest of the summer. Assuming that summer is taken to end on August 23, Figure 8 shows the r^2 for every initial condition day from May 1 to July 31. Similarly, Figure 9 shows the results for the case where summer is taken to end on September 19, with initial condition days moving from May 1 to August 31.

Again, the linear correlation is significant for much of the summer. Figure 8 shows a maximum of $r^2 > 0.5$ at the end of June, while Figure 9, with summer lasting until September 19, reaches this same r^2 level in mid-July. Figure 10 shows the 14 data points used to obtain these r^2 values for the June 25 initial condition and August 23 end of summer. The number beside each data point denotes the year of the event, and the r^2 is given in the upper left corner. Though the nonextreme years show little pattern, we see that the most extreme years, 1988 and 1993, fit the expected pattern of a dry (wet) spring being followed by a dry (wet) summer. If the two variables were completely unrelated, then the probability of both of these events randomly occurring within one data set would be quite low.

The dashed horizontal and vertical lines in Figure 10 divide the data into three spring soil moisture classes: high, normal, and low, and into three summer rainfall classes: again, high, normal, and low. The lines are calculated by taking the average of the 14 data points plus or minus 1 standard deviation. These groupings show that during these 14 years, no abnormally dry spring was followed by an abnormally wet summer, and vice versa. Though these analyses are based on only 14 years of data, it is currently the most comprehensive data set of its kind. The conclusions should be reassessed as more data are made available.

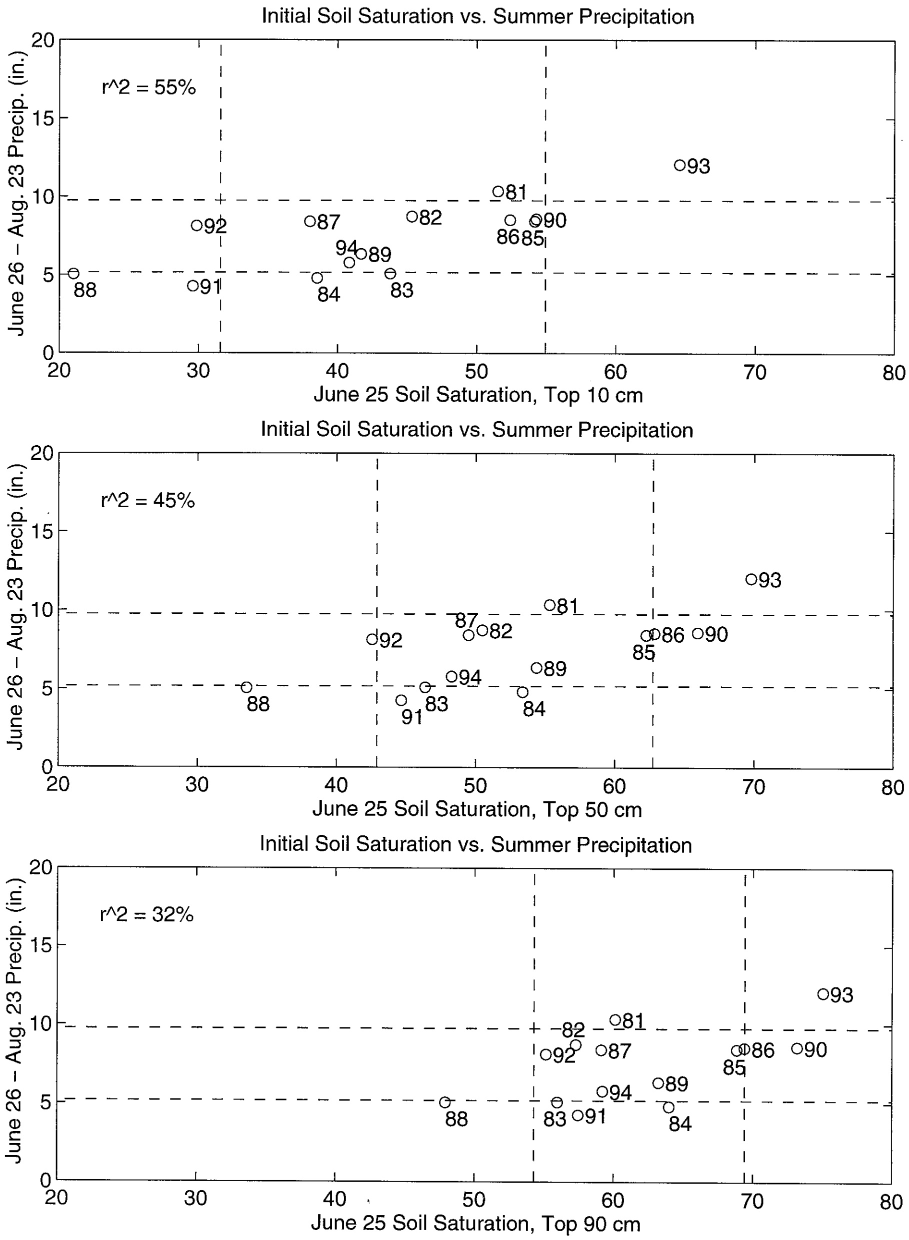

Figure 10. Average initial soil saturation on June 25 for a given year versus summer (July 1 to August 23) precipitation for each year. Numbers beside each data point indicate sample year. Dotted lines are means of the 14 years plus or minus 1 standard deviation, separating data into low, normal, and high categories of soil saturation and summer precipitation.

7. Conclusions

This study tests the hypothesis that soil saturation is positively correlated with subsequent precipitation by analyzing a 14-year soil moisture data set from the state of Illinois. The linear correlation between an initial soil saturation condition and subsequent rainfall is significant during the summer months, reaching a peak of $r^2 > 0.4$ in mid-June. This result is consistent with the hypothesis that knowledge of late spring/early summer soil moisture conditions can aid in the prediction of drought or flood years, but it does not necessarily prove that feedback from anomalous soil moisture reservoirs is the cause of anomalous summer conditions. Further analyses indicate that from early June to mid-August, persistence in rainfall cannot fully account for the observed correlations, suggesting the likelihood of a physical feedback mechanism linking early summer soil saturation with subsequent precipitation.

Though these conclusions are striking, they must be accepted with some restraint: the observed results suggest that though the physical feedback is significant, it is by no means the only pertinent physical process. Furthermore, the data set is limited in both spatial and temporal resolution. The 14 years comprising this data set have very few nonnormal events from which we can make inferences regarding the association between soil moisture and subsequent summer rainfall. Additionally, the aerial coverage is quite small: the entire midwestern United States would provide a much more comprehensive study region. However, despite these deficiencies, this data set is by far the largest of its kind that is readily available for analysis.

Observations made here should be useful to those working on the dynamics of droughts and floods for midlatitude continental interiors. The results of many GCMs [*Shukla and Mintz*, 1982; *Oglesby*, 1991; *Rind*, 1982; *Trenberth et al*., 1988; *Atlas et al*., 1993; *Oglesby and Erickson*, 1989] and regional studies [*Pan et al*., 1995; *Huang et al*., 1996] are consistent with those observed in the Illinois data set: extreme soil moisture availability (or lack thereof) acts as either a feedback mechanism maintaining the wet (or dry) conditions established in the beginning of each summer or as a flag indicative of some large-scale process that is affecting both the soil moisture and the precipitation regime.

Neither these observations nor the modeling studies discussed earlier answer the question of how these links between soil moisture and precipitation are forged. This study provides some empirical evidence to highlight the importance of understanding these physical processes. Some of our future research will be directed toward understanding the processes controlling these links.

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