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A soil moisture–rainfall feedback mechanism
1. Theory and observations

Elfatih A. B. Eltahir

Ralph M. Parsons Laboratory, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge

Abstract. This paper presents a hypothesis regarding the fundamental role of soil moisture conditions in land-atmosphere interactions. We propose that wet soil moisture conditions over any large region should be associated with relatively large boundary layer moist static energy, which favors the occurrence of more rainfall. Since soil moisture conditions themselves reflect past occurrence of rainfall, the proposed hypothesis implies a positive feedback mechanism between soil moisture and rainfall. This mechanism is based on considerations of the energy balance at the land-atmosphere boundary, in contrast to similar mechanisms that were proposed in the past and that were based on the concepts of water balance and precipitation recycling. The control of soil moisture on surface albedo and Bowen ratio is the fundamental basis of the proposed soil moisture–rainfall feedback mechanism. The water content in the upper soil layer affects these two important properties of the land surface such that both variables decrease with any increase in the water content of the top soil layer. The direct effect of soil moisture on surface albedo implies that wet soil moisture conditions enhance net solar radiation. The direct effect of soil moisture on Bowen ratio dictates that wet soil moisture conditions would tend to enhance net terrestrial radiation at the surface through cooling of surface temperature, reduction of upwards emissions of terrestrial radiation, and simultaneous increase in atmospheric water vapor content and downwards flux of terrestrial radiation. Thus, under wet soil moisture conditions, both components of net radiation are enhanced, resulting in a larger total flux of heat from the surface into the boundary layer. This total flux represents the sum of the corresponding sensible and latent heat fluxes. Simultaneously, cooling of surface temperature should be associated with a smaller sensible heat flux and a smaller depth of the boundary layer. Whenever these processes occur over a large enough area, the enhanced flux of heat from the surface into the smaller reservoir of boundary layer air should favor a relatively large magnitude of moist static energy per unit mass of the boundary layer air. The dynamics of localized convective storms as well as the dynamics of large-scale atmospheric circulations have been shown to be sensitive to the distribution of boundary layer moist static energy by several previous studies. These theoretical concepts are tested using field observations from Kansas and explored further in a companion paper [*Zheng and Eltahir*, this issue] using a simple numerical model.

1. Introduction

Soil moisture plays a significant role in land-atmosphere interactions. The state of soil moisture, as described by the level of saturation in the upper soil layer relative to the soil field capacity, is regulated by rainfall and potential evaporation. Both of these atmospheric forcings exert significant control on the evolution of the soil moisture state and appear explicitly in the soil water balance equation. On the other hand, the level of soil saturation determines the availability of water as well as the hydraulic properties of the soil and for this reason soil saturation exerts significant control on the rates of exfiltration and subsequent evaporation. However, the role of soil moisture conditions in dictating the occurrence of future rainfall is less understood. Clarification of this role requires identification of the pathways through which soil moisture may regulate the atmospheric variables that are relevant to the dynamics of storms and rainfall. If future rainfall levels over any region reflect in some way the current state of soil moisture, then that condition implies the existence of a feedback mechanism between the two variables. In this paper we propose a pathway for relating soil moisture conditions and subsequent rainfall.

The earliest speculations in the literature about the role of soil moisture in the dynamics of rainfall were cited by *Holzman* [1937, p. 14]: S. Aughey wrote in 1880 about the physical geography of Nebraska, that "year by year as cultivation of the soil is extended, more of the rain that falls is absorbed and retained to be given off by evaporation or to produce springs. This of course must give increasing moisture and rainfall." Similar arguments were offered by *Jensen* [1935], *McNish* [1936], and *Horton* [1943]. However, these early studies provided no evidence from observations to support the implied soil moisture–rainfall feedback. A different view on this topic was presented by *Holzman* [1937] and *McDonald* [1962], who criticized the idea that local precipitation is related to local evaporation and soil moisture through moisture recycling. These two studies emphasized the role of the rainfall-

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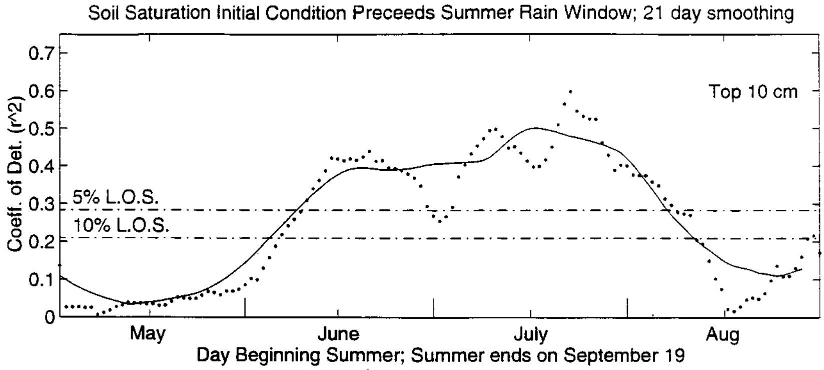

Figure 1. The observed relationship between the level of soil saturation and subsequent rainfall during summer in Illinois. The figure describes the correlation between initial soil saturation and precipitation in the rest of the summer. Solid line is 21-day moving average (from *Findell and Eltahir* [1997]).

producing mechanisms in inducing the necessary vertical motion associated with rainfall. In this paper we investigate the role of soil moisture conditions in the radiative and thermodynamic processes that lead to vertical motion and occurrence of rainfall.

Several simple water balance models have been proposed to describe land-atmosphere interactions, including the soil moisture–rainfall feedback, on the basis of the concept of precipitation recycling [e.g., *Lettau et al.*, 1979; *Eltahir*, 1989; *Rodriguez-Iturbe et al.*, 1991; *Savenije*, 1995]. For example, *Eltahir* [1989] proposed a feedback mechanism relevant to regions with large swampy areas or shallow lakes. A wet year increases the storage volume of the swamp, extends its surface area, and results in increased evaporation and rainfall in that year and the following years. In a more recent study *Rodriguez-Iturbe et al.* [1991] presented a water balance model that describes the interannual soil moisture dynamics at the regional scale. The model assumes that recycled precipitation is partly a function of evaporation and soil moisture. The solution of the stochastic soil moisture differential equation may result in a bimodal distribution for the spatially averaged soil saturation. Although simple water balance models may be useful in illustrating statistically the nature of the soil moisture–rainfall feedback, these same models consider only water balance, and for this reason they are too simple to describe accurately the physics of the coupled land-atmosphere system. In addition to water balance, land-atmosphere interactions are governed by the energy balance at the land-atmosphere boundary, energy balance of the atmospheric boundary layer, and by the nature of the coupling between boundary layer conditions and rainfall processes. In this paper we discuss all these processes in some detail.

Entekhabi et al. [1996] reviewed the recent literature on the interactions between soil moisture and atmospheric processes. The role of soil moisture conditions in land-atmosphere interactions was studied by *Brubaker and Entekhabi* [1996]. They developed a stochastic model that describes the physical interactions at the land-atmosphere boundary. They concluded that the soil moisture control on evaporation is the major mechanism by which the moisture state tends to reinforce temperature anomalies and that the temperature dependence of surface saturation–specific humidity is a major factor in reinforcing soil moisture anomalies. Thus anomalies in soil moisture and temperature could be self-reinforcing resulting in persistent hydrologic conditions.

Many studies have investigated the soil moisture-rainfall feedback using modeling approaches [e.g., *Shukla and Mintz*, 1982; *Rind*, 1982; *Yeh et al.*, 1984; *Oglesby and Erickson*, 1989; *Oglesby*, 1991; *Pan et al.*, 1995]. In most of these studies general circulations models (GCMs) are used to perform numerical experiments on the role of soil moisture in climate variability. The results of most studies indicate that changes in soil moisture conditions at the late spring/early summer may significantly impact the simulated summer rainfall over continental land regions. A relatively wet initial soil moisture condition results in relatively more rainfall, which in general supports the existence of a positive soil moisture–rainfall feedback. However, most of these modeling experiments involve extreme changes of soil moisture conditions at continental scales. The magnitude and spatial scales of such extreme anomalies are not likely to be observed. In absence of any global data set on long term variability of soil moisture conditions, the conclusions of these modeling studies have not been confirmed with observations.

In a recent study *Findell and Eltahir* [1997] analyzed direct observations on soil moisture and rainfall from Illinois and found a significant but small lag correlation between soil moisture and rainfall. Figure 1 describes some of the results of their analysis. The correlation between average soil moisture saturation and subsequent summer rainfall over Illinois is positive and statistically significant during most of the summer season. This analysis represents the only observational evidence that supports the existence of a positive feedback mechanism relating soil moisture conditions and subsequent summer rainfall. The corresponding analysis for the other seasons of the year does not show any significant association between soil moisture conditions and subsequent rainfall. Although the observed correlation between the two variables is statistically significant during the summer season, the magnitude of this correlation is rather small. Initial soil moisture condition explains a small but significant fraction of the interannual variability in summer rainfall. The proposed hypothesis on the soil moisture–rainfall feedback may shed some light on the physical mechanisms that are responsible for the observed correlation between soil moisture and future rainfall.

The proposed hypothesis on the role of soil moisture in land-atmosphere interactions will be presented in section 2. Section 3 describes relevant observations from Kansas that were collected during the First ISLSCP Field Experiment (FIFE) (see the FIFE special issue of the *Journal of Geophysi-*

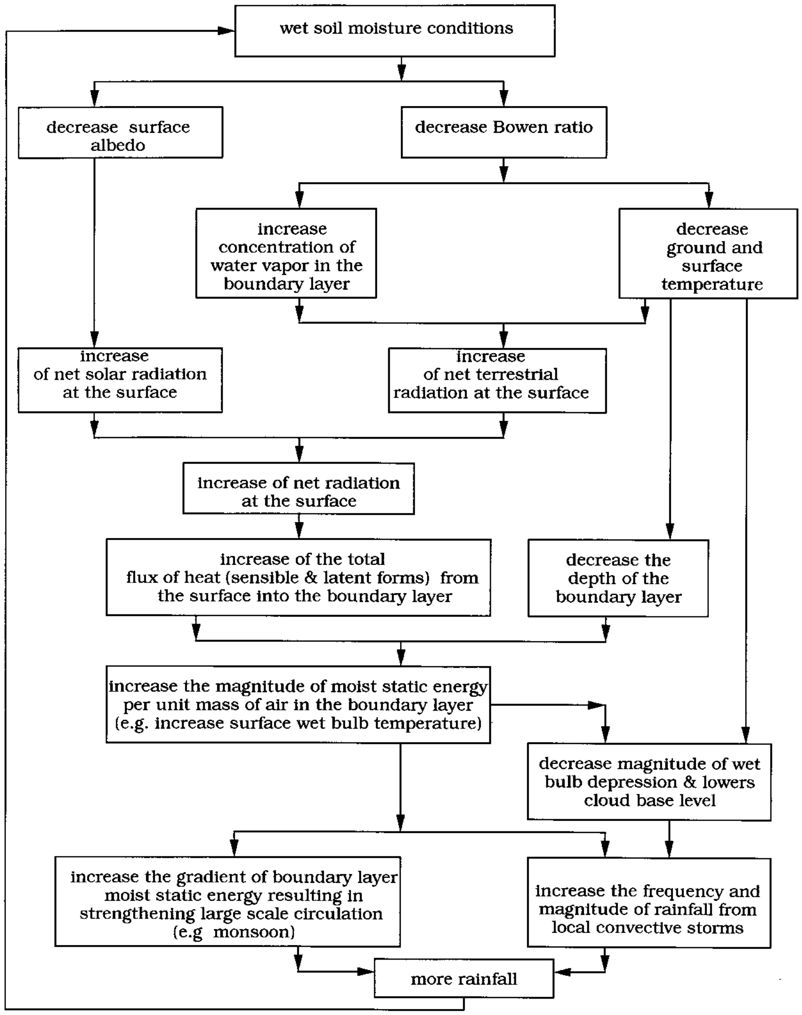

Figure 2. The proposed hypothesis for relating soil moisture conditions and subsequent rainfall processes.

cal Research [*Sellers et al.*, 1992]) and are presented here to support the proposed hypothesis. Section 4 describes the relationship between soil moisture and boundary layer energy. Section 5 covers the role of clouds in the surface radiation processes. Section 6 includes a discussion and conclusions.

2. Theory

Here we propose a hypothesis that describes the role of soil moisture in land-atmosphere interactions. In particular, we suggest that wet soil moisture conditions enhance the following related variables: net surface radiation, total heat flux from the surface into the atmosphere, and moist static energy in the atmospheric boundary layer. The latter can be quantified using several variables including wet bulb potential temperature and equivalent potential temperature. These two variables are important for the energetics and dynamics of local convective storms [*Williams and Renno*, 1993; *Eltahir and Pal*, 1996; *Zawadzki and Ro*, 1978; *Zawadzki et al.*, 1981] as well as the dynamics of large-scale atmospheric circulations in the tropics [*Emanuel et al.*, 1994; *Eltahir*, 1996; *Eltahir and Gong*, 1996]. The proposed pathways for relating soil moisture conditions and subsequent rainfall are described in Figure 2. We hypothesize that Figure 2 describes the dominant pathways for relating soil moisture and subsequent rainfall. However, this figure is not designed to describe all possible interactions. The proposed hypothesis is based on considerations of the following: (1) the relationship between soil moisture conditions and two basic properties of the land-surface, albedo and Bowen ratio; (2) the surface radiation balance; (3) the energy balance at the land-atmosphere boundary; (4) the energy balance of the atmospheric boundary layer; and (5) the thermodynamic and dynamic processes that relate boundary layer conditions and subsequent rainfall.

2.1. Basic Properties of the Land Surface: The Relationship Between Soil Moisture Conditions, Surface Albedo, and Bowen Ratio

The role of soil moisture conditions in regulating surface albedo and Bowen ratio is the fundamental basis of the proposed hypothesis. Basic radiation physics suggests that water absorbs significantly more solar radiation than dry soil. As a result, absorption of solar radiation increases with the relative fraction of water in any mixture of soil and water. Several observations confirm these theoretical arguments. *Bowers and Hanks* [1965] and *Bowker et al.* [1985] studied the spectral reflectance of soil surfaces and confirmed that at all wave lengths of solar radiation, reflectance decreases with the level of soil saturation. *Idso et al*. [1975] performed comprehensive field studies on the dependence of bare soil albedo on soil water content. They found that albedo is negatively correlated with average water content in the soil up to the depth of about 10 cm. However, this relation is sensitive to the distribution of water within the top soil layer; water content in the upper centimeter of the soil has the most significant impact on surface albedo.

The water content of the top soil layer (~10–50 cm) plays a significant role in the partition of net radiation at the surface into sensible and latent heat fluxes. In addition to controlling water availability for evaporation from the surface, the relative level of soil saturation controls the hydraulic conductivity of the top soil layer, which regulates the rate of exfiltration [*Eagleson*, 1978]. Under certain conditions, the rate of exfiltration may limit the rate of evaporation from the deep soil layers that are subsaturated. *Lowry* [1959] reviews theoretical and observational bases for the relationship between this level of soil saturation and the ratio of actual evaporation to potential evaporation. Under most conditions this ratio tends to increase with the level of saturation in the top soil layer. *Owe and Van De Griend* [1990] present field observations on the same relationship which confirms that for bare soil as well as vegetated surfaces the ratio of actual evaporation to potential evaporation increases with the level of soil saturation. The Bowen ratio is inversely related to the ratio of actual evaporation to potential evaporation. Thus over large areas the Bowen ratio decreases with the level of saturation in the top soil layer.

2.2. The Surface Radiation Balance: The Relationship Between Soil Moisture Conditions and Surface Net Radiation

The radiation balance at the land-atmosphere boundary can be described by

$$R_n = R_s + R_t \tag{1}$$

where R_n is net radiation, R_s is net solar radiation defined as the difference between the incoming and the reflected fluxes of solar radiation, and R_t is net terrestrial radiation defined as the difference between the downwards flux of terrestrial radiation and the terrestrial radiation emitted by the surface. Mathematically, the net solar radiation and net terrestrial radiation are given by

$$\begin{aligned} R_s &= S - \alpha S \\ R_t &= \varepsilon(q)\sigma T_a^4 - \sigma T_s^4 \end{aligned} \tag{2}$$

where S is incoming solar radiation; α is albedo; ε is emissivity of the atmospheric boundary layer, which is an increasing function of the atmospheric water vapor content denoted by q; σ is the Stefan-Boltzmann constant; T_a is effective atmospheric temperature; and T_s is surface temperature.

The negative relation between soil water content and albedo implies that wet soil moisture condition would tend to enhance net solar radiation at the surface. However, the corresponding relationship between soil moisture conditions and net terrestrial radiation is less obvious. As relative saturation of the top soil layer increases, latent heat flux from the surface increases at the expense of the corresponding sensible heat flux which results in two direct impacts: (1) lower ground surface temperature and (2) higher water vapor content in the atmospheric boundary layer. In other words, the soil water content should be negatively correlated with the surface temperature and positively correlated with water vapor content in the boundary layer. According to (2), the decrease in surface temperature implies less emission of terrestrial radiation by the surface. On the other hand, the increase of water vapor content of the boundary layer implies more downwards flux of terrestrial radiation at the surface, because of the greenhouse effect of water vapor. Both of these processes are likely to occur as a result of increased soil moisture content and they both favor an increase in net terrestrial radiation at the surface. Thus everything else being the same, wet soil moisture conditions should enhance net solar radiation and net terrestrial radiation, and according to (1) such conditions should enhance net radiation at the surface. However, the relationship between soil moisture could be further complicated if soil moisture has any impact on the formation of clouds and rainfall. The cloudiness feedback could have significant role in the surface radiation balance. This role is discussed in section 5.

2.3. The Surface Energy Balance: The Relationship Between Soil Moisture Conditions and the Total Surface Heat Flux

The proposal that wet soil moisture conditions enhance net radiation has important implications on the surface energy balance. The simplest statement of the surface energy balance is that net surface radiation has to be balanced by a combination of sensible, latent, and soil heat fluxes. The magnitude and direction of the soil heat flux depend on the relative magnitudes of the ground surface temperature and the temperature of the underlying soil layer. For long term equilibrium conditions soil heat flux is negligible and net radiation is balanced by the total flux of latent and sensible heat into the atmosphere.

$$R_n = F \qquad F = \lambda E + H \tag{3}$$

It is interesting to note that while the magnitude of net radiation is, in part, regulated by the relative partition of the total flux of heat into latent and sensible forms (the Bowen ratio), as discussed in the previous section, the magnitude of the total heat flux from the surface into the atmosphere responds directly to variability in net radiation according to (3). Thus the same factors that modify the relative magnitudes of latent and sensible heat fluxes into the atmosphere, such as soil moisture conditions and vegetation density, also play a significant role in determining the magnitude of the total heat flux into the atmosphere including both latent and sensible forms. Here we emphasize that relatively wet soil moisture conditions favor larger net radiation and more flux of heat, including latent and sensible forms, from the surface into the atmospheric boundary layer.

2.4. Energy Balance of the Atmospheric Boundary Layer: The Relationship Between Soil Moisture Conditions and Boundary Layer Energy

The total energy in the atmospheric boundary layer can be described by moist static energy (mse) which includes potential energy, sensible heat, and latent heat. (mse $= gz + C_pT + Lq$, where g is gravitational acceleration, z is elevation, C_p is the specific heat capacity at constant pressure, T is temperature, L is latent heat of vaporization, and q is water vapor mixing ratio). Moist static energy is supplied by the total heat flux from the surface into the atmosphere, F. The same energy reservoir is depleted by a combination of three processes: entrainment at the top of the boundary layer (EN), radiative cooling flux (R), and the negative heat fluxes associated with convective downdrafts during rainfall events (C). If we consider large spatial scales, such that vertical fluxes of heat from the surface are significantly larger than the corresponding horizontal heat fluxes, then we may neglect horizontal heat advection, and express the boundary layer moist static energy budget by

$$\frac{\partial \mathrm{mse}}{\partial t} = F - \mathrm{EN} - R - C \tag{4}$$

Both entrainment and convective downdrafts mix relatively dry air from above the boundary layer downwards. Since in general the distribution of atmospheric moist static energy decreases with elevation, these two processes bring air of relatively low moist static energy into the boundary layer and hence both processes deplete the boundary layer reservoir of moist static energy.

The total heat flux from the surface into the atmosphere is the main source of energy in the atmospheric boundary layer. This is particularly true over large regions where heat advection is small compared to vertical heat fluxes. In the previous section we proposed that wet soil moisture conditions enhance the total heat flux from the surface into the boundary layer. Thus, everything else being the same, wet soil moisture conditions should favor a larger magnitude of moist static energy in the atmospheric boundary layer. This statement implicitly assumes that the fluctuations in EN, R, and C in response to variability in soil moisture conditions are relatively small compared to the corresponding fluctuations in F. While this is likely to be the case for R and C, previous studies have suggested that EN responds significantly to variability in soil moisture conditions [*Betts et al.*, 1994; *Betts and Ball*, 1998]. Wet soil moisture conditions should be associated with a small flux of sensible heat and a small rate of entrainment. The latter is consistent with the creation of a relatively small depth of the boundary layer. Thus, under wet soil moisture conditions, a relatively large flux of heat occurs from the surface into a boundary layer that is characterized by a relatively small depth. Both of these factors would tend to increase the magnitude of moist static energy per unit mass of boundary layer air. This issue will be discussed further in section 4.

2.5. Rainfall Processes: The Relationship Between Boundary Layer Energy and Subsequent Rainfall

Boundary layer moist static energy plays an important role in the dynamics of local convective storms as well as the dynamics of large-scale atmospheric circulations. Whenever a significant vertical gradient of moist static energy exists over any region, with moist static energy decreasing upwards, an unstable condition develops. As a result, moist convection occurs to redistribute energy in the vertical adjusting the conditions towards a neutral vertical distribution of energy. This energy redistribution results in local convective storms. Similarly, whenever a significant horizontal gradient of moist static energy exists over any large region, large-scale thermally direct circulations develop to redistribute energy towards a flatter horizontal distribution of moist static energy. In conclusion, boundary layer moist static energy plays an important role in the dynamics of storms at a range of scales.

These theoretical arguments have been supported by several observations. At local scales *Williams and Renno* [1993] presented observations which indicate that wet bulb potential temperature (a measure of boundary layer moist static energy) is strongly correlated with convective available potential energy (CAPE) over most of the tropics. (Wet bulb temperature is the temperature to which air may be cooled by evaporating water into it at constant pressure, until saturation is reached; dry bulb temperature is the temperature of the air.) CAPE is an important variable that describes the atmospheric environment of local convective storms. It quantifies the amount of energy that is available for conversion into kinetic energy by undiluted air parcels that are rising during a convective storm. *Eltahir and Pal* [1996] studied the relationship between surface wet bulb temperature and subsequent rainfall in convective storms using observations from the Amazon forest. Both the frequency and magnitude of localized convective storms were found to increase with surface wet bulb temperature which confirms the concept that boundary layer moist static energy plays an important role in the dynamics of local convective storms.

The impact of soil moisture conditions on surface dry bulb temperature and surface wet bulb temperature (that is, wet soil moisture corresponds to relatively cool dry bulb temperature and relatively warm wet bulb temperature) implies that the wet bulb depression (dry bulb temperature minus wet bulb temperature) has to be negatively associated with soil saturation. Wet bulb depression should have higher sensitivity to soil moisture conditions than any of the two temperatures taken individually. As the soil saturation level increases, conditions over land approaches oceanic conditions, where the wet bulb depression is close to zero. A lower magnitude of wet bulb depression should correspond to a lower lifting condensation level, which defines the cloud base. Everything else being the same, a lower cloud base should enhance the likelihood for triggering of moist convection and occurrence of rainfall. This is particularly true for situations when triggering of convection is facilitated by external forcings such as mesoscale or synoptic-scale disturbances in surface pressure.

Emanuel et al. [1994] proposed that at large scales of atmospheric motion, atmospheric circulations in the tropics are driven by gradients of boundary layer entropy. The latter is strongly related to boundary layer moist static energy. *Eltahir and Gong* [1996] presented observations from west Africa that demonstrate that the distribution of boundary layer entropy plays an important role in the dynamics of wet and dry years over that region. On the basis of the results of these studies we suggest that the impact of soil moisture conditions on the boundary layer moist static energy is an important part of the pathway through which soil moisture conditions impact rainfall processes.

In the next section we analyze observations from Kansas, which were collected during FIFE, to study the relationship between soil moisture, surface radiation components, surface energy fluxes, and rainfall.

3. Observations

In this section we analyze field observations from FIFE with the objective of testing the different aspects of the hypothesis presented in section 2. The original data sets collected during FIFE are described in the FIFE special issue of the *Journal of Geophysical Research* [*Sellers et al.*, 1992]. The observations presented in this paper are site averages that have been analyzed and supplied to us by A. Betts. They are described in significant detail by *Betts and Ball* [1998]. They represent spatial averages over the domain of FIFE, which covers an area of about 15 by 15 km, and cover the summer seasons of 1987,

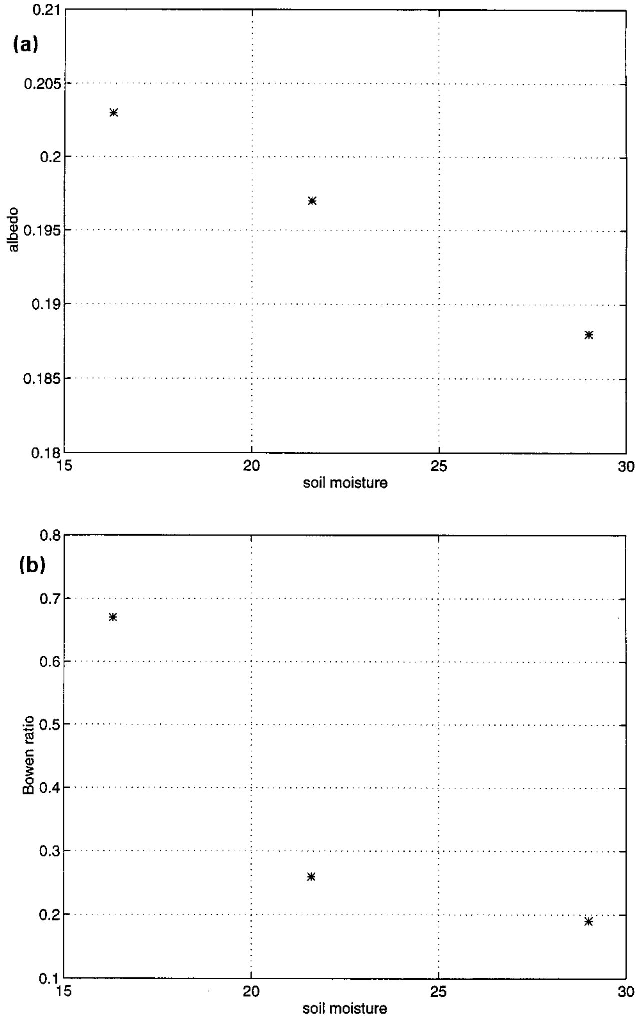

Figure 3. Observations on soil moisture (volume of water per bulk volume of soil) and on (a) albedo and (b) Bowen ratio during FIFE. The data are averaged into three categories using three bins of similar soil moisture conditions; each bin contains an equal number of data points.

1988, and 1989. All the observations presented in this paper represent daily averages and site averages. Although the FIFE data set is one of the most extensive data sets available for describing land surface processes, the spatial domain as well as the density of the observation stations are rather limited. In particular, the overall domain of the experiment is not large enough for the assumption of negligible horizontal heat advection to hold true. Owing to this factor, some caution should be exercised in interpretation of the FIFE observations in the light of the proposed hypothesis: The data for similar soil moisture conditions will be averaged together. This averaging technique is designed to isolate trends in the data that are attributable to the role of soil moisture from those which reflect the influence of other factors. Only three categories of soil moisture conditions that describe relatively dry, medium, and wet conditions will be considered.

3.1. The Relationship Between Soil Moisture Conditions, Surface Albedo, and Bowen Ratio

The relationships between soil moisture and surface albedo, and between soil moisture and Bowen ratio will be examined first. The data on soil moisture and surface albedo is presented in Figure 3a. It describes daily average values of surface albedo and soil moisture in the top 10 cm of the soil (volumetric water content obtained using the gravimetric method). An equal number of observations that fall within each of three bins of similar soil moisture conditions are averaged to describe the typical albedo for those conditions. The purpose in this averaging, which is also applied in the data analysis throughout this paper, is to isolate the trends of surface albedo with soil moisture content from the effects of the other factors that may influence surface albedo. The land cover for the FIFE site is short grass; variation in the density of this biomass could contribute to the variability in albedo. This issue will be discussed further in the last section of this paper. According to Figure 3a, extreme changes in soil moisture conditions are associated with an average change in surface albedo of about 2%. The magnitude of this change, though small, is indeed significant. In terms of energy fluxes this change in surface albedo corresponds to about 5 W/m^2.

The data on soil moisture and Bowen ratio are presented in Figure 3b. As expected, the Bowen ratio decreases significantly with the increase in soil water content. For relatively dry to medium conditions the Bowen ratio decreases sharply by about a factor of 3 and then levels off at about 0.2 for relatively wet conditions. Figures 3a and 3b confirm the fundamental basis of the stated hypothesis, namely, that surface albedo and Bowen ratio decrease significantly with any increase in the soil water content. However, the variation of albedo with soil water content has a small magnitude compared to the large variation of Bowen ratio with the same variable.

3.2. The Relationship Between Soil Moisture Conditions and Net Radiation

The decrease of the Bowen ratio with increasing soil water content implies that ground surface temperature should decrease as the soil water content increases and that the atmospheric water vapor content should increase similarly. The observations of these variables during FIFE, which are not shown here, confirm this prediction. As a result, emissions of terrestrial radiation by the surface increase, downwards flux of terrestrial radiation decreases, and thus net terrestrial radiation increases with soil water content. Although soil moisture may play an important role in the radiation processes at the land-atmosphere boundary, it is by no means the only relevant variable. Other factors play similar or even more important roles in these radiative processes. One of these important factors is the variability in incoming daily solar radiation, which reflects the seasonal cycle of solar radiation as well as variability in cloudiness and atmospheric water vapor distribution. Figure 4 presents observations on the association between incoming solar radiation and each of the following variables: net radiation, total heat flux from the surface into the atmosphere, net terrestrial radiation, and soil heat flux. A significant fraction of the variability in each of these four fluxes can be explained by the variability in incoming solar radiation. Hence, in order to focus on the role of soil moisture in influencing the variability in these fluxes, we will examine the relationships between soil moisture and any of these fluxes normalized by the corresponding observation on incoming solar radiation. The role of clouds in the surface radiation processes is discussed in section 5.

The observations on soil moisture and net terrestrial radiation are presented in Figure 5a. Net terrestrial radiation has

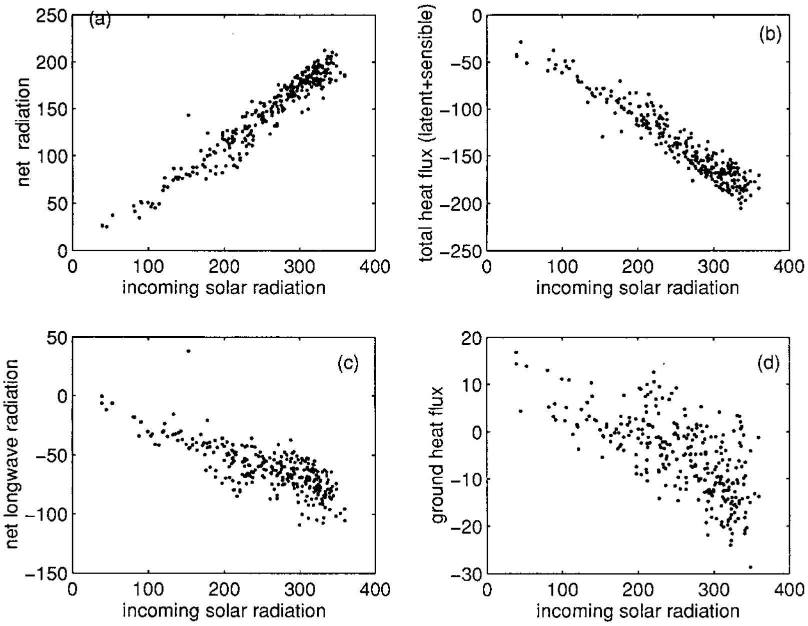

Figure 4. Observations on incoming solar radiation (W/m^2) and (a) net radiation (W/m^2), (b) total heat flux (W/m^2), (c) net terrestrial radiation (W/m^2), and (d) soil heat flux (W/m^2) during FIFE. The observations represent daily and site averages.

been normalized by incoming solar radiation. The resulting fraction increases significantly with soil moisture from about -0.26 for relatively dry conditions up to a value of about -0.23 for relatively wet conditions. The corresponding observations on soil moisture and net radiation are presented in Figure 5b. These observations confirm the prediction that wet soil moisture conditions enhance net radiation at the surface. The average fraction of incoming solar radiation that is available to fuel turbulent transport of heat away from the surface increases by about 0.05 (corresponds to about 10–12 W/m^2) as soil water content increases from a level close to the wilting point to a higher level close to field capacity. By comparing Figures 3a, 5a, and 5b we deduce that the relationship between net radiation and soil moisture is mainly a reflection of the dependence of net terrestrial radiation on soil moisture conditions.

3.3. The Relationship Between Soil Moisture Conditions and Total Heat Flux

The observations on soil moisture and total heat flux are presented in Figure 6. The total heat flux increases significantly with soil water content. This pattern is quite is similar to that exhibited in Figure 5b by the observations on soil moisture and net radiation. This similarity is expected since net radiation and the total heat flux are strongly related. At relatively long timescales net radiation is equivalent to the total heat flux into the atmosphere. However, over relatively short timescales net radiation is balanced by the sum of the heat flux into the atmosphere and the corresponding soil heat flux into the ground. Observations on the soil heat flux and soil moisture, which are not shown here, indicate little dependence of the soil heat flux on soil moisture conditions.

3.4. The Relationship Between Soil Moisture Conditions and Boundary Layer Energy

In section 2 we proposed that the total heat flux from the surface into the atmosphere responds to variability in soil moisture conditions and that the same flux is a significant forcing for variability in the boundary layer moist static energy. The observations during FIFE indicate that the total heat flux is influenced in part by soil moisture conditions. Here we examine the proposed relationship between the total heat flux and boundary layer moist static energy. We use surface wet bulb temperature as a measure of moist static energy. This directly observable measure was found to be useful for such purpose by previous studies [*Williams and Renno*, 1993; *Eltahir and Pal* [1996]. The observations on the total heat flux and wet bulb temperature are presented in Figure 7. The surface wet bulb temperature responds to variability in the total heat flux from the surface. The observed association between the two variables is significant, specially, if we recall the small spatial domain of these observations and the importance of horizontal heat advection in influencing the variability of surface wet bulb temperature.

The observed relationships between soil moisture and the total heat flux into the atmosphere (Figure 6) and between the latter and surface wet bulb temperature (Figure 7) imply a similar relationship between soil moisture and surface wet bulb temperature. Figure 8 presents direct observations on soil moisture and wet bulb temperature. Although considerable scatter marks the relationship between these two variables, averaging into three categories of soil moisture conditions reveals a positive trend in the average wet bulb temperature with soil moisture.

Similar analysis on the observations of soil moisture and dry bulb temperature at the surface (not shown here) reveals a negative correlation between soil moisture and temperature. This result, considered in conjunction with the observed trend in Figure 8 and the definition of wet bulb depression, suggests a negative trend between soil moisture and wet bulb depression. Such trend is evident in Figure 9, which describes the observations on soil moisture and wet bulb depression.

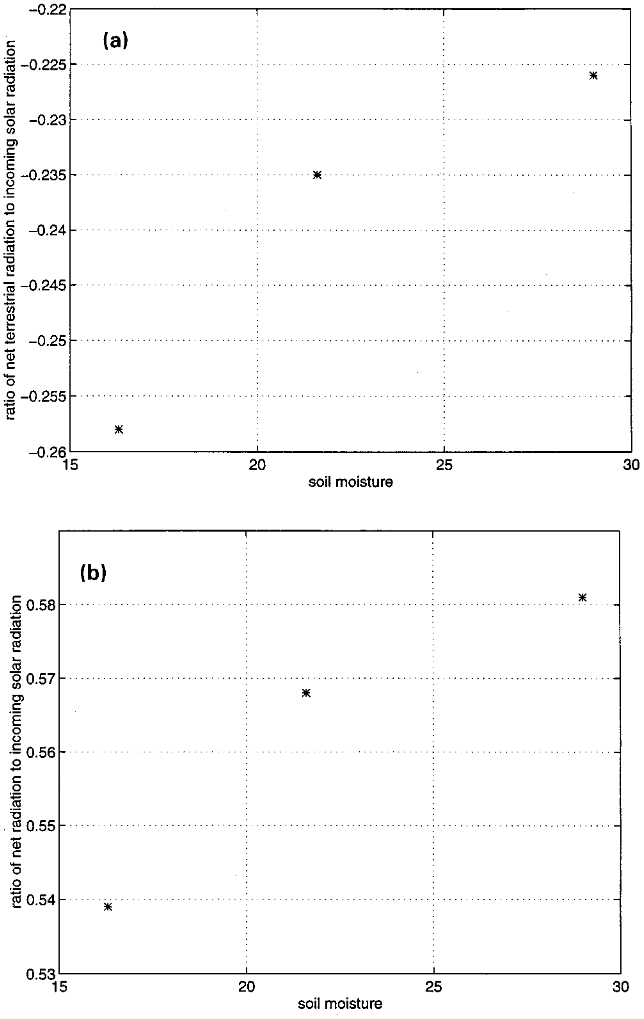

Figure 5. Observations on soil moisture (volume of water per bulk volume of soil) and on the ratios of (a) net terrestrial radiation and (b) net radiation to the incoming solar radiation during FIFE. The data are averaged into three categories using three bins of similar soil moisture conditions; each bin contains an equal number of data points.

3.5. The Relationship Between Boundary Layer Energy and Subsequent Rainfall

The final step in the proposed hypothesis is the link between boundary layer moist static energy and rainfall processes. The average wet bulb temperature for the wet soil moisture category is warmer by about 1°C than the average wet bulb temperature for the relatively dry category (Figure 8). This difference is indeed significant. *Williams and Renno* [1993] and *Eltahir and Pal* [1996] demonstrated that CAPE as well as frequency of storms are sensitive to small differences (1°C or smaller) in surface wet bulb temperature. Figure 10 presents observations on the maximum wet bulb temperature and the likelihood for subsequent occurrence of convective storms in the afternoon over the FIFE site. The latter is quantified by the conditional probability of rainfall occurrence in the future given the observed wet bulb temperature, which describes the prestorm environment. The analysis on rainfall and wet bulb temperature focus on local convective storms that occur in the afternoon period. This analysis is similar to that of *Eltahir and Pal* [1996], and considers convective storms starting between 2:00 and 4:00 P.M. and with a duration of 6 hours or less. The likelihood of occurrence of these storms increases significantly with wet bulb temperature. These observations are consistent with the results of a similar analysis for the Amazon region presented by *Eltahir and Pal* [1996] and provide additional evidence to support the fact that boundary layer moist static energy plays a significant role in rainfall processes. A similar analysis on the observations of wet bulb depression in the afternoon and subsequent rainfall is presented in Figure 11. For this analysis the starting time of the storm could be any time after 3:00 P.M. up to midnight, and the duration of the storms is not restricted to 6 hours. (Since the analysis here is different from that of wet bulb temperature, the ranges for the probabilities in Figures 10 and 11 are different.) The conditional probability of rainfall decreases as the wet bulb depression (and hence the cloud base level) increases.

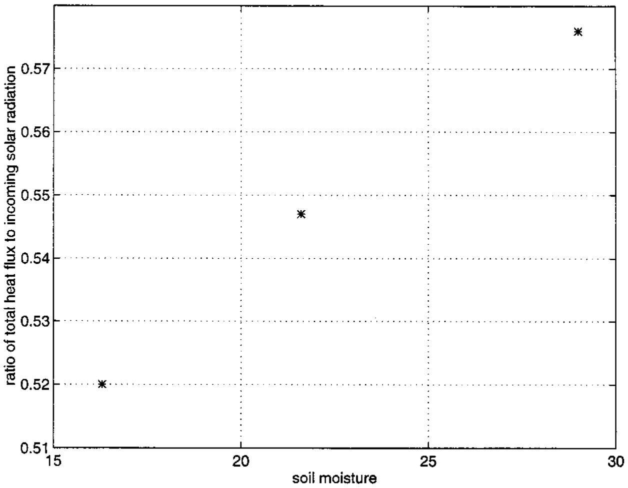

Figure 6. Observations on soil moisture (volume of water per bulk volume of soil) and the ratio of the total heat flux to the incoming solar radiation during FIFE. The data are averaged into three categories using three bins of similar soil moisture conditions; each bin contains equal number of data points.

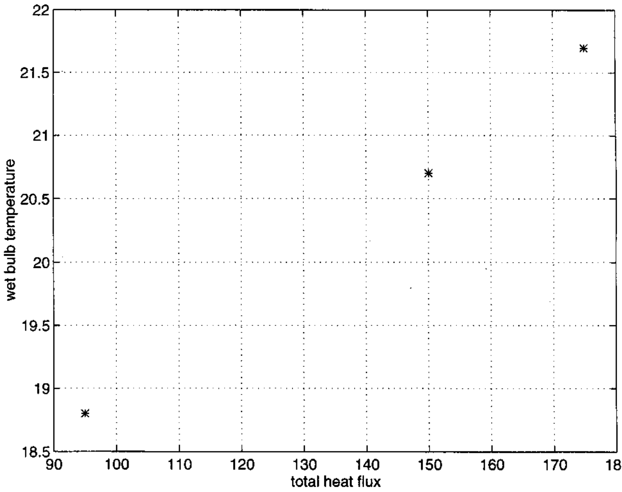

Figure 7. Observations on the total heat flux (W/m^2) and wet bulb temperature (°C) during FIFE. The data are averaged into three categories using three bins of similar total heat flux conditions; each bin contains equal number of data points.

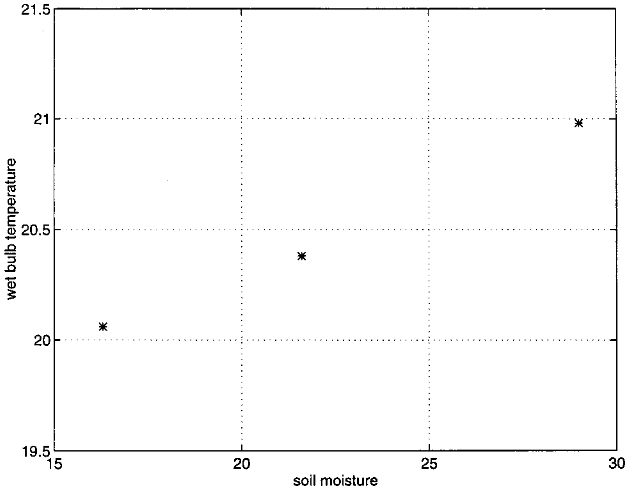

Figure 8. Observations on soil moisture (volume of water per bulk volume of soil) and wet bulb temperature (°C) during FIFE. The data are averaged into three categories using three bins of similar soil moisture conditions; each bin contains equal number of data points.

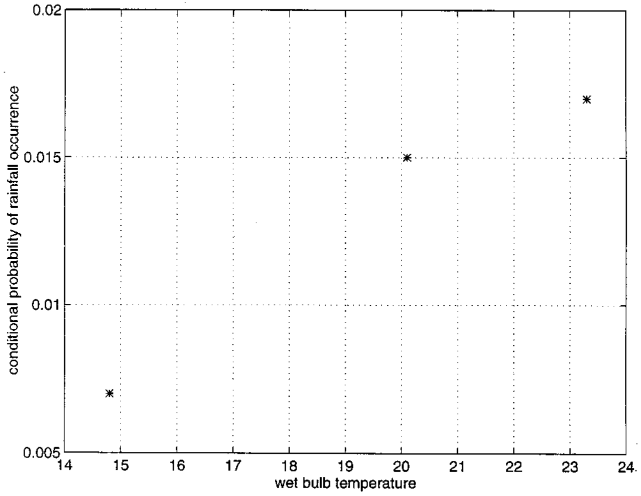

Figure 10. Observations on maximum daily wet bulb temperature (°C) and the conditional probability of occurrence of rainfall in the afternoon given wet bulb temperature, during FIFE.

The analysis presented in this paper does not cover the role of the gradients of moist static energy in large-scale circulations (e.g., monsoons), which are responsible for producing a significant fraction of the observed rainfall. This issue was addressed using observations by *Eltahir and Gong* [1996] and will be covered using a modeling approach in the companion paper [*Zheng and Eltahir*, this issue].

4. Soil Moisture and Boundary Layer Energy

This section explores the relationship between soil moisture conditions and boundary layer moist static energy using a simple model of the boundary layer. The model is based on the principle of conservation of energy in the boundary layer over large regions (equation (4)) applied to predict the moist static energy in the afternoon given the initial condition of moist static energy and the daily flux of heat, which includes sensible and latent heat forms. For simplicity we neglect the contributions of radiation, which has a timescale that is longer than 1 day. We also neglect the contribution of convective downdrafts by considering only clear sky conditions. By integrating (4) between the morning hour, which corresponds to the minimum of boundary layer moist static energy, and the afternoon hour, which corresponds to the maximum of the same variable, we get

$$\mathrm{mse}_{\max} = \mathrm{mse}_{\min} + g\,\frac{F}{\Delta p} \tag{5}$$

where F is the total flux of heat at the daily timescale. Δp is the depth of the boundary layer in the afternoon.

Equation (5) is used to compare the relative roles of the boundary layer depth and the total flux of heat in determining

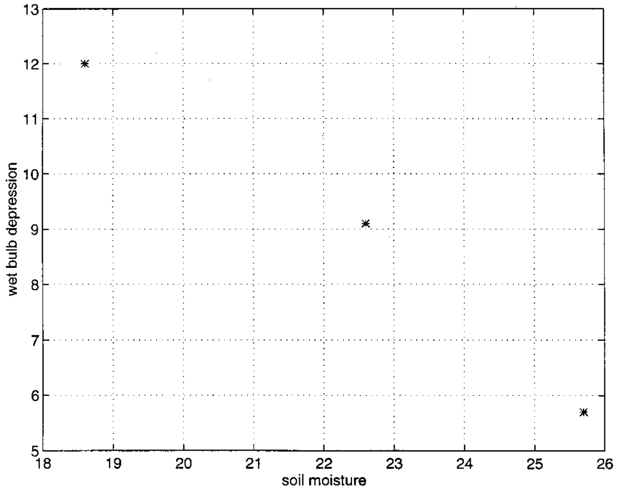

Figure 9. Observations on soil moisture (volume of water per bulk volume of soil) and wet bulb depression (°C) during FIFE. The data is averaged into three categories using three bins of similar soil moisture conditions; each bin contains equal number of data points.

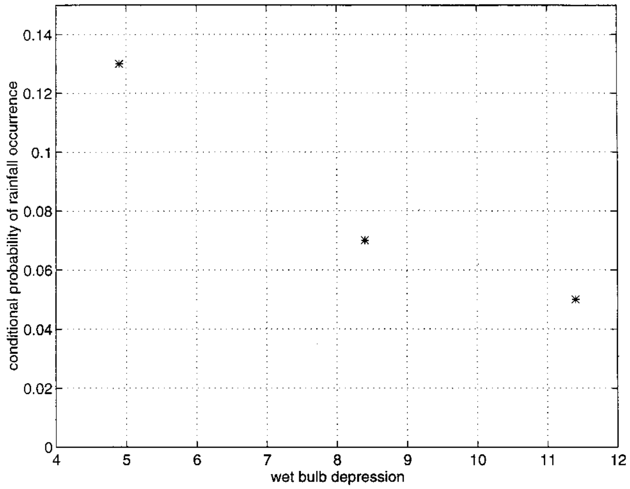

Figure 11. Observations on maximum daily wet bulb depression (°C) and the conditional probability of occurrence of rainfall in the afternoon given wet bulb depression, during FIFE.

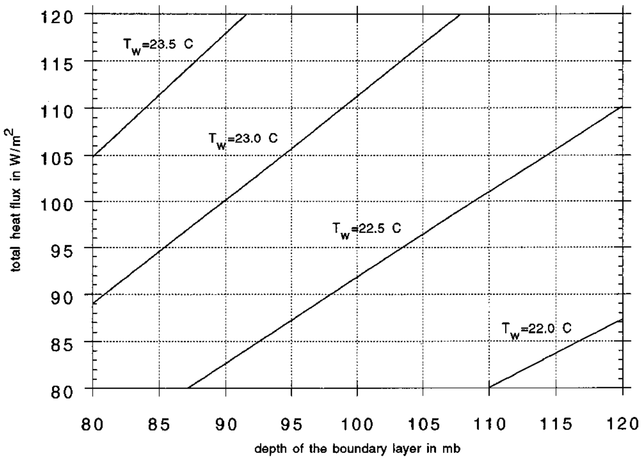

Figure 12. Contours of the maximum wet bulb temperature as function of the maximum depth of the boundary layer in (mbar) and the total heat flux in (W/m^2).

the magnitude of the boundary layer moist static energy in the afternoon. These two roles correspond to the two pathways that relate soil moisture and boundary layer moist static energy in Figure 2. Here we use wet bulb potential temperature, T_w, as a measure of moist static energy in the boundary layer. Equation (5) is used to compute the maximum T_w in the boundary layer for a range of nominal values of daily F and maximum $\Delta p (F = 100$ W/m$^2 \pm 20\%$, $\Delta p = 100$ mbar $\pm 20\%)$. These ranges are selected to represent the likely range of variability in F and Δp due to variability in soil moisture conditions. We assume that the atmosphere during the early morning hours is characterized by a constant T_w of about 20°C. The results are presented in Figure 12.

According to the theory in section 2, the boundary layer depth and the total flux of heat both reflect soil moisture conditions. Wet conditions correspond to relatively small depth and large flux of heat. Equation (5) suggests that both factors would tend to enhance the moist static energy in the boundary layer which is uniquely related to wet bulb potential temperature, T_w. Variability in soil moisture should force trajectories, in Figure 12, that are roughly perpendicular to the lines of constant maximum T_w: between relatively dry conditions (small F/large Δp) and relatively wet conditions (large F/small Δp). The responses of F and Δp to variability in soil moisture conditions collaborate in shaping the response of T_w to variability in soil moisture conditions.

5. The Role of Clouds in the Surface Radiation Balance

While considering the role of soil moisture conditions in the surface radiation balance, in section 2, we attempted to isolate and discuss the role of soil moisture in the complex set of interactions that determine the surface radiation balance. An important factor in these interactions, that may not be entirely independent of soil moisture, is the presence of clouds and their radiative effects. As proposed in section 2, wet soil moisture conditions would tend to increase the likelihood for occurrence of convection, and formation of clouds and rainfall. Therefore we need to assess the potential impact of this enhanced cloudiness on the radiation fields and hence the role of clouds in the proposed soil moisture–rainfall feedback mechanism.

Clouds play a significant role in the climatology of surface radiation over any region. They modify the incoming surface radiation at short and long waves. The incoming solar radiation decreases with increasing cloud cover because of the shielding effects of clouds. At the same time, the downwards flux of long wave radiation increases with cloud cover and cloud depth because clouds scatter back to the surface some of the upwards long wave (terrestrial) radiation that reaches the clouds level. However, the impact of clouds on the short wave (solar) radiation is more significant: The decrease in net short wave radiation per unit increase in cloudiness is larger than the corresponding increase in net long wave radiation. Thus net surface radiation decreases with any increase in cloud amount. E. A. B. Eltahir and E. J. Humphries (The role of clouds in the surface energy balance over the Amazon Forest, submitted to *International Journal of Climatology*, 1997) use surface observations on short and long wave radiation from the Amazon forest to infer the role of clouds in the surface radiation balance at the monthly timescale. Net solar radiation decreases by about 1.7 W/m^2 per 1% increase in cloudiness; net long wave radiation increases by about 0.7 W/m^2 per 1% increase in cloudiness. As a result of this cancellation, the impact of clouds on net surface radiation is somewhat weakened; net surface radiation decreases by about 1.0 W/m^2 per 1% increase in cloudiness. This conclusion, which is based on observations is consistent with the results of several modeling studies which are discussed in the companion paper [*Zheng and Eltahir*, this issue].

The relationship between soil moisture and cloudiness depends on the timescale of interest. For short timescales, those of few hours or shorter, the association between soil moisture level, cloud cover, and rainfall is likely to be weak. The discussion in section 2 was focused on how soil moisture conditions impact surface radiation and boundary layer conditions before the occurrence of a storm. During the prestorm period (before triggering of convection) the role of the cloudiness feedback is insignificant. However, after the triggering of convection and the formation of rainfall, clouds are likely to play a significant role in the surface radiation field. Hence for long timescales, those of a day or longer, the positive association between soil moisture level, cloud cover, and rainfall could be relatively strong. At those timescales the cloudiness feedback should enhance the impact of soil moisture conditions on net long wave radiation. The same feedback may significantly weaken the impact of soil moisture on net solar radiation. The role of clouds is particularly important in the surface radiation balance of the poststorm environment (after triggering of convection). However, in discussing the soil moisture–rainfall feedback the prestorm environment, and not the poststorm environment, is where the important feedbacks take place. During the prestorm period clouds are not important in dictating the surface radiation balance.

6. Discussion and Conclusions

This paper presents a new hypothesis on the role of soil moisture conditions in land-atmosphere interactions. The hypothesis of Figure 2 describes a pathway by which variability in soil moisture conditions over large regions may influence atmospheric conditions and in particular those boundary layer conditions that are important for rainfall processes. Since soil moisture conditions themselves reflect past occurrence of rainfall, the proposed hypothesis implies a positive feedback mechanism between soil moisture and rainfall. Although the observations presented in section 3 generally support the proposed hypothesis for relating soil moisture conditions and future rainfall occurrence, the same observations do not provide further indications of how significant the proposed pathways are in comparison to other possible mechanisms such as those based on water balance and the concept of precipitation recycling. This issue will be explored in a companion paper [*Zheng and Eltahir*, this issue].

The proposed hypothesis on the role of soil moisture shares some basic concepts with our previous theory on the role of vegetation in the climate system [*Eltahir*, 1996]. This observation highlights the similarity between the roles of vegetation cover and soil moisture content in land-atmosphere interactions. Basically, each of the two variables dictates the magnitudes of surface albedo and Bowen ratio, and for this reason both of them influence hydrologic, radiative, and turbulent processes at the land-atmosphere boundary in similar ways. However, the role of vegetation roots in supplying moisture for evaporation from deep soil depths, the role of the canopy in enhancing evaporation through rainfall interception, and the role of vegetation roughness in enhancing the degree of turbulence at the land-atmosphere boundary should enhance the ability of the vegetated land surface to control the Bowen ratio. Soil moisture and vegetation cover are not independent, since soil moisture conditions are important to the growth and health of any vegetation cover. The similarity between the roles of soil moisture and vegetation cover in influencing atmospheric conditions suggests that growth of short vegetation under wet soil moisture conditions would only enhance the previous role of the land surface in land-atmosphere interactions through further reduction of albedo and the Bowen ratio.

Some aspects of the soil moisture-rainfall feedback presented in this paper are similar to the mechanism proposed by *Betts et al*. [1994] and *Betts and Ball* [1995, 1998]. While *Betts and Ball* [1998] use equivalent potential temperature to describe boundary layer moist static energy, we use wet bulb potential temperature to describe the same variable. Equivalent potential temperature is uniquely related to wet bulb potential temperature. Both theories suggest that wet soil moisture conditions would tend to enhance boundary layer moist static energy, and hence the two theories agree in suggesting that the role of soil moisture conditions in determining the boundary layer moist static energy should be part of the pathway that relates soil moisture conditions and rainfall processes. However, the two theories are some what different in their emphasis about how soil moisture impacts boundary layer moist static energy. We argue in this paper that wet soil moisture conditions would tend to increase the magnitude of the total heat flux from the surface into the atmosphere, reduce the size of the boundary layer, and for this reason wet soil moisture conditions should favor a larger magnitude of boundary layer moist static energy per unit mass. *Betts and Ball* [1998], however, emphasize that wet soil moisture conditions are associated with a small depth of the boundary layer, a relatively small rate of entrainment at the top of the boundary layer, and a relatively small heat flux from the boundary layer into the upper atmosphere. The two theories emphasize the importance of two different heat fluxes: the flux from the surface into the boundary layer and the flux away from the boundary layer into the free atmosphere. Both arguments are valid, however; determining the conditions under which any of the two processes may dominate the relationship between soil moisture and boundary layer moist static energy remains a subject for future research.

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E. A. B. Eltahir, Ralph M. Parsons Laboratory, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Rm. 48-207, Cambridge, MA 02139. (e-mail: eltahir@mit.edu)

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