Atmospheric controls on soil moisture-boundary layer interactions: Three-dimensional wind effects

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[1] This paper expands the one-dimensionally based CTP-HI_{low} framework for describing atmospheric controls on soil moisture-boundary layer interactions [*Findell and Eltahir*, 2003] to three dimensions by including low-level wind effects in the analysis. The framework is based on two measures of atmospheric thermodynamic properties: the convective triggering potential (CTP), a measure of the temperature lapse rate between approximately 1 and 3 km above the ground surface, and a low-level humidity index, HI_{low}. These two measures are used to distinguish between three types of early morning soundings: those favoring rainfall over dry soils, those favoring rainfall over wet soils, and those whose convective potential is unaffected by the partitioning of fluxes at the surface. The focus of this paper is the additional information gained by incorporating information about low-level winds into the CTP-HI_{low} framework. Three-dimensional simulations using MM5 and an analysis of observations from the FIFE experiment within this framework highlight the importance of the winds in determining the sensitivity of convection to fluxes from the land surface. A very important impact of the 3D winds is the potential for low-level backing or unidirectional winds with great shear to suppress convective potential. Because of this suppression of convection in certain wind conditions, far fewer simulations produced rain than would be anticipated based solely on the 1D framework of understanding. However, when the winds allowed, convection occurred in a manner consistent with the 1D-based expectations. Generally speaking, in the regime where dry soils were expected to have an advantage, convection was triggered over dry soils more often than over wet; in the regime where wet soils were expected to have an advantage, convection was more frequently triggered over wet soils than over dry. Additionally, when rainfall occurred in both simulations with wet soils and simulations with dry soils for a given day, rainfall depths were typically greater in the simulations with wet soils. Similarly, the FIFE data showed numerous days with convective potential but no rainfall: each of these days had low-level backing or strongly shearing winds. Four days with high humidity deficits and veering winds in the lowest 300 mbar did have rain, highlighting the enhanced buoyancy effects of low-level veering winds. *INDEX TERMS:* 1833 Hydrology: Hydroclimatology; 1854 Hydrology: Precipitation (3354); 1866 Hydrology: Soil moisture; 3307 Meteorology and Atmospheric Dynamics: Boundary layer processes; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; *KEYWORDS:* Land/atmosphere interactions, boundary layer processes, hydroclimatology, soil moisture, precipitation, convective processes

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1. Introduction

[2] Many recent studies have addressed the question of how the fluxes of heat and moisture from the land surface influence the development of convective rainfall, but consensus about the physical mechanisms and the dominant effects has not yet emerged. At issue are the strengths of the competing influences of the sensible heat flux, which leads to deep, turbulent mixing, and the latent heat flux, which increases the moisture and the moist static energy of the boundary layer (BL). Both of these factors are important contributors to BL growth and development, but at the extremes they suggest opposite modes of feedback from the

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land surface to the atmosphere. If the sensible heat flux is the more important factor in the initiation of rainfall, then dry, arid surfaces would be more likely to trigger rain, suggesting a negative feedback between soil moisture and rainfall. If, on the other hand, the latent heat flux is the more important factor, then a positive feedback is suggested. The work presented here builds on that of *Findell and Eltahir* [2003] (hereinafter referred to as FE2003): it is based on the hypothesis that the structure of the atmosphere in the early morning largely determines which method of triggering is more effective on that day.

[3] Both types of feedback show up in various modeling and observational studies. Many studies of the midwestern US drought of 1988 and flood of 1993, for example, suggest that the soil moisture condition in these cases helped to sustain the extreme circumstances throughout the summer [*Trenberth and Guillemont*, 1996; *Trenberth et al.*, 1988; *Atlas et al.*, 1993]. Others suggest that there is actually a negative feedback between soil moisture and drought/flood conditions [*Giorgi et al.*, 1996]. In other studies, *Avissar and Liu* [1996] found a negative feedback when landscape contrasts are extreme and can help initiate a sea breeze-like mesoscale circulation. However, when they ran their simulations without these landscape contrasts, rainfall occurred over wet soils but not over dry soils. *Emori* [1998] found a negative feedback in two-dimensional simulations of interactions between soil moisture and cumulus convection, while *Clark and Arritt* [1995] report finding deeper rainfall over wet soils than over dry soils.

[4] *Ek and Mahrt* [1994] caution against extending the results of individual studies to all locations and synoptic settings. They show that the influence of the land surface on the development of boundary layer (BL) clouds is highly dependent on the initial (early morning) condition of the atmosphere. *Baker et al.* [2001] also note the importance of existing atmospheric conditions in soil moisture-rainfall feedback studies: they found a positive feedback between soil moisture and rainfall over the Florida peninsula, but they noted that an already moist atmosphere was a necessary prerequisite for this positive feedback.

[5] *Crook* [1996] performed a detailed analysis of the sensitivity of convection to a number of near-surface thermodynamic parameters. The most important of these parameters were the temperature and moisture dropoffs between the ground and the boundary layer. These values will be strongly influenced by surface fluxes. Crook explains these sensitivities through their influence on the convective inhibition (CIN) and the convective available potential energy (CAPE). Most importantly for the work presented here, *Crook* [1996] discusses that the relative sensitivity of CIN to temperature variations compared to moisture variations depends on the ratio of the environmental stratification to the moist potential lapse rate. In this work, we make use of the convective triggering potential (CTP; see FE2003 or definition in Appendix A) which is, in essence, a measure of this ratio.

[6] With the one-dimensional boundary layer modeling detailed in FE2003 we established a framework for understanding the nature of land-atmosphere interactions based on the early morning conditions of the atmosphere. This framework (Figure 1) makes use of two measures of atmospheric thermodynamic properties: the convective triggering potential (CTP), a measure of the temperature lapse rate between approximately 1 and 3 km above the ground surface, and a low-level humidity index, HI_{low}. These two measures are used to distinguish between three types of early morning soundings: those favoring rainfall over dry soils, those favoring rainfall over wet soils, and those whose convective potential is unaffected by the partitioning of fluxes at the surface. A crucial third dimension of the CTP-HI_{low} framework is the vertical profile of the winds: this third dimension is the focus of this paper. Here, we describe results of three-dimensional modeling work using the Fifth-Generation Penn State/NCAR Mesoscale Model (MM5 [*Grell et al.*, 1995]), focusing on low-level wind effects. We also present some analysis of data from the FIFE experiment in Kansas which highlight the importance of the wind effects. Further research into the effects of middle and upper level winds is underway.

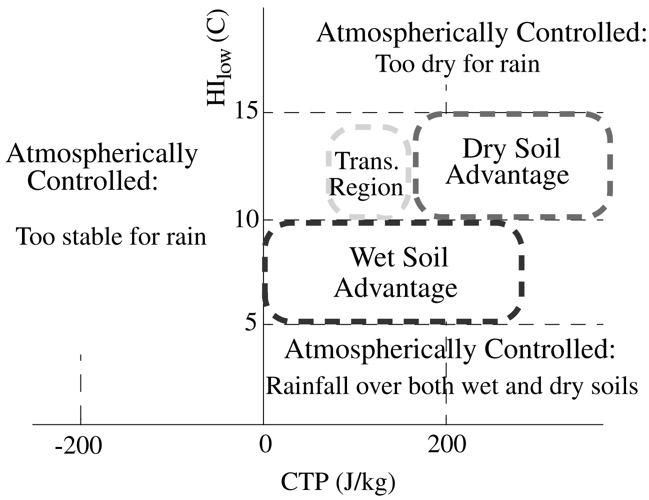

Figure 1. The CTP-HI_{low} framework for describing atmospheric controls on soil moisture-rainfall feedbacks. Only when the early morning atmosphere has CTP > 0 J/kg and $5 < HI_{low} < 15°C$ can flux partioning at the surface influence the triggering of convection. Trans Region is short for Transition Region.

[7] The CTP-HI_{low} framework is depicted in Figure 1. The CTP axis is an indicator of the temperature lapse rate between 100 and 300 mbar above the ground surface (about 1 to 3 km; see full definition in Appendix A). When the lapse rate is close to dry adiabatic, the CTP is large and areas of high sensible heat flux have an advantage in triggering convection. A smaller but still positive CTP means that the lapse rate is closer to moist adiabatic, giving areas of high latent heat flux a convective advantage. Finally, a negative CTP indicates a temperature inversion which is likely to prevent deep convection over any land surface. Examples of these conditions are presented in FE2003.

[8] The HI_{low} axis of Figure 1 is a measure of the humidity deficit in low-level air (see full definition in Appendix A). When the deficit is large, rainfall is prohibited by this atmospheric condition. When the deficit is small, the atmosphere is so close to saturation that rainfall is likely over any land surface. In between these extremes, flux

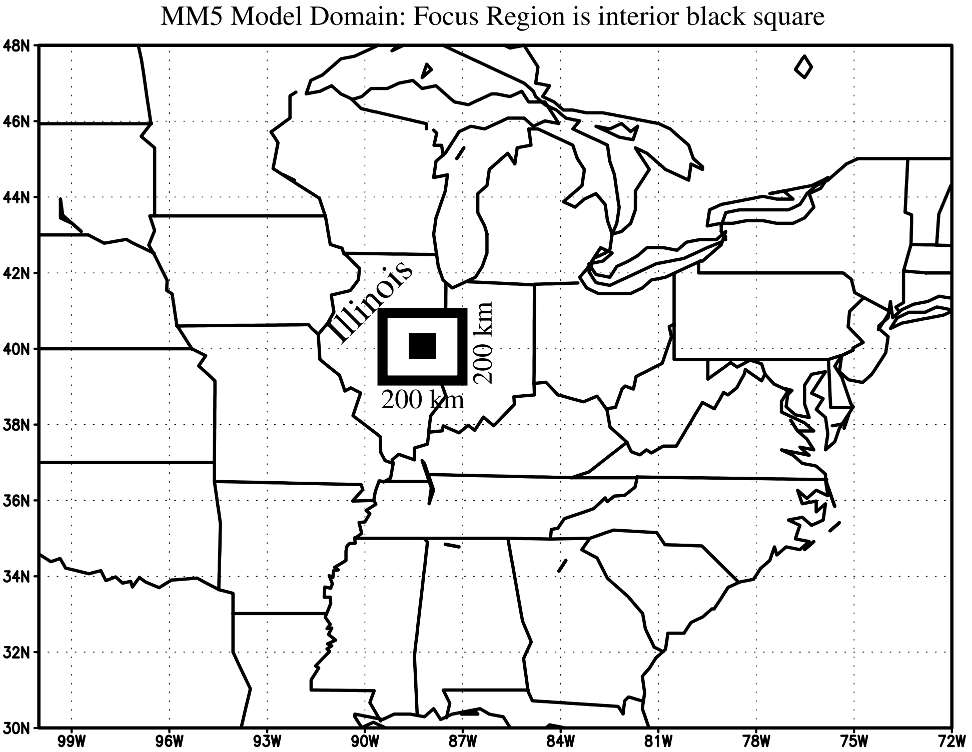

Figure 2. Model domain. Thick black line encloses full model domain (200 × 200 km); solid square covers focus region (64 × 64 km), which is entirely within the state of Illinois.

partitioning at the land surface can greatly influence the development of convection. In moderately dry atmospheres high sensible heat flux is the best trigger of convection, while in moderately humid atmospheres large contributions of humidity from the land surface can more effectively trigger convection. (See FE2003 for a more thorough description.)

[9] As briefly stated above, these descriptions of the temperature and humidity controls on land-atmosphere interactions were based on one-dimensional boundary layer modeling using individual soundings as the initial atmospheric profile. Nature, however, is three-dimensional, and the most important 3D effects are captured by the winds: the winds can also prohibit or enhance the likelihood of convection. This topic is the focus of the work presented here. In section 2 we will give a brief description of the MM5 configuration used for 3D simulations. In section 3 we will present MM5 results for the atmospherically controlled regimes of CTP-HI_{low} space, highlighting how strong wind shear can suppress convective development, while veering winds in the lowest 300 mbar can enhance it. In section 4 we focus on the Wet Soil Advantage Regime and discuss how low-level backing winds can suppress convection. In section 5 we focus on the Dry Soil Advantage Regime. Section 6 is a brief presentation of FIFE data in the context of the CTP-HI_{low} framework. Finally, a brief discussion is given in section 7, followed by the conclusions of section 8.

2. Model Configuration

[10] Three-dimensional simulations were performed using MM5, version 2.12 [*Grell et al.*, 1995]. The model runs detailed here were all run with a single-nested domain centered over Illinois (Figure 2), near the Flatland site at 40.0°N, 88.3°W [*Angevine et al.*, 1998]. The simulations were run on a 200 km by 200 km domain with a 2 km horizontal grid interval. Detailed analysis and comparisons with observations were performed on the central 64 km by 64 km portion, in order to be sufficiently far from any potential boundary effects. Boundary effects may still reach the interior of the domain, particularly at upper levels. At lower levels, however, the land surface has significant influence on BL growth and development, and it is these land surface influences that we are most interested in. Initial and boundary conditions were provided by Eta Model Assimilated Data with a horizontal grid spacing of 40 km, a temporal resolution of three hours, and 25 vertical levels. The 25 vertical levels were on constant pressure surfaces between 1000 and 25 mbar, with 25 mbar intervals in the lowest 2.0 km and at the tropopause jet level, and 50 mbar intervals in the rest of the vertical domain [*Rogers et al.*, 1995; *Black*, 1994]. Single-day simulations were initialized at 6 am using Eta Data for 98 days during the summers of 1996–1999 and run through 9 pm. The questions addressed by these simulations concerned the interactions between the early morning atmosphere and fluxes from the land surface and how these conditions impact the triggering and the amount of rainfall on a given day.

[11] The choice of 2 km as the horizontal grid interval in this study is a compromise between the desire for detailed simulations and the constraints of computational efficiency. This length is smaller than the typical scale of individual convective clouds (~5 km); hence, we resolve the scale of such basic cloud entities. Initial multi-nested runs with

outer nest grid interval ranging from 6 to 18 km on a side indicated that results were dependent on the convection scheme used. This is consistent with the work of *Pal* [1997] and *Pan et al.* [1996]. The current model configuration was designed to remove the dependence on convection schemes and explicitly resolve vertical velocities and convective motion. A few initial experiments with a 1 km grid interval in a single domain were far too computationally expensive, and did not produce significantly different results from experiments on the same days with a 2 km grid interval.

[12] MM5 was configured with twenty-three vertical levels between the 100 mbar top and the surface, including ten half-sigma levels below 0.67, which is near the top of the critical CTP region. The simulations run for this study all used the mixed phase explicit moisture scheme, which is built on *Dudhia*'s [1989] simple ice scheme, and also allows for snow and ice to exist at temperatures above zero. A modified version of the CCM2 radiation scheme [*Hack et al.*, 1993] was used. Both *Kiehl et al.* [1994] and *Hack* [1998] found the need for improvements in the treatment of clouds and their radiative properties in the CCM2 parameterization. *Hack* [1998] showed that small improvements in the cloud liquid water path and the cloud drop effective radius lead to substantial improvements in CCM2 performance. These two changes were also made in the radiation code used in this work (see *Findell* [2001] for details).

[13] The sensible and latent heat fluxes from the surface are determined by the boundary layer parameterization. The Blackadar planetary boundary layer (PBL) scheme used in MM5 is well documented by *Zhang and Anthes* [1982]. *Blackadar* [1979] made a strong argument for the need for a PBL scheme with high vertical resolution in order to adequately model the transition from well-mixed daytime conditions to stratified nighttime conditions, which are often characterized by strong gradients of temperature, wind and moisture. The MRF scheme (originally used in NCAR's Medium-Range Forecast model [*Hong and Pan*, 1996; *Troen and Mahrt*, 1986]) is quite similar to the Blackadar scheme, except in its treatment of countergradient fluxes during free convection. Early sensitivity studies showed that these MM5 experiments were not sensitive to changes between these two schemes. The results presented in this paper are for simulations with the MRF BL scheme.

[14] The version 2.x series of MM5 releases all treat soil moisture with a moisture availability term that is dependent on vegetation type and season. The moisture availability does not change with evaporation or precipitation: it is constant for the vegetation type throughout the course of a simulation. The land use type over the entire experimental domain is agriculture. The default moisture availability for this vegetation class is 30%. Results presented here show model runs with wet conditions simulated using a moisture availability of 80%, and dry conditions simulated using a value of 10%. Though this treatment is crude, it is suitable to the task at hand for a number of reasons. First, our primary concern is the response of the growing boundary layer to different fluxes from the land surface. A more intricate land surface scheme would add many unnecessary (for the purposes of this study) layers of complexity to the calculation of evapotranspiration. Second, on the time scale of 15 hours it is not unreasonable to assume that the soil moisture changes little, except in the event of rainfall over dry soils. (Clearly some drying will occur over the course of a day, but the change from the very wet to the very dry conditions that we are considering typically takes on the order of a week, if not longer.)

[15] The distribution of domain averages of initial CTP and HI_{low} from the 98 days simulated at both 10% and 80% moisture availability is not the same as the generally observed early morning CTP-HI_{low} distribution from Illinois. Sixty-eight cases were from the summer of 1996, nine were from 1997, 14 were from 1998, and seven were from 1999. Almost all days with data available from the summer of 1996 were simulated, both to cover the range of observed CTP-HI_{low} combinations and to provide ample data for the comparisons with observed rainfall. Days from other summers were specifically selected for their CTP-HI_{low} characteristics in order to better understand the behavior in each of the regimes. This led to a greater frequency of days in the dry soil advantage regime in the model runs than would typically be observed in a given summer in Illinois.

[16] The results from the simulations of these 98 days (196 simulations) are presented in the rest of this paper. Additional reduced-winds simulations were also performed over both wet and dry soils for 34 of these 98 days. In these runs, the boundary and initial winds were set to 10% of their observed values, though calculated winds in the interior of the domain were not altered. This allowed us to isolate the effects of strong winds and determine if rainfall occurrence and depth changed in a systematic and understandable manner when the influence of the winds was largely removed. Figure 3 shows the number of simulated days with initial conditions falling in each of the regimes of CTP-HI_{low} space for both the normal-wind runs and the reduced-wind runs. Figure 3 also shows how many of these cases led to rain over wet soils and how many led to rain over dry soils.

[17] Simple comparisons between atmospheric sounding data from the Flatland Boundary Layer Experiments [*Angevine et al.*, 1998] and profiles at the model grid point closest to the Flatland site showed that the observations of temperature and humidity in the boundary layer tended to fall on or between the values simulated by the wet soil and the dry soil simulations. Potential temperature was consistently well simulated, but on some days the humidity was well-mixed in the simulated boundary layers but decreased between the surface and the top of the BL in the observations. Since this behavior was not always observed in the Flatland data, and since we were not trying to re-create individual storm events, we did not tune the model to improve our simulations on these days. These comparisons suggest that the modeled BL is sensitive to changes in surface properties, and that the range of sensitivity demonstrated by the model is consistent with the range observed in Illinois.

[18] A comparison of modeled and observed rainfall for the 68 cases from 1996 is given by *Findell* [2001]. Of these 68 cases, the rainfall in 62 cases was simulated reasonably well by at least one of the two simulations for the day of interest: the r^2 between modeled-to-observed rainfall was 72.8% for the wet soil runs and 41.4% for the dry soil runs. Four of the six poor-performers were model under-estimates

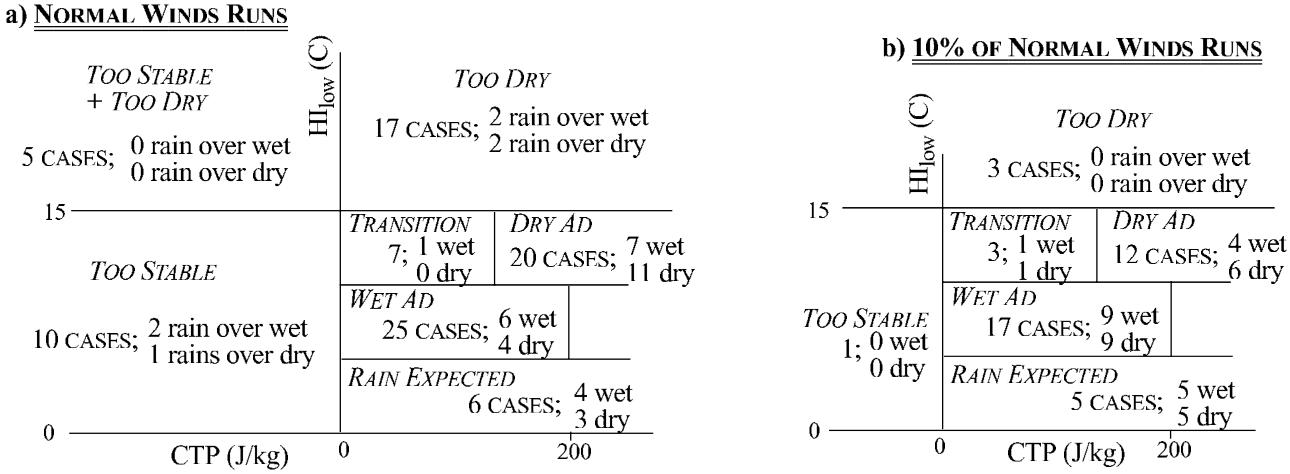

Figure 3. Number of case studies with CTP and HI_{low} characteristics in each of the regimes from Figure 1. (a) Simulations with original initial and boundary winds (supplied by Eta Model data). (b) Simulations with initial and boundary winds reduced to 10% of original values. These simulations were only run for cases that were not extremely dry and/or stable (very near the boundaries with other regimes). Wet Ad and Dry Ad are short for wet soil and dry soil advantage regimes, respectively.

(in three cases rain was already occurring at 6 am), and two were model over-estimates. The model under-estimate cases were all very high rainfall events, and were the only events in this range of rainfall observation. This suggests that the model is unable to adequately model extreme events, particularly when rainfall is already occurring at initialization time. However, the model is capable of capturing and adequately modeling nonextreme rainfall events. In addition, the model shows sensitivity to changes in soil moisture. These two suggestions allow us to go forward using the model to address questions of atmospheric controls on soil moisture-rainfall feedbacks.

3. Atmospherically Controlled Conditions

3.1. Too Dry for Rain

[19] When the early morning atmosphere is quite dry, rainfall cannot be triggered regardless of the flux partitioning at the surface. The HI_{low} cutoff value determined from the 1D work presented in FE2003 is 15°C. Most of the days that fell into this regime occurred when the domain was under a strong high pressure system. Such a system would typically be accompanied by subsidence, bringing dry, cold air from aloft down to lower levels. Indeed, this would lead to the high humidity deficits exhibited in each of these cases.

[20] The results presented in Figure 3a show that simulations of 20 of the 22 days with high humidity deficits produced no rain over wet or dry soils. (Note that some simulations fall into both the too stable and the too dry regimes.) Both of the rainy runs, V10 (domain average CTP = 261 J/kg, HI_{low} = 15.9°C) and V116 (domain average CTP = 105 J/kg, HI_{low} = 17.5°C), were relatively close to the HI_{low} cutoff value, and they were also two of the extreme events mentioned above. Run V10 had veering winds close to the surface which contribute additional buoyancy to the boundary layer air and enhance the likelihood of convection. (This effect will be discussed in detail in section 4.1.) Indeed, no rainfall occurred in an experiment with initial and boundary winds reduced to 10% of their original values. Run V116 was one of the three scenarios with observed rainfall at the time of model initialization. Each of these three cases were poorly simulated by the model. Other than these two rainy simulations, the CTP-HI_{low}-based expectations were consistent with the simulations of days in this atmospheric regime.

3.2. Too Stable for Rain

[21] When the early morning atmosphere is very stable, usually as a result of an upper air inversion (frequently with inversion base between 800 and 700 mbar), then, as in the very dry atmospheric conditions, rainfall cannot be triggered regardless of the flux partitioning at the surface. The CTP cutoff value determined from the 1D work presented in FE2003 is 0 J/kg. The results presented in Figure 3a show that of the 15 simulated days with characteristics in this regime, two had rain over wet soils and 1 had rain over dry soils.

[22] The runs that did show some convective activity all had HI_{low}s less than 7°C where, according to the one-dimensional results, shallow clouds were likely to result over wet soils (FE2003). Run V18 (domain-average CTP = −18 J/kg, HI_{low} = 6.6°C) and run V73 (domain-average CTP = −61 J/kg, HI_{low} = 5.7°C), were two of the six outliers mentioned in section 2. Run V18 was one of the three cases where the observed rainfall occurred in the morning: conditions that the model simulated poorly in all three circumstances. It is interesting to note that the modeled rainfall in run V18 occurred only over wet soils, and only in the portion of the domain where the CTP was greater than zero, consistent with the CTP-HI_{low} framework. Run V73, on the other hand, was one of the model overestimates: a day with only minimal rainfall at two of nine nearby rain gauges. Rainfall may have occurred in the simulations because there was no nocturnal stable layer at the surface in the initial condition: the boundary layer was already developed and the surface air was ready to freely convect at initialization time. This was not commonly

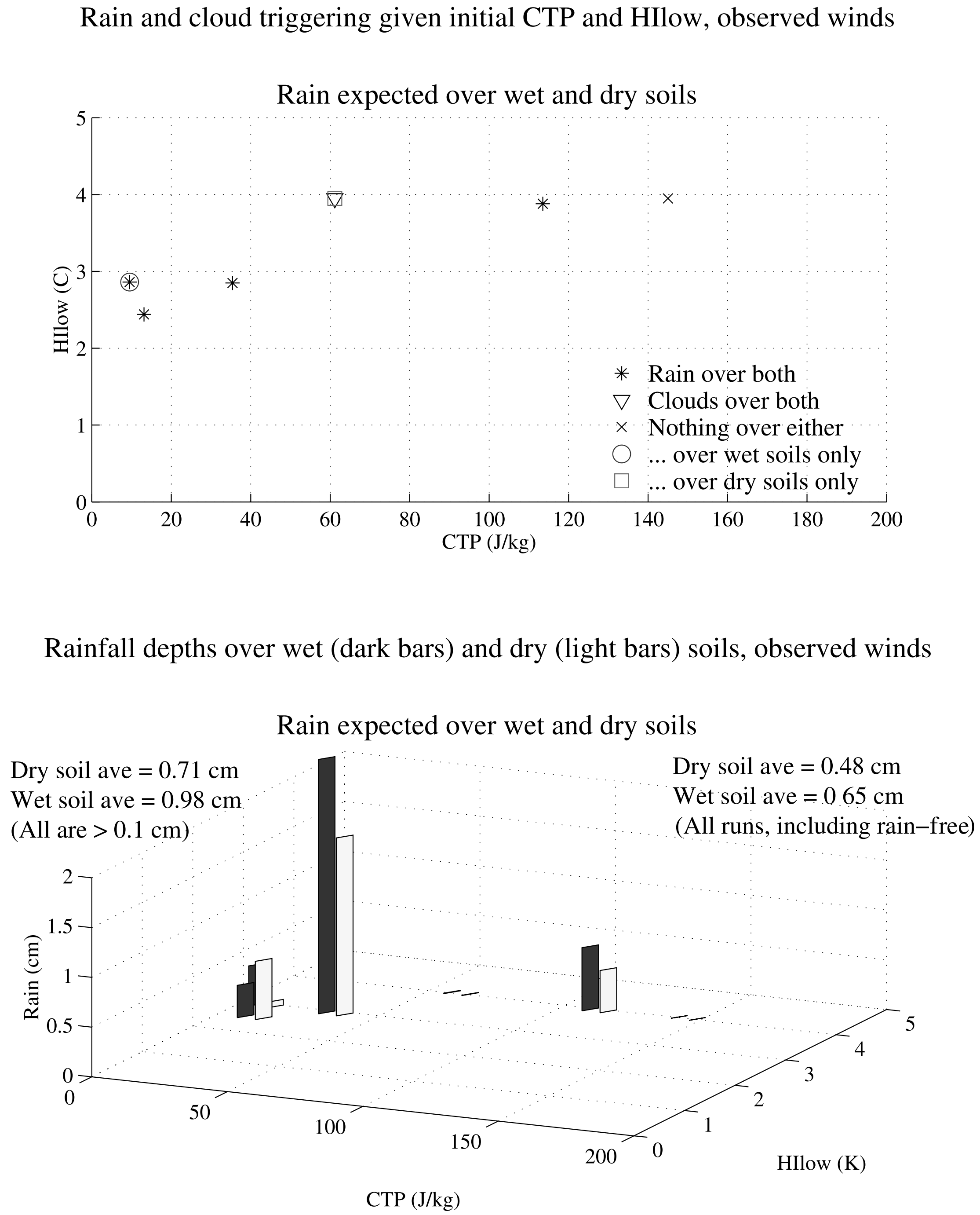

Figure 4. Outcome of the MM5 simulations with initial conditions falling in the rainfall expected region (HI_{low} < 5°C, CTP > 0 J/kg). Symbols in top plot represent rain (stars), shallow clouds (triangles), or no convection (crosses). When the symbol is surrounded by a circle, this outcome occurred over wet soils only; when surrounded by a square, this outcome occurred over dry soils only; when the symbol is not enclosed by either a circle or a square, this outcome occurred over both wet and dry soils. Bottom plot shows rainfall depths in runs with wet soils (dark bars) and in runs with dry soils (light bars).

observed in the initial conditions for these MM5 runs, and the model did not deal well with these conditions.

3.3. Rainfall Expected Regime

[23] Rainfall is expected over both wet and dry soils when the early morning atmosphere is close to saturation (HI_{low} < 5°C) and exhibits some degree of instability (CTP > 0 J/kg). Figures 3a and 4 show that the MM5 results do not fit the 1D-based expectations for this regime as closely as anticipated. Despite domain-average instability and very low humidity deficits, two of six cases show no rain over either wet or dry soils, and one rains only over wet soils. Note that the total rainfall depth was greater over wet soils than over dry soils in three of the four cases with rain. On

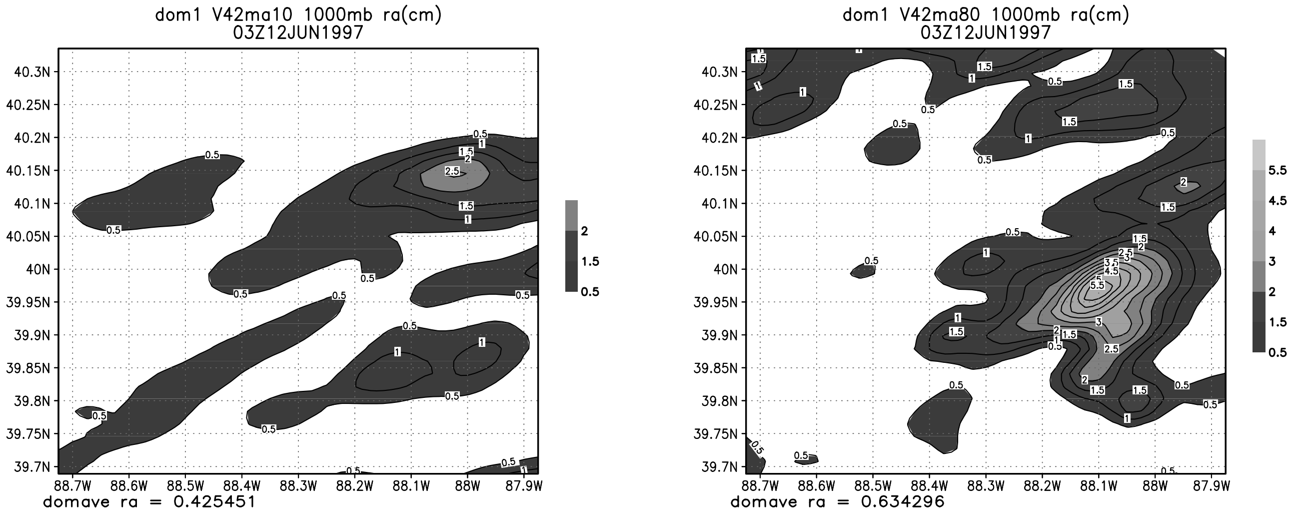

Figure 5. Total rainfall depths (cm) (left) over dry soils and (right) over wet soils in run V42 (initial sounding shown in 6; domain average CTP = 113 J/kg, HI_{low} = 3.9°C).

average, the domain-average rainfall was 0.65 cm over wet soils, but only 0.48 cm over dry soils. In the cases where rainfall occurred in at least one of the soil moisture cases, rain over the wet soils was 0.98 cm, but only 0.71 cm over the dry soils. This is consistent with the results from the 1D work showing higher CAPEs over wet soils (FE2003), since higher CAPEs are typically associated with higher rainfall depths [*Eltahir and Pal*, 1996].

[24] In the six scenarios that fall in this rainfall expected regime, the main differences between the runs with rain and those without is in the vertical profile of the winds. The next section highlights two cases to show that strongly sheared winds can suppress convection, and that veering winds can enhance convection. These two cases have similar CTP and HI_{low} values, but markedly different wind profiles. The discussion of the wet soil advantage regime results (section 4) includes specifics of cases which demonstrate that strongly backing winds can also suppress convection.

[25] Both runs V42 and V22 fall well within the interior of the rainfall expected regime of CTP-HI_{low} space, yet one ends with rainfall over much of the domain (Figure 5) and one does not. The rainy scenario, run V42 (domain average CTP = 113 J/kg, HI_{low} = 4.0°C), has gentle veering and shearing of the winds in the lowest 300 mbar and moderately shearing, unidirectional winds above 700 mbar (Figure 6). Run V22 (domain average CTP = 61 J/kg, HI_{low} = 4.5°C), on the other hand, has very strongly sheared unidirectional winds both in the lowest 300 mbar and above (Figure 7), and it fails to produce any rainfall over either land surface condition.

[26] The hodograph traces of runs V42 and V22 highlight these differences. The hypothesis that the strong shearing in V22 prohibits the development of deep convection is supported by the work of *Ziegler and Rasmussen* [1998]. They observed this in their analysis of data from the COPS (Central Oklahoma Profiler Studies project) and VORTEX (Verification of the Origins of Rotation in Tornadoes Experiment) field experiments. They found many cases where the convective initiation energy (CIN) went to zero, but convection was not triggered because of excessive wind shear. Since highly sheared winds enhance mixing between updrafts from low levels and typically drier air from higher levels, shearing tends to be accompanied by drying of the updraft air. This, in turn, will elevate the lifted condensation level (LCL) and the level of free convection (LFC), making convection more difficult to trigger. *Barnes and Newton* [1986] also note that though the slantwise organization of convection caused by pronounced wind shear creates an efficient thermodynamical-mechanical process, the precipitation efficiency of squall lines and large thunderstorms actually decreases with an increase of vertical shear. *Ziegler and Rasmussen* [1998] determined that "moist boundary layer air parcels must be lifted to their lifted condensation level and level of free convection prior to leaving the mesoscale updraft to form deep convection" (p. 1106). Furthermore, they found that "initiation of forced or active cumulus convection requires that the magnitude of the horizontal flux of dry air... be locally negligible in relation to the vertical flux of moist air in the mesoscale updraft below the LCL or LFC, respectively" (p. 1126).

[27] In the one-dimensional boundary layer modeling used to develop the CTP-HI_{low}-based expectations (FE2003), the assumed trigger for convection was CIN = 0. (Actually, triggering could even occur when CIN was slightly positive [order < 5 J/kg], since turbulence can often overcome small amounts of CIN. See *Findell* [2001] for more details.) Given the above observations from field studies, it is not surprising that there would be fewer rainy cases in the full three-dimensional simulations than predicted by this assumption. In order to study these wind effects in more detail, another set of MM5 experiments were performed where the boundary and initial winds were reduced to 10% of their actual values. Results from these runs are summarized in Figure 3b. Model-calculated winds within the domain were not altered from their calculated values: only the forcing winds were reduced. These reduced-winds runs were intended to more closely mimic the 1D simulations, since the most important 3D effect was severely minimized.

[28] Reducing the highly sheared winds in run V22 unleashed torrential (and probably unrealistic) downpours

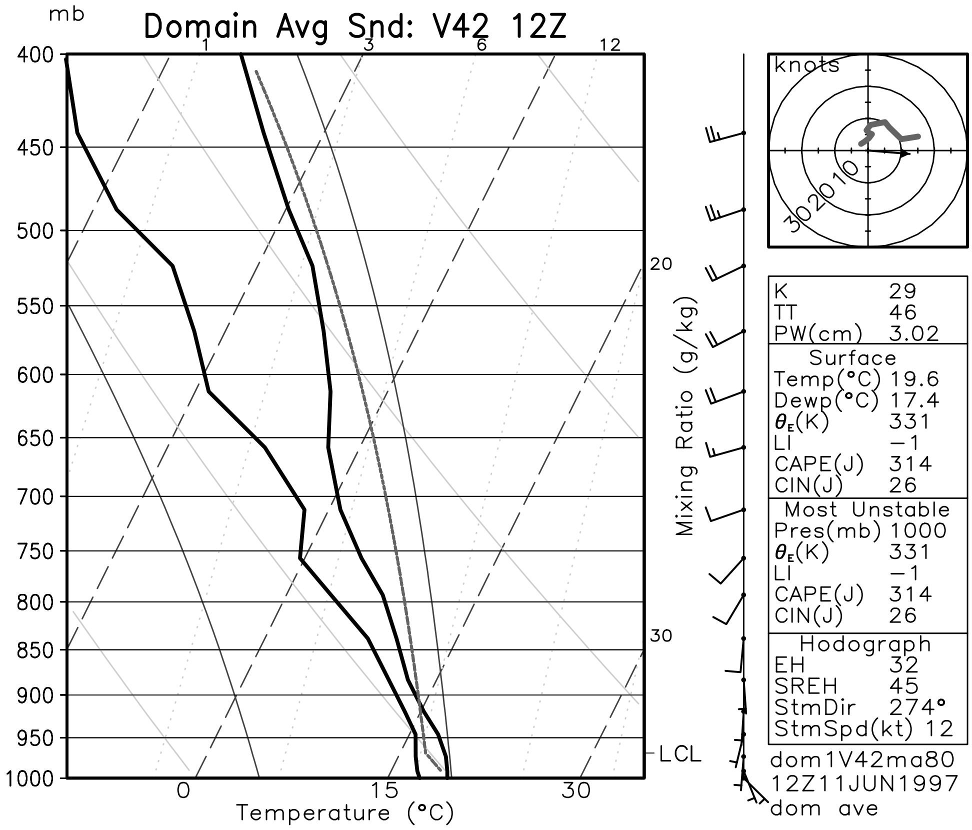

Figure 6. Initial domain average sounding for run V42 on a thermodynamic diagram. Thick solid lines are the temperature and dew point temperature profiles; thin solid lines are dry adiabats (constant potential temperature); dashed lines are constant temperature; dotted lines are constant mixing ratio; solid shaded lines are moist adiabats (constant equivalent potential temperature); and the solid line originating near the surface between the solid lines marks the trajectory of a lifted surface parcel. The hodograph tracks the winds in the lowest 300 mbar.

in both the wet and dry soil runs (not shown; domain average rainfall 3.97 cm over wet soils, 3.13 cm over dry soils). In contrast, the total rainfall in scenario V42 was actually less over wet soils in the reduced winds runs than in the normal winds runs (domain average rainfall 0.22 cm over wet soils, 0.52 cm over dry soils). This is because some degree of shear and veer is helpful for rainfall production; mild shearing allows the convective downdraft to develop downwind of the updraft, rather than directly on top of it [*Barnes and Newton*, 1986], and low-level veering winds impart additional buoyancy to rising air. (This will be discussed in more detail in the next section.) When the forcing winds were reduced, these influences were removed.

[29] Figure 8 and Table 1 show that all five of the cases from the rainfall expected regime run with reduced winds produced significant amounts of rainfall. This includes the three cases that did not rain in both soil conditions with the normal winds, and two of the three cases that produced rain over both soil moisture states. One case was not run because of the demand for computing time.

4. Wet Soil Advantage Regime

[30] Results of MM5 simulations falling in the wet soil advantage regime are summarized in Figure 9. The most striking feature of Figure 9 is the lack of convection in this regime. Based on the 1D expectations, rainfall should definitely occur over wet soils, and is likely to occur over dry soils in all of these cases. In stark contrast to these expectations, rain occurs over dry soils in only 4 of 25 cases, and over wet soils in only 6 of these 25 cases. However, as in the rainfall expected regime, when rain does occur, rainfall depths are larger over wet soils than over dry soils: domain averages of 0.64 cm versus 0.42 cm in the runs with rain over at least one of the soil moisture conditions, and 0.16 cm versus 0.11 cm when all cases are averaged. Again, this is consistent with the 1D results and with a small but significant positive soil moisture-rainfall feedback in Illinois [*Findell and Eltahir*, 1997, 1999].

[31] As mentioned in the previous section, the suppression of convection in many of the cases is due to the influence of the low-level winds. We have already provided an example and an explanation of the impact of excessive unidirectional shear on convection. Table 2 shows that there were six cases in this regime with strongly shearing winds in the lowest 300 mb. Of these six, rain did not develop at all over dry soils and in only one of the simulations over wet soils. When the boundary and initial winds were reduced to 10%, rain developed over both wet and dry soils in three of the six cases. Another means of convective suppression is

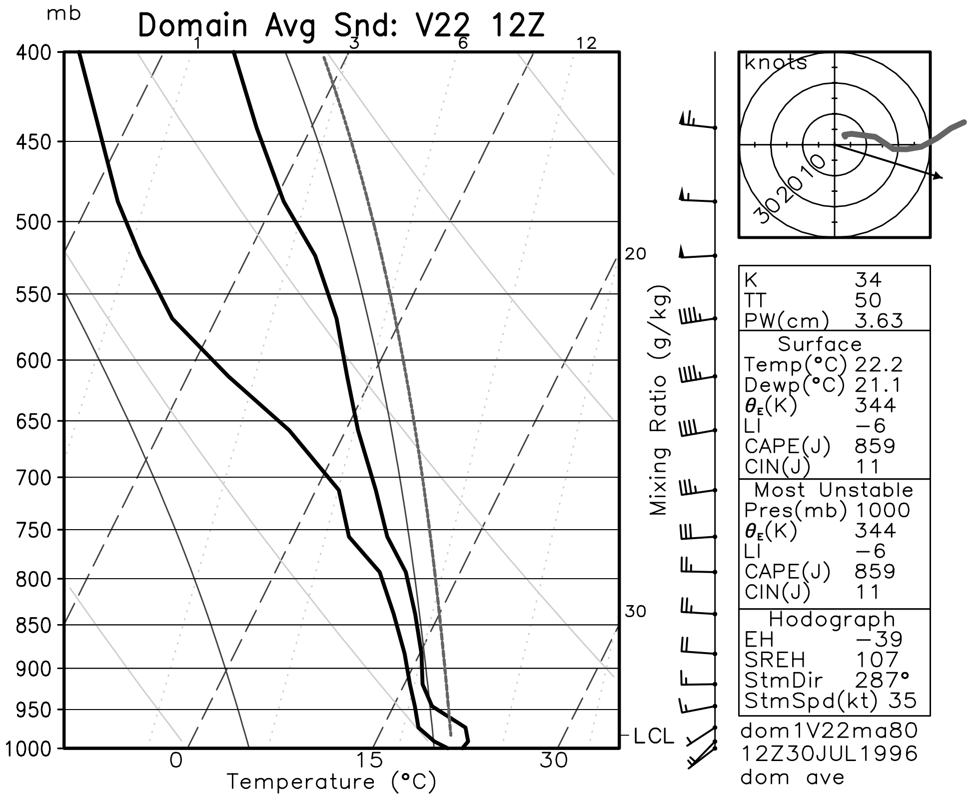

Figure 7. As in Figure 6 but for run V22.

seen when the low-level winds are backing with height. This was the case on three of the wet soil advantage regime days. We will now discuss the thermal wind equation and the impact of backing and veering winds on the buoyancy of rising air.

[32] The thermal wind equation relates the vertical shear of the geostrophic wind to the horizontal temperature gradient. (For a more complete description see, e.g., *Rogers and Yau* [1989] or *Wallace and Hobbs* [1977].) This equation tells us that the geostrophic wind is constant with height only when the potential temperature is uniform in the horizontal. Backing of the winds occurs when the geostrophic wind vector turns with increasing height in the same sense as the planetary rotation (counterclockwise in the northern hemisphere). Veering, on the other hand, is when the geostrophic wind vector rotates with increasing height in the opposite sense as the planetary rotation (clockwise in the northern hemisphere). The differential advection of temperature in different layers of the atmosphere caused by this thermal wind effect can alter atmospheric stability [see, e.g., *Wallace and Hobbs*, 1979, pp. 387–390; *Barnes and Newton*, 1986]. Backing winds indicate advection of air from the colder portion of the region defined by thermal gradients into the warmer portion. Conversely, veering winds indicate warm advection. When the turning is confined to low levels of the atmosphere, veering winds lend additional buoyancy to rising air parcels, while backing winds decrease the buoyancy. If the turning is above the LFC, then the effects on convection would be the opposite: warm advection associated with veering would act to stabilize the thermal profile, while the cold advection associated with backing would destabilize the profile. In this paper we focus on the winds between the surface and 700 mb. Preliminary analysis of thermal and moisture advection associated with veering and/or backing in these lowest 300 mbar bears no relationship to advection above these levels. Variability in the wind speed and direction at all levels may influence convection; in this work we focus on the lowest levels in an attempt to understand the cases that are strongly influenced by wind behavior in the critical CTP region. Wind effects outside of this region may also be important. The wind effects described in this paper explain the behavior in about half of the cases that do not conform to the 1D-based CTP-HI_{low} framework.

[33] Figure 10 shows the 300 mbar hodographs for the three cases in the wet soil advantage regime where the winds in the lowest 300 mbar clearly back with height (Table 2). Since low-level backing winds are associated with cold air advection and a decrease of buoyancy, reducing the initial and boundary winds allows rising parcels to maintain their surface buoyancy, thereby increasing the convective activity. In two of the cases, no convection developed over wet or dry soils with these observed winds, while rain developed over both soil conditions in the reduced-winds runs. In the third case rainfall still developed over both wet and dry soils (1.02 cm over wet, 0.31 cm over dry). However, as in the other cases with backing winds, removing the negative effect of the winds allowed even more rain (perhaps unrealistic amounts of rain) to develop (3.98 cm over wet, 2.99 cm over dry).

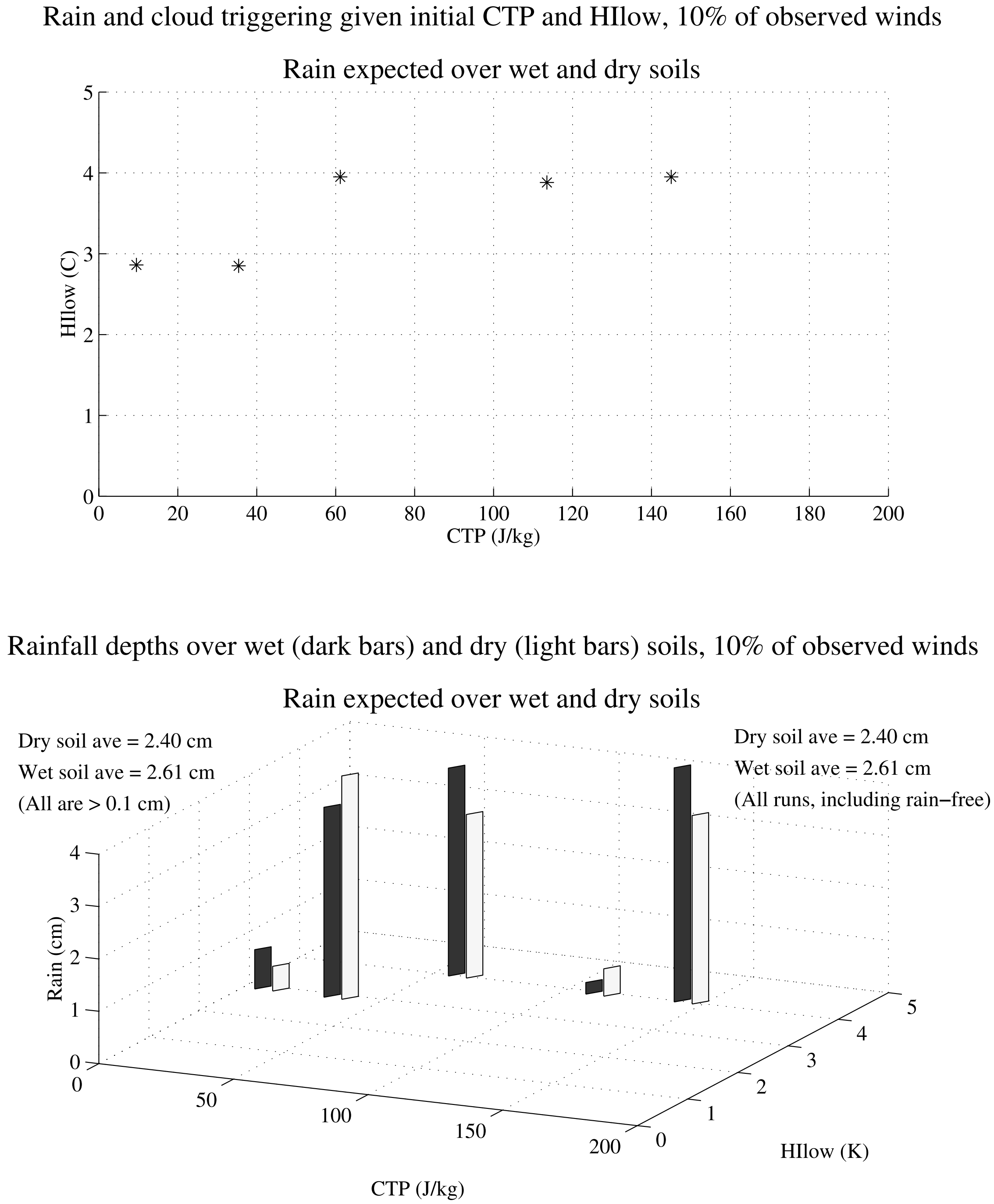

Figure 8. As in Figure 4 but for runs with reduced winds. Only five of the original six simulations were performed. Symbols in top plot are as in Figure 4.

Table 1. Results of MM5 Simulations in the Five Rainfall Expected Regime Cases Run in Both Wind Conditions

Wind Condition[a]	Run ID	Normal Winds	10% Winds
Shearing	V22	neither rain	both rain (4 cm wet; 3.1 cm dry)
Shearing	V61	neither rain	both rain (4.5 cm wet; 3.6 cm dry)
Veering	V42	both rain (0.6 cm wet; 0.4 cm dry)	both rain (0.2 cm wet; 0.5 cm dry)
Weak (<10 knots) and/or highly variable	V50	both rain (2.6 cm wet; 1.8 cm dry)	both rain (3.6 cm wet; 4.3 cm dry)
Weak (<10 knots) and/or highly variable	V87	rain over wet soils (0.4 cm)	both rain (0.8 cm wet; 0.5 cm dry)

[a]Wind descriptors refer only to the lowest 300 mbar.

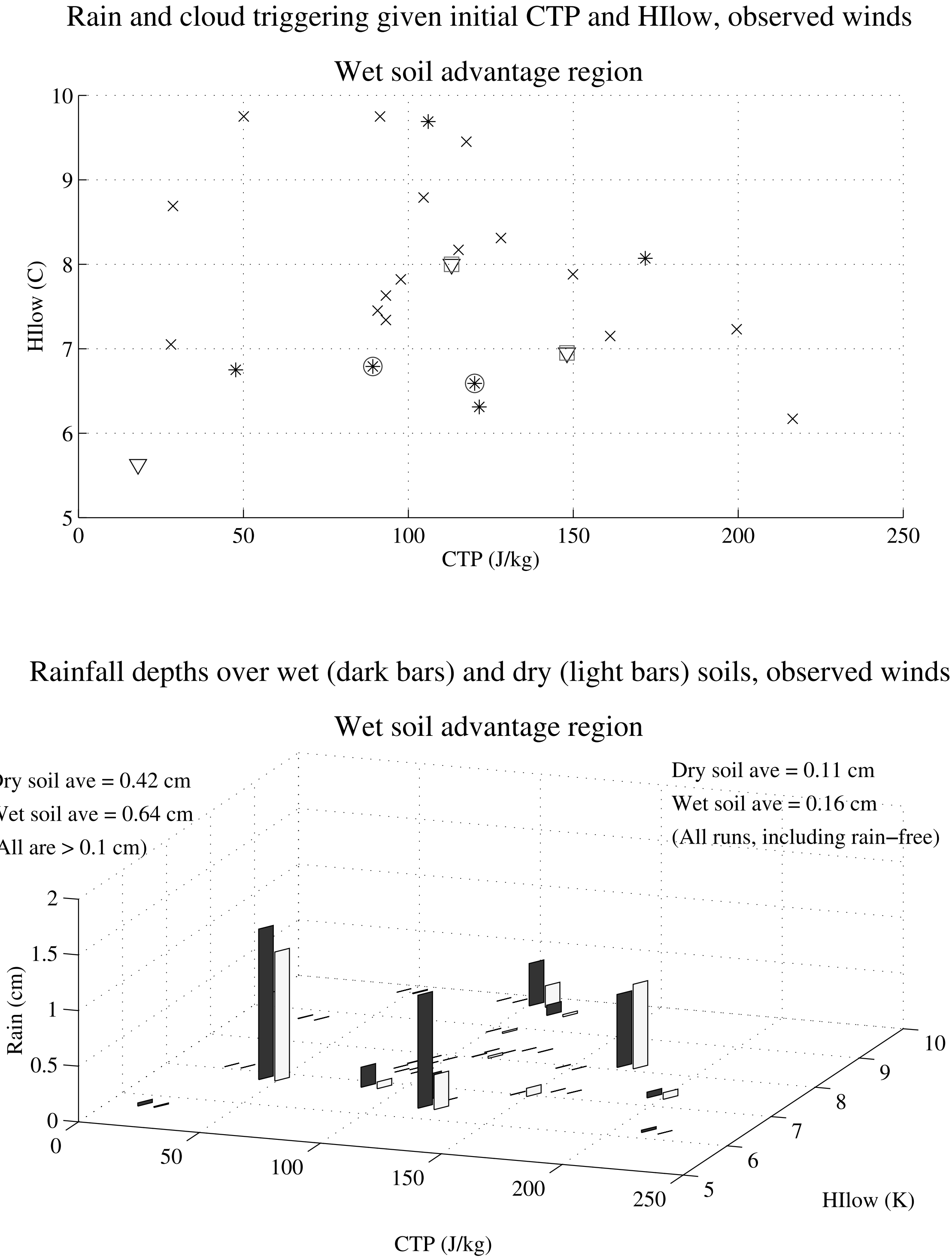

Figure 9. Outcome of the MM5 simulations with initial conditions falling in the wet soil advantage regime. Symbols in the top plot are as in Figure 4.

[34] Though the low-level winds of run V43 veer, their speed reaches 30 knots and no rainfall occurs over either soil condition. The analysis of FIFE data presented in section 6 show 30 knots as a threshold value where the influence of the shear in suppressing convection is more important than the influence of the low-level veer in enhancing convection.

[35] Many other cases in this wet soil advantage regime are also limited in their production of rainfall by the observed winds. As shown in Table 2, however, the wind profiles in most of these cases are highly variable and difficult to classify. The winds in run V30, for example, veer from the surface to about 950 mbar, shear from there to about 890 mbar, then slow to about 800 mbar, and then begin to back while continuing to slow. The processes described in this paper do not address these more complicated wind conditions. Figure 11 shows the results of all the

Table 2. Results of MM5 Simulations in the 17 Wet Soil Advantage Regime Cases Run in Both Wind Conditions

Wind Condition[a]	Run ID	Normal Winds	10% Winds
Backing	V38	neither rain	both rain (1.2 cm wet; 0.7 cm dry)
Backing	V58	neither rain	both rain (5.1 cm wet; 4.6 cm dry)
Backing	V95	both rain (1 cm wet; 0.3 cm dry)	both rain (4 cm wet; 3 cm dry)
Shearing	V37	rain over wet soils (0.2 cm)	both rain (1.6 cm wet; 1.8 cm dry)
Shearing	V39	neither rain	both rain (2.1 cm wet; 1.1 cm dry)
Shearing	V40	neither rain	both rain (0.4 cm wet; 0.2 cm dry)
Shearing	V69	neither rain	neither rain
Shearing	V86	neither rain	neither rain
Shearing	V88	neither rain	neither rain
Veering but with wind speeds >30 knots	V43	neither rain	neither rain
Weak (<10 knots) and/or highly variable	V24	neither rain	both rain (0.7 cm wet; 1.3 cm dry)
Weak (<10 knots) and/or highly variable	V30	neither rain	neither rain
Weak (<10 knots) and/or highly variable	V41	neither rain	neither rain
Weak (<10 knots) and/or highly variable	V62	both rain (0.4 cm wet; 0.2 cm dry)	both rain (0.6 cm wet; 0.6 cm dry)
Weak (<10 knots) and/or highly variable	V71	both rain (0.7 cm wet; 0.8 cm dry)	both rain (6.2 cm wet; 5.9 cm dry)
Weak (<10 knots) and/or highly variable	V82	neither rain	neither rain
Weak (<10 knots) and/or highly variable	V85	neither rain	neither rain

[a]Wind descriptors refer only to the lowest 300 mbar.

reduced-wind simulations from this regime. Rainfall frequency and depth are both significantly increased by removing the winds, and average rainfall depths remain greater over wet soils than over dry soils (1.22 cm versus 1.07 cm).

5. Dry Soil Advantage Regime

[36] The results of the observed winds simulations for cases in the dry soil advantage regime are presented in Figure 12 (see also Figure 3 and Table 3). Figure 12 shows that rainfall is triggered more frequently over dry soils than over wet, as anticipated (eleven times versus seven times). Additionally, the average rainfall depths no longer favor wet soils: they are now essentially equal at 0.26 cm over wet soils and 0.24 cm over dry soils. Five of the seven cases where rain occurs over both soil types have more rainfall over wet soils, but in two cases the rainfall depth is greater over dry soils, and in four additional cases rainfall only occurs over dry soils. As predicted by the 1D modeling work, triggering can occur over both wet and dry soils in this regime, but is more likely over dry soils since boundary layers over dry soils are more likely to reach the neutrally bouyant layers which yield the high CTP. In the five cases where rainfall was greater over wet soils, the boundary layer over both soil conditions reached this neutrally buoyant layer. In the six cases with more rainfall over dry soils, the boundary layer over the wet soils did not grow high enough early enough in the day to benefit from the high CTP zone, though in two of these cases there were small pockets of rain over wet soils.

[37] Run V90 is a good example of the advantage that boundary layers growing over dry soils have in these high CTP environments. The domain-average initial sounding (Figure 13) shows an extensive zone between 945 mbar and 710 mbar with a lapse rate that is nearly dry adiabatic. The domain-average CTP and HI_{low} in this case are 282 J/kg and 13.7°C, respectively. Figure 14 shows that six hours into the run (local noon), the boundary layer has grown to 3.5 km over dry soils but only to 2 km over wet soils. This allows for convection to occur over the dry soils, but not over the wet, despite the 7°C difference in the surface θ_E between the two simulations at local noon. Clouds have already developed and free convection has already begun at this time

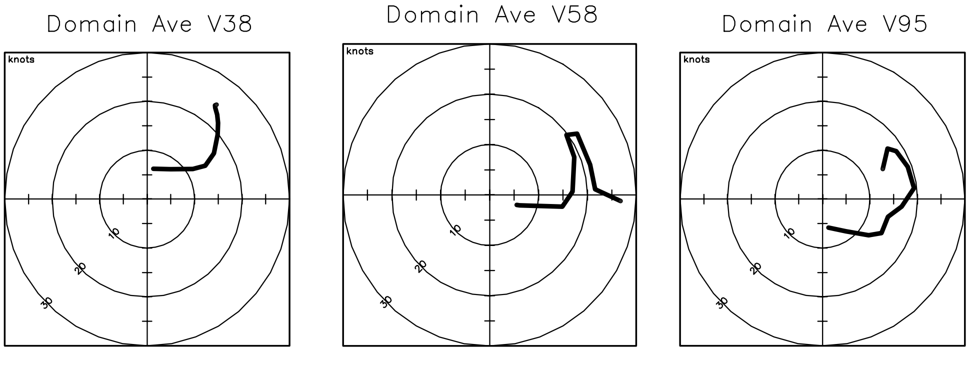

Figure 10. Hodographs to 300 mbar above ground surface (AGS) for three cases in the wet soil advantage regime where reduction of the initial and boundary winds increased the convective activity. In all three cases the winds back with height, and in all three cases, convective activity was greater in the reduced-winds runs than in the observed winds runs. See text for more information.

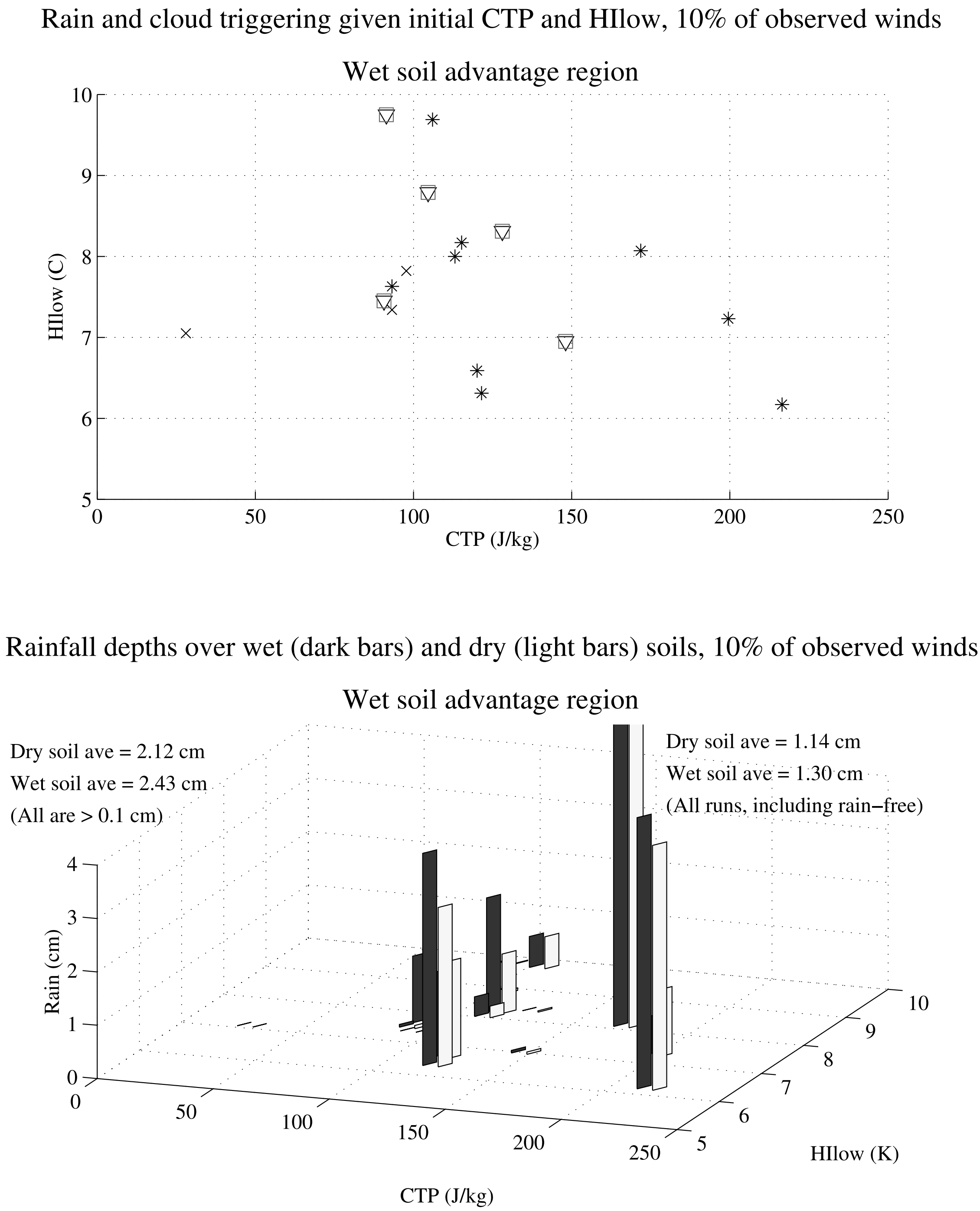

Figure 11. As in Figure 9 but for reduced winds.

over dry soils. Over wet soils, however, surface parcels could not reach their level of free convection at noontime, and Figure 14 shows that the boundary layer did not grow any deeper and θ_E did not increase from the noontime values until after the evening collapse of the BL. Thus the higher boundary layer growth over dry soils allowed for convective triggering, while the high moist static energy in the BL over wet soils was not large enough to trigger convection in this high CTP environment.

[38] As in the wet soil advantage regime, wind effects played an important role in the production of rainfall in the dry soil advantage regime, though there are fewer clear-cut examples of the wind effects described in the previous sections. Of 12 reduced-winds simulations from this region, three of the runs showed decreased convective activity when the initial and boundary winds were reduced to 10% of observations (Table 3). In each of the runs with less convection than their normal-wind counterpart (V9, V20, and V25), the original winds veered with height, but only V20 could be described by this veer alone. In run V9 the wind speeds reached a maximum at only 10 knots, placing it in the weak winds category. Run V25 only veered in the

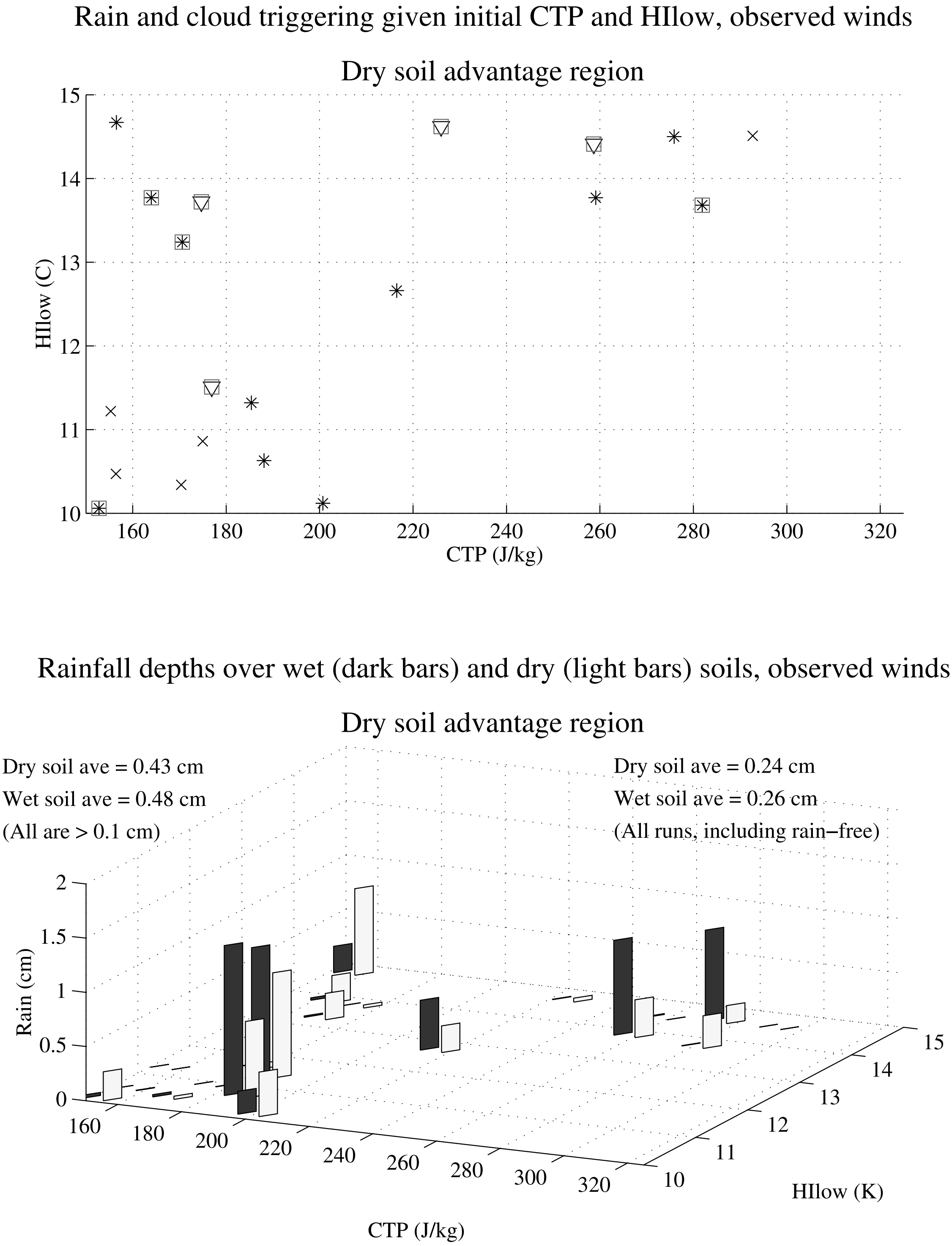

Figure 12. Outcome of the MM5 simulations with initial conditions falling in the dry soil advantage regime. Symbols in the top plot are as in Figure 4.

lowest 50 mbar, and based on the behavior of the other three examples with winds like this (V36, V44, V89), it is not clear that this is deep enough veering to impart the additional buoyancy required to trigger convection. There were a few cases with increased convection in the reduced-winds runs. In run V33 the original winds backed with height, while the winds in run V44 veered in the lowest 50 mbar and then sheared, and the winds in run V34 were highly variable and difficult to categorize. Run V21 had shearing low-levels winds and produced no rainfall in the normal-winds runs; in the reduced-winds runs, there was a trace amount of rainfall in the dry soil simulation. It is encouraging that the results in the easily categorized cases, particularly Runs V33 and V20, met expectations. More research

Table 3. Results of MM5 Simulations in the 12 Dry Soil Advantage Regime Cases Run in Both Wind Conditions

Wind Condition[a]	Run ID	Normal Winds	10% Winds
Backing	V33	neither rain	rain over dry soils (0.2 cm)
Shearing	V21	neither rain	neither rain
Veering but with wind speeds >30 knots	V27	neither rain	neither rain
Veering in lowest 50–100 mbar, then unidirectional; stays under 20 knots	V25	rain over dry soils (0.3 cm)	neither rain
Veering in lowest 50–100 mbar, then unidirectional; stays under 20 knots	V36	neither rain	neither rain
Veering in lowest 50–100 mbar, then unidirectional; stays under 20 knots	V44	neither rain	both rain (0.2 cm wet; 0.7 cm dry)
Veering in lowest 50–100 mbar, then unidirectional; stays under 20 knots	V89	neither rain	neither rain
Veering	V20	rain over dry soils (0.3 cm)	neither rain
Weak (<10 knots) and/or highly variable	V9	both rain (0.5 cm wet; 0.2 cm dry)	rain over dry soils (0.1 cm dry)
Weak (<10 knots) and/or highly variable	V19	both rain (0.2 cm wet; 0.4 cm dry)	both rain (0.2 cm wet; 0.1 cm dry)
Weak (<10 knots) and/or highly variable	V34	rain over dry soils (0.2 cm dry)	both rain (0.2 cm wet; 0.5 cm dry)
Weak (<10 knots) and/or highly variable	V45	both rain (0.9 cm wet; 0.3 cm dry)	both rain (2.5 cm wet; 2.0 cm dry)

[a]Wind descriptors refer only to the lowest 300 mbar.

is needed to fully understand the behavior in the cases with more complicated low-level winds.

6. Analysis of FIFE Observations

[39] The First International Satellite Land Surface Climatological Project (ISLSCP) Field Experiment (FIFE) was an internationally coordinated project conducted in Kansas during the summers of 1987 and 1989 [*Sellers et al.*, 1992]. There were 38 days with early morning radiosonde profiles, soil moisture measurements and rainfall observations. These 38 days provide the opportunity for testing the theory of the CTP-HI_{low} framework on observations. As this section will show, however, more data are needed.

[40] The 38 days were divided into three groups based on observed soil moisture values. The bounds between the groups were determined by the mean ±1 standard deviation. These categories are therefore relative to the available observations and do not precisely match the format of the MM5 experiments described in the earlier sections of this paper.

[41] Figure 15 shows that none of the days with low soil moisture fall into the dry soil advantage regime of CTP-HI_{low} space, and only two high soil moisture days fall into the wet soil advantage regime. Additionally, there are only

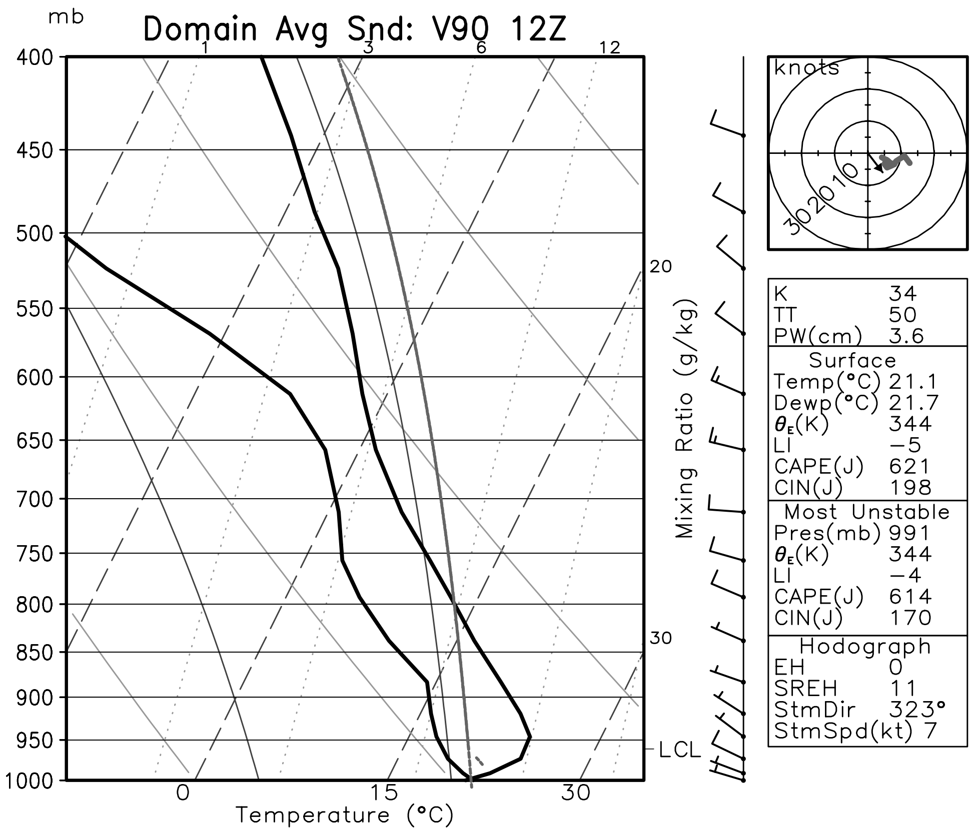

Figure 13. As in Figure 6 but for run V90.

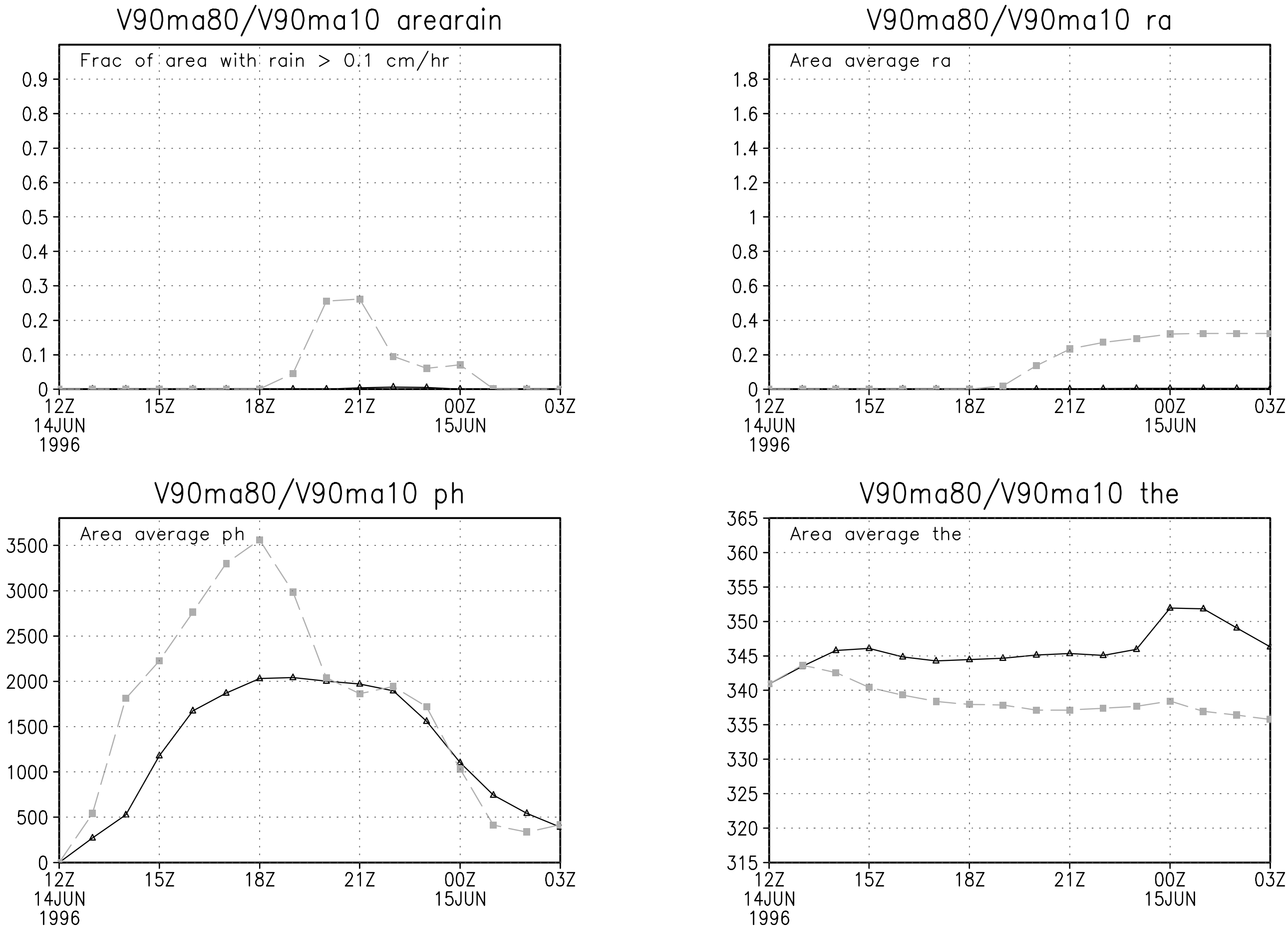

Figure 14. Time series of (top left) fractional coverage of rainfall, (top right) cumulative rainfall depth (in cm), (bottom left) planetary boundary layer height (in m), and (bottom right) surface θ_E (in K) in the wet soil (solid lines) and dry soil (dashed light lines) simulations for case V90.

six days with rainfall greater than 5 mm (averaged over as many as 42 rain gauges), and four of these six have an HIlow significantly larger than 15°C. However, each of these four days had low-level veering winds. As explained in section 4.1, this should enhance buoyancy and help overcome the high humidity deficit. Indeed, five days had winds that veered in the lowest 300 mbar at speeds under 30 knots, and rainfall occurred on all of these days, though on

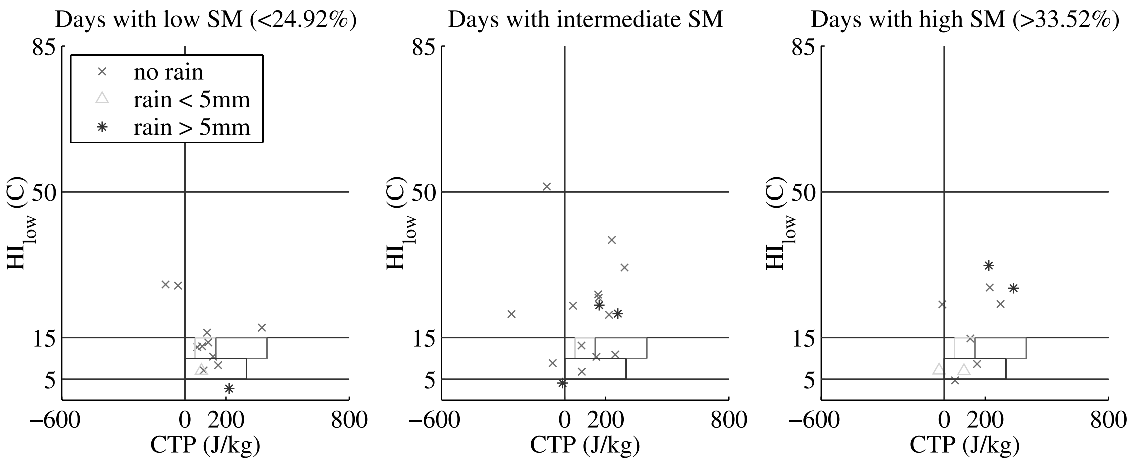

Figure 15. CTP, HI_{low}, and area-average rainfall for days with (left) low, (middle) intermediate, and (right) high soil moisture. Crosses indicate no rain, triangles indicate rain <5 mm, and stars indicate rain >5 mm.

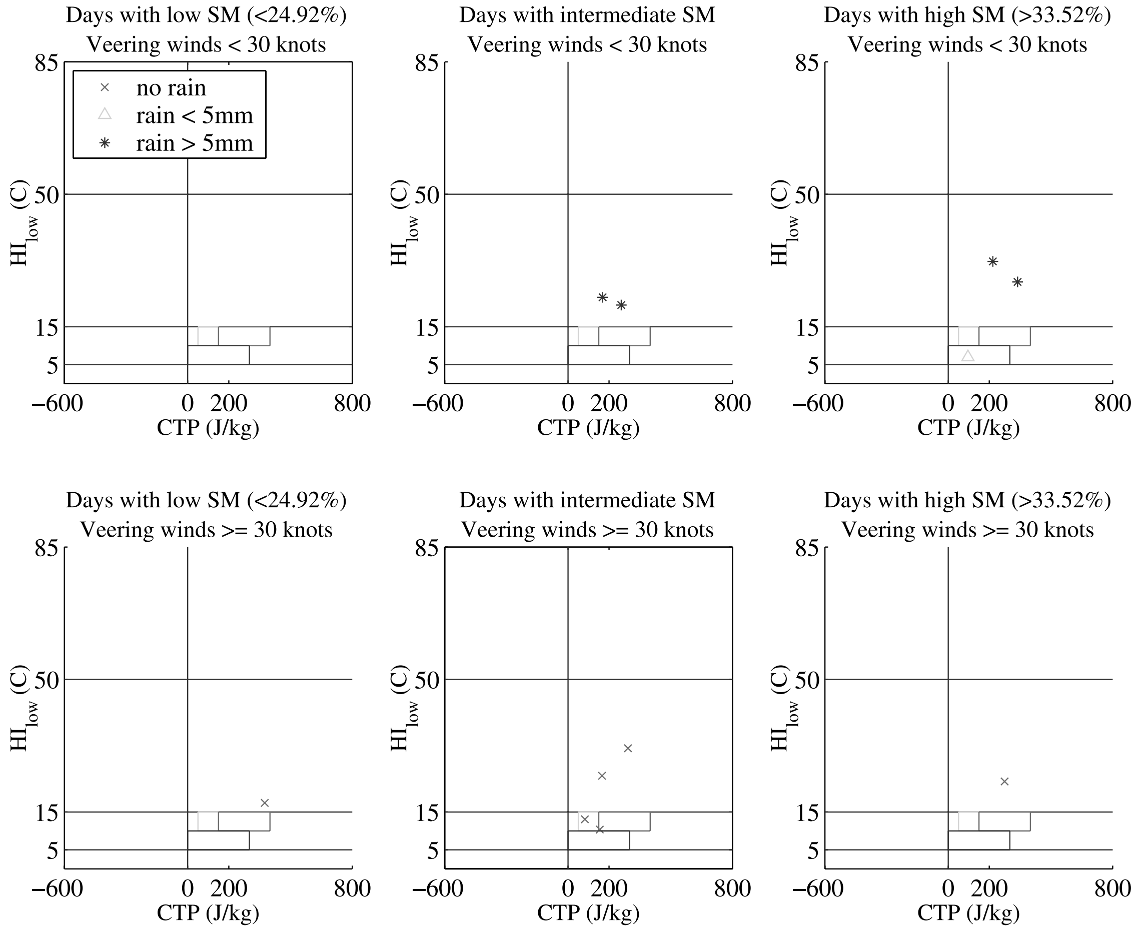

Figure 16. As in Figure 15 but only for those days with veering winds. Top row of plots is for those days with veering winds <30 knots; bottom row is for those >30 knots.

one day the site-wide average was less than 5 mm (Figure 16, top row). There were six days with veering winds that exceeded 30 knots, and no rainfall was observed on any of these days (Figure 16, bottom row). Example hodographs from each of these veering wind conditions are shown in Figure 17.

[42] Similarly, there were a number of days with low-level backing winds where rainfall does not occur, even though the CTP and HI_{low} values indicate a high likelihood of rain. Of the 13 days with backing and/or strongly shearing winds, none showed significant rainfall, though there were two with <5 mm (Figure 18). Figure 19 shows hodographs from two of these 13 days.

[43] Of the eight remaining days (Figure 15), five are in one of the CTP-HI_{low} regions where rainfall is not expected, and no rain occurred on any of these days. The other three are in or on the border of the positive CTP/low HI_{low} regime where rainfall is expected; rainfall greater than 5 mm occurred on two of these days.

[44] These results are consistent with the earlier discussion (sections 3.3.1 and 4.1) of the effects of strongly sheared winds and of the directional changes with height described by the thermal wind equation. They highlight two important points: 1) more data are needed to adequately test the theory, and 2) low-level wind effects are crucial to the triggering of rainfall and to the understanding of land surface impacts on rainfall triggering and depth: the vertical structure of the winds form the basis for a crucial third dimension in the CTP-HI_{low} framework.

7. Discussion

[45] Though convection occurred less frequently than anticipated, the general picture created from the MM5 simulations is consistent with the CTP-HI_{low} framework, as long as the structure of the low-level winds is considered. In the regime where dry soils were expected to have an advantage, convection was triggered over dry soils more often than over wet; in the regime where wet soils were expected to have an advantage, convection was more frequently triggered over wet soils than over dry. Additionally, when rainfall occurred in both the wet soil and dry soil simulations for a given day, rainfall depths were typically greater over wet soils. The limited data from FIFE support the MM5-based conclusions that backing and strongly sheared winds suppress convection, while veering winds enhance convection. However, there are not enough data to fully test the CTP-HI_{low} framework.

[46] It is relevant to note the relationship between these results and the work that originally inspired this investigation of atmospheric controls on soil moisture-rainfall interactions. *Findell and Eltahir* [1997] found a small but

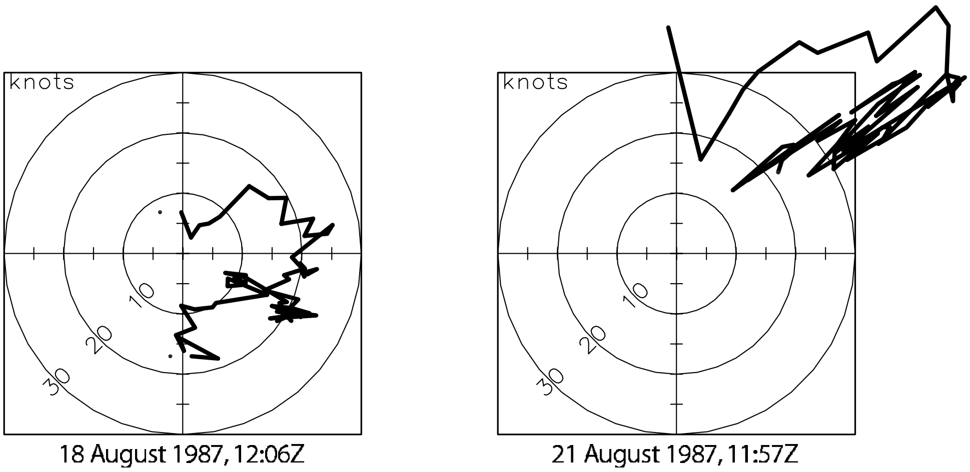

Figure 17. Hodographs (bottom 300 mbar) for 18 August 1987 (winds veer but stay under 30 knots; CTP = 217 J/kg; HI_{low} = 32°C; soil moisture = 37%; rain = 6.3 mm) and for 21 August 1987 (winds veer at speeds greater than 30 knots; CTP = 292 J/kg; HI_{low} = 32°C; soil moisture = 27%; rain = 0.0 mm).

significant positive feedback between soil moisture and rainfall in Illinois. Expanding on this work, *Findell and Eltahir* [1999] used near-surface atmospheric data and found a significant correlation between soil moisture and wet-bulb depression, T_{dpr}, and then between T_{dpr} and subsequent rainfall. They did not, however, find a significant correlation between soil moisture and wet-bulb temperature, T_w, or between T_w and subsequent rainfall.

[47] The current results seem to be consistent with these findings. HI_{low} should be closely correlated with T_{dpr}, since

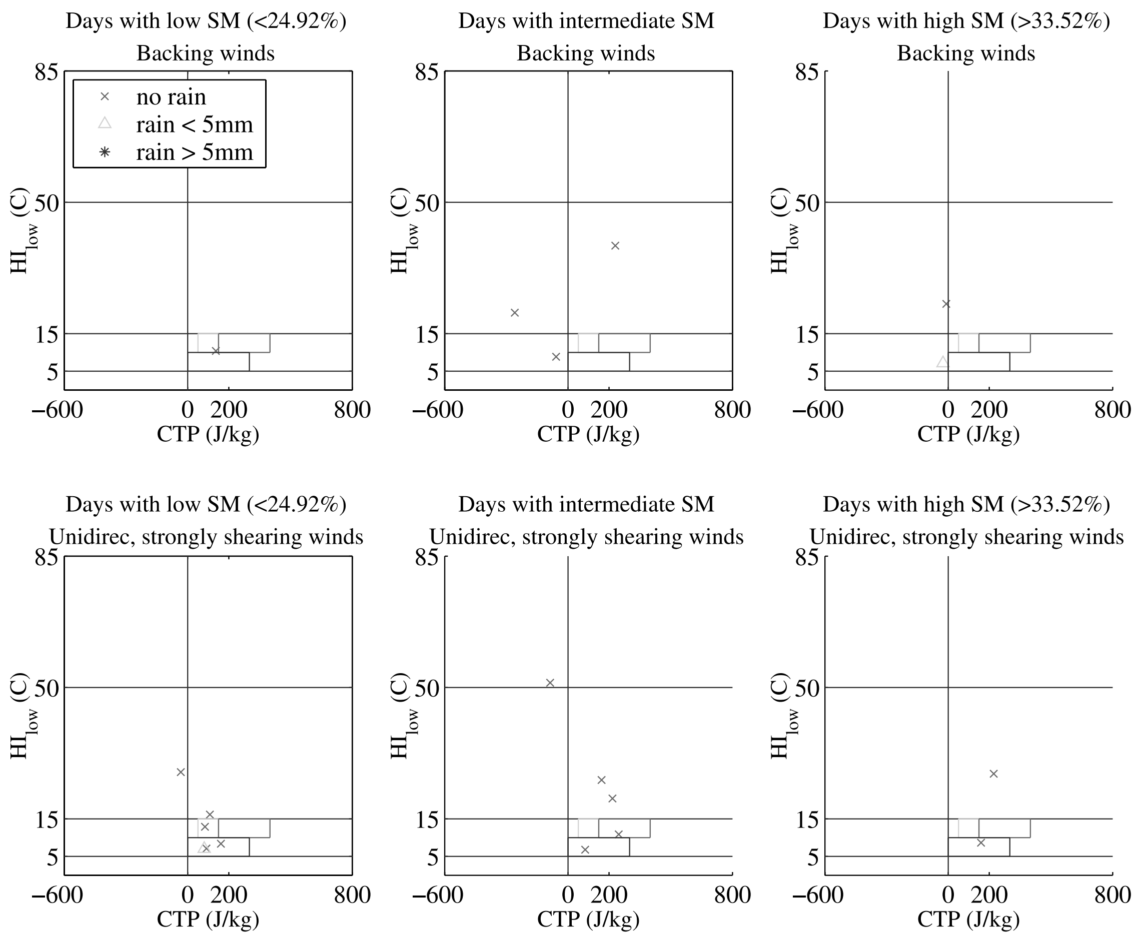

Figure 18. As in Figure 15 but only for those days with (top) backing or (bottom) strongly shearing unidirectional winds.

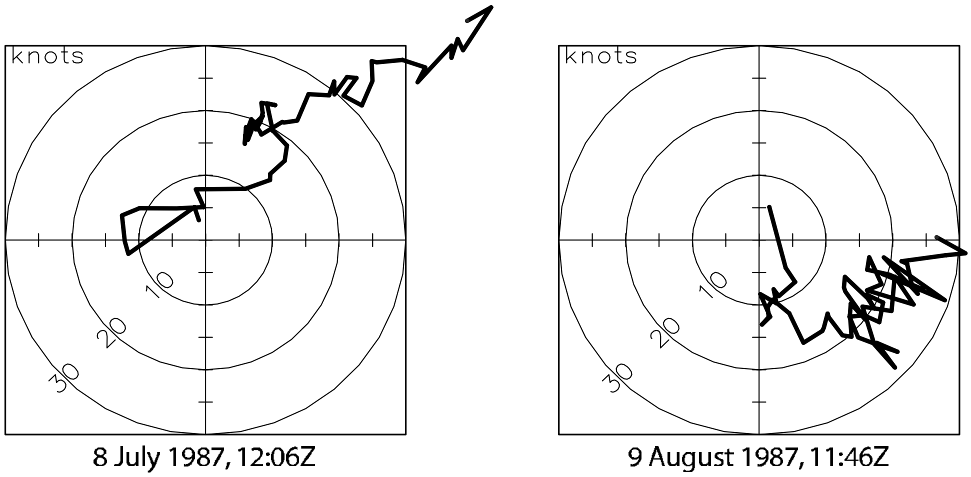

Figure 19. Hodographs (bottom 300 mbar) for 8 July 1987 (rain = 0.07 mm; strong low-level shear; CTP = 247 J/kg; HI_{low} = 11°C; soil moisture = 33%) and for 9 August 1987 (rain = 0.0 mm; strong low-level backing of the winds; CTP = −58 J/kg; HI_{low} = 9°C; soil moisture = 30%).

it considers the dew point depression at relatively low levels (specifically 950 mbar and 850 mbar). Given the importance of HI_{low} in the current results, it is not surprising that the surface wet-bulb depression is also a helpful indicator of the link between the land and the atmosphere. The wet-bulb temperature, on the other hand, is a measure of the surface energy, much like θ_E. The current work shows that the surface energy alone is not enough to determine either the potential for rainfall or the impact of the surface moisture on this potential. The CTP is helpful in both of these determinations because it considers the temperature profile well above the surface, and because it focuses on the portion of the atmosphere that is between the region that is almost always incorporated into the growing boundary layer and the portion of the free atmosphere that is almost never incorporated into the growing BL.

8. Conclusions

[48] General conclusions about the CTP-HI_{low} framework are threefold: (1) The convective triggering potential (CTP) offers significant information regarding the likely impact of the land surface condition on the potential for rainfall, particularly when coupled with a measure of the humidity in the lowest levels of the atmosphere (e.g., HI_{low}). (2) The land surface condition can impact the potential for convection only when the atmosphere is not already predisposed to convect or not to convect. This atmospheric predisposition can be determined by analyzing the CTP, the HI_{low}, and the vertical profile of the winds. (3) Areas such as Illinois exhibit a small but significant positive feedback between soil moisture and rainfall because the frequency of days falling in the wet soil advantage regime of CTP-HI_{low} space exceeds the frequency of days falling in the dry soil advantage regime.

[49] Additional insight is gained by adding an analysis of low-level winds: (1) Wind effects play a crucial role in the development of convection. Winds that are backing or strongly shearing in the lowest 300 mbar can suppress convective potential. Due to this suppression of convection in certain wind conditions, rain occurred in far fewer MM5 simulations and on far fewer days at the FIFE site than would be anticipated based solely on the 1D framework of understanding. (2) In contrast, winds that veer in the lowest 300 mbar without too much shear (wind speeds remain <30 knots) enhance the buoyancy of rising air and increase the likelihood of rainfall. This effect was particularly noticeable in the FIFE data, where rainfall occurred on all five days with low-level veering winds under 30 knots, even with high humidity deficits in four of the cases. (3) Variability in the wind speed and direction at all levels may influence convection; in this work we focused on the lowest levels in an attempt to understand the cases that are strongly influenced by wind behavior in the critical CTP region. Wind effects outside of this region may also be important. The wind effects described here explain the behavior in about half of the cases that do not conform to the 1D-based CTP-HI_{low} framework. More research is needed to fully understand the behavior in the cases with more complicated low-level winds. Further research into the effects of middle and upper level winds is underway.

[50] These conclusions are based on MM5 simulations with homogeneous soil moisture throughout the domain. Therefore they do not address mesoscale circulations induced by abrupt land use and land surface contrasts. The scale of these processes therefore may be at least partially determined by the scale of relative homogeneity at the ground. When large regions of the continent experience flood or drought conditions, the processes described by the CTP-HI_{low}-wind effects framework are expected to dominate land-atmosphere interactions. When soil moisture conditions are less extreme, these processes are expected to be an instrumental tool to help understand the interactions between the land surface soil moisture and/or vegetative condition and the development of rainfall.

[51] The nature of the atmospheric structure in the critical region of the troposphere assessed by the CTP, about 1 to 3 km above the ground surface, determines the manner in which soil moisture can impact rainfall. A positive feedback is likely when the temperature profile in this region is close to moist adiabatic. In these circumstances, convection is most easily triggered by increasing boundary layer moist

static energy (MSE) because this greatly reduces the level of free convection. The high latent heat flux over wet soils increases the BL MSE more than the smaller latent heat flux over dry soils. A negative feedback is likely when this region has a temperature profile close to dry adiabatic. In these circumstances, convection is most easily triggered by increasing the height of the BL: a process requiring a high sensible heat flux like that seen over dry soils. Additionally, the structure of the winds below this 3 km level has a strong influence on the likelihood of convection. Low level veering can enhance buoyancy, as long as the shear is not too great, and improve the chances of rainfall occurring. Similarly, low-level backing or strong shearing can cut off convective development. These effects should be considered when analyzing field data or modeling results investigating the role of the land surface on atmospheric processes.

Appendix A: Definitions of CTP and HI_{low}

A1. Convective Triggering Potential

[52] The CTP is determined by integrating the area between the observed temperature sounding and a moist adiabat originating at the observed temperature 100 mbar above the surface. The top of the area of integration is bounded by a constant pressure line 300 mbar above the surface. Note that the CTP can be negative if the temperature of the moist adiabat originating from the $P_{surf} - 100$ mbar level is less than the observed temperatures. Also, the CTP will be zero if the observed profile is moist adiabatic above the point of origin. A diagram of this definition is provided in FE2003.

A2. Humidity Index

[53] *Lytinska et al.*'s [1976] original definition of the humidity index is the sum of the dew point depressions at 850 mbar, 700 mbar, and 500 mb:

$$HI = (T_{850} - T_{d,850}) + (T_{700} - T_{d,700}) + (T_{500} - T_{d,500}), \quad \text{(A1)}$$

where T_p is the temperature at pressure level p and $T_{d,p}$ is the dew point temperature at pressure level p. A more useful parameter for assessing this group of soundings from Illinois is the sum of the dew point depressions at 950 mbar and 850 mb:

$$HI_{low} = (T_{950} - T_{d,950}) + (T_{850} - T_{d,850}). \quad \text{(A2)}$$

Lytinska et al. [1976] suggested as threshold for rain HI $\leq$ 30°C. The threshold for HI_{low} is 15°C (see text).

[54] **Acknowledgments.** This research has been supported by NASA under agreement NAG5-7525 and NAG5-8617. The views, opinios, and/or findings contained in this paper are those of the authors and should not be constructed as an official NASA position, policy or decision unless so designated by other documentation. The authors would like to thank Wayne Angevine, Alison Grimsdell, and Tony Delany for sharing their data from the Flatland experiment. We would also like to thank Chris Weaver and two anonymous reviewers for their helpful comments and suggestions.

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