IMPACTS OF SOIL MOISTURE VARIABILITY ON CONVECTIVE PRECIPITATION IN THE CENTRAL PLAINS THROUGH LAND-ATMOSPHERE FEEDBACKS

IMPACTS OF SOIL MOISTURE VARIABILITY ON CONVECTIVE PRECIPITATION IN THE CENTRAL PLAINS THROUGH LAND-ATMOSPHERE FEEDBACKS

BY

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Abstract

A suite of regional climate model runs was conducted to examine the impacts of mean soil moisture and model resolution on precipitation events in the U.S. Central Plains, and to investigate the relative impacts of energy balance partitioning and net radiation in soil moisture-precipitation feedbacks. Results indicate the presence of a positive feedback between soil moisture and precipitation in the U. S. Central Plains. Energy balance partitioning controls the occurrence of feedbacks, while net radiation was not impacted by mean soil moisture. Spatial scaling properties of modeled fields were examined to determine whether these fields exhibit scale invariance. There is large temporal variability in the scaling coefficients of soil moisture, Bowen ratio and soil temperature. Results imply that scaling characteristics determined from a limited time series of remotely sensed images may not be sufficient for inferring spatial dynamics of soil moisture.

CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

The objective of this research was to examine the impacts of varying mean soil moisture and spatial resolution on soil moisture-precipitation feedbacks in the U.S. Central Plains using a regional climate model. According to general circulation model (GCM) predictions, climate change in this region will lead to longer intervening dry periods resulting from precipitation events of greater magnitude and reduced frequency, which will generally lead to lower soil moisture (Knapp et al. 2002). The spatial and temporal variability of soil moisture are highly dependent on precipitation patterns. Altering precipitation regimes will impact soil moisture variability, which may then alter precipitation patterns through land-atmosphere feedbacks. This has potential ramifications for agricultural production in the Central Plains, which provides a large portion of the country's food supply. Understanding the physical processes that drive these feedbacks has important implications for improved forecasting of crop yields and water availability for both agricultural and urban uses.

Obtaining data at the appropriate spatial and temporal scales to observe land-atmosphere interactions has posed a significant challenge. The wide availability of remotely sensed data has the potential to alleviate this problem, however there are major limitations involving scale issues related to the resolution of satellite data (Brunsell and Gillies 2003a). Remotely sensed fields are obtained on spatial and temporal scales that cannot typically be compared with model output and surface measurements. In order to potentially circumvent this issue, scaling coefficients can be calculated from spatial fields that exhibit statistical self-similarity. Significant research has already been conducted in this area, specifically on soil moisture and precipitation fields (Brunsell and Gillies 2003b; Waymire 1985; Western et al. 2002). Here, the spatial scaling properties and temporal variability of scaling coefficients for soil moisture, precipitation, soil temperature, and Bowen ratio are examined. If the fields exhibit statistical self-similarity and low temporal variability of scaling coefficients, this has important implications for potentially widespread application of remotely sensed data.

Chapter two of this thesis specifically investigates how varying the mean soil moisture and model resolution impacts the magnitude and frequency of precipitation events in the Central Plains through land-atmosphere feedbacks. Secondly, it examines the scaling properties of soil moisture and precipitation fields to determine whether they exhibit scale invariance, i.e. whether or not they can be used to predict properties at other spatial scales.

Chapter three seeks to determine the relative importance of energy balance partitioning and net radiation in soil moisture-precipitation feedbacks and examines how the dominant physical process are impacted by changes in mean soil moisture and spatial resolution. It also investigates the scaling properties of soil temperature and Bowen ratio, and assesses the impacts of varying mean soil moisture on the scaling coefficients, as these variables are strongly influenced by soil moisture in a non-linear way.

The final chapter provides a summary of the conclusions drawn in the previous chapters and provides suggestions for future research.

CHAPTER 2

A SCALING ANALYSIS OF SOIL MOISTURE-PRECIPITATION INTERACTIONS IN A REGIONAL CLIMATE MODEL

2.1 Introduction

Global climate change has been a major theme in recent research, and many studies are beginning to examine the potential impacts it will have at smaller scales. Changes in regional climate may have profound impacts on the ability of agricultural regions to maintain sufficient crop yields, and as a result many studies have already begun to examine the ways in which these areas may be affected.

Climate change has a potential impact on the Central Plains of the United States, where a large portion of the country's food production takes place. Predicted climate changes in the Central Plains include altered precipitation regimes with increased occurrence of growing season droughts and higher frequencies of extreme rainfall events (Harper et al. 2005). General circulation models (GCMs) predict precipitation events of a greater magnitude and reduced frequency, but with longer intervening dry periods which will generally lead to reduced soil moisture levels (Knapp et al. 2002). Altering precipitation regimes will have a profound impact on the spatial and temporal variability of soil moisture, which may then alter precipitation occurrence through land-atmosphere feedbacks.

Estimates from satellite and census data indicate that about 12% of the earth's surface, an area roughly the size of South America, has been converted into agricultural land (Raddatz 2007). Much of the motivation for studying the effects of vegetative cover and soil moisture on local weather and climate comes from the associated potential increase in predictability of long-term weather (Koster 2003). Changes in vegetative cover and soil moisture impact surface energy partitioning, water and carbon fluxes, and precipitation patterns. Human actions that alter soil moisture and vegetation properties, through changes in land-surface cover and increased/decreased irrigation, can potentially have significant impacts on local climate and weather. These changes affect the amount of moisture available for evaporation, transpiration, and rainfall. Agricultural land tends to be characterized by cooler temperatures and a shallower boundary layer, and exhibits a tendency for increased cloudiness and precipitation (Gameda et al. 2007). The Central Plains of the U.S. provides an excellent example of how humans have altered the landscape and conditions natural to the area by replacing native plant species with crops and setting up irrigation systems which alter the local moisture conditions.

Understanding how the spatial variability of soil moisture impacts feedbacks between the land surface and atmosphere will provide a clearer understanding of how climate change might alter the physical processes involved in this system, including the local hydrologic cycle, the surface energy budget, and biogeochemical cycling. Feedbacks between soil moisture and precipitation can potentially lead to the persistence of flood or drought conditions due to the altered availability of moisture for rainfall. In 2003 an extreme heat wave over Europe was responsible for 35,000 heat related deaths, in addition to forest fires and economic losses which resulted from shortages in crop production (Fischer et al. 2007). Using the Climate High-Resolution Model (CHRM) version 2.3, Fischer et al. (2007) showed that soil moisture anomalies resulting from a pronounced deficit in spring precipitation had a large impact on the strength of the 2003 European heat wave through a reduction in latent cooling. Based on the output from a heterogeneous ensemble of 11 high-resolution climate models from the PRUDENCE project which focused on Europe, Vidale et al. (2007) conclude that warmer and drier conditions are more likely during the peak of the summer, which they find consistent with an enhanced soil moisture-precipitation feedback. Having a clear understanding of the processes governing land-atmosphere feedbacks, as well as the spatial and temporal variability of these processes, will improve the forecasting of droughts and floods (Koster 2003). This has potential ramifications for forecasting of crop yields and water availability for both urban and agricultural uses and could potentially offset some of the associated societal and economic consequences of drought and flood events.

One of the major limitations related to studies involving soil moisture lies in the inability to obtain data which accurately represent the heterogeneity of soil moisture. Soil moisture observations are lacking both spatially and temporally and this lack of observations must be addressed in any study involving soil moisture. This lack of data has important implications for our understanding of soil moisture-precipitation interactions, which remain limited as surface soil moisture observations are not readily available over most scales relevant for the study of land-atmosphere interactions (Taylor and Ellis 2006).

As surface soil moisture measurements remain generally unavailable, many studies rely on remotely sensed soil moisture values. It must be noted, however, that some uncertainty exists as to the accuracy of remotely sensed soil moisture data due to the difficulty involved in comparing remotely sensed measurements with surface observations (Brunsell 2006).

Satellites using passive microwave sensing can be used to detect moisture variations in the top several centimeters of soil (Jackson et al. 1997). Quantitative estimates of soil moisture can be made from measurements of horizontally and vertically polarized brightness temperatures. This technique has been used in multiple studies using data from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (Taylor and Ellis 2006). In one such example, Taylor and Ellis (2006) found evidence for a negative feedback mechanism using hourly Meteosat thermal infrared (TIR) data to assess the evolution of deep convective clouds along TRMM scans containing wet strips over the West African Sahel. A limitation of TRMM for global monitoring of soil moisture is that its geographic coverage is limited to 40^{o}N - 40^{o}S.

When using remotely sensed data it is important to remember that these are only estimates, as the brightness temperature may in fact be significantly different from the actual temperature. The interpretation of spatial patterns of soil moisture from microwave remote sensing is further complicated by the fact that the depth of penetration is not clearly defined and may also vary spatially (Western and Bloschl 1999) due to differences in soil and vegetation properties.

There are other issues associated with relying on remotely sensed data. One of the major limitations involves scale issues related to the satellite's resolution

(Brunsell and Gillies 2003a). Satellites obtain data on different spatial and temporal scales than those that are typically required for comparison with model output and observations. When comparisons can be made between modeled and remotely sensed fields, the observed soil moisture typically shows more rapid dry downs and faster saturation than the modeled soil moisture (Drusch 2007).

The resolution of both models and observations are not increasing as quickly as the resolution of surface remote sensing (Kustas et al. 2003). Even in the case of observations, point samples of soil moisture are not necessarily representative of a regional value of the variable (Entekhabi et al. 1996), though techniques such as temporal stability may be used to address this issue (Vachaud et al. 1985). Temporal stability involves the identification of persistent soil moisture patterns and selection of representative sensor locations to use in estimating the large scale average (Cosh et al. 2006).

Determining and using the scaling properties of soil moisture fields to infer variability at scales other than the measurement scale is another way to overcome issues related to resolution. Many studies have already investigated this, including Dubayah et al. (1997), Rodriguez-Iturbe et al. (1995), Manfreda et al. (2007), and Western and Bloschl (1999). A scaling field exhibits self-similarity over many different scales or resolutions (Halley et al. 2004). It is possible to use this self-similarity to infer properties at other scales. Self-similarity can be described by:

$$\phi(x) = \lambda^{-\beta} \cdot \phi(\lambda \cdot x) , \quad (1)$$

where ϕ refers to the field or property of interest, x is the spatial scale, λ is the ratio of the large scale $\lambda \cdot x$ to the small scale x, and β is the scaling exponent, or slope (Bloschl 1996).

Some studies have chosen to focus on the scaling properties of variance as a function of resolution (Manfreda et al. 2007; Rodriguez-Iturbe et al. 1995), while others use higher-order statistical moments (Brunsell and Gillies 2003b; Dubayah et al. 1997; Peters-Lidard et al. 2001). Peters-Lidard et al. (2001) define a field ϕ to be spatially scaling with respect to moment q if the following relationship holds:

$$E[(\phi_\lambda)^q \propto \lambda^{K(q)} E[(\phi_1)^q], \tag{2}$$

where $K(q)$ is the scaling exponent associated with moment q (same as β in equation 1 above). A process is said to be simple scaling, often referred to as fractal, if the exponents $K(q)$ are linear in q:

$$K(q) = Cq, \tag{3}$$

where C is a constant. A process is said to be multiscaling, or multifractal, if the scaling exponents, or slopes, are a non-linear function of q (Peters-Lidard et al. 2001).

This idea of scaling and multiscaling has been applied extensively in many scientific fields, including hydrology and ecology. Aside from soil moisture, it has also been used to examine the spatial and temporal scaling properties of precipitation (Deidda et al. 1999; Gupta and Waymire 1990; Kumar and Foufoula-Georgiou 1993; Menabde et al. 1997; Rodriguez-Iturbe et al. 1998).

Having soil moisture data at the appropriate spatial and temporal scale is important for the study of land-atmosphere interactions. Interactions between soil moisture and precipitation can lead to a feedback, and previous studies have relied upon surface soil moisture measurements (Findell and Eltahir 1997), remotely sensed soil moisture fields (Taylor and Ellis 2006), and modeled soil moisture (Kim and Wang 2007). A number of studies have already investigated the existence of a feedback mechanism between soil moisture and precipitation (Brubaker and Entekhabi 1996a; Findell and Eltahir 1999; Koster et al. 2004; Pal and Eltahir 2001).

Feedbacks can either be positive or negative (Brunsell 2006). In the case of a positive feedback the initial soil moisture state is reinforced. For example, when a surplus of moisture exists in the soil, it results in increased precipitation over the area (Eltahir 1998). Alternatively, if the amount of moisture in the soil drops below normal levels it may contribute to persistent dry spells. A negative feedback would occur if anomalously wet soils suppressed precipitation over a region (Cook et al. 2006).

The existence, magnitude, and sign of feedback between soil moisture and precipitation vary in both space and time. Precipitation in the United States, as well as other regions, is sensitive to the amount of moisture in the soil during months with substantial convective activity, including summer months at mid-latitudes (Pal and Eltahir 2001). By examining the linear correlation between an initial soil saturation and subsequent rainfall, Findell and Eltahir (1997) found the magnitude of the feedback to be dependent upon the time of year. Kim and Wang (2007), using a modified version of the Community Atmosphere Model version 3 and the Community Land Model version 3 (CAM3–CLM3), determined that anomalies in shallow soil can persist long enough to influence subsequent precipitation at the seasonal time scale and that the impacts of spring soil moisture anomalies are not felt until early summer, although they do impact the large-scale circulation which results in slight changes in spring precipitation.

Yet even with foreknowledge of soil moisture, the improvements in the ability to predict precipitation and temperature are not uniform in space and time (Yang et al. 2004). Other studies have provided evidence to support this. For example, Conil (2007), using the Arpege-climat coupled land-atmosphere model, designed to assess the relative influence of sea-surface temperature (SST) and soil moisture on climate variability and predictability, found that soil moisture contributes to a significant enhancement of the predictability primarily during mid-latitude summer. While the SST forcing enhances the potential predictability in the tropical regions and during winter at mid-latitudes, the soil moisture forcing is the major contributor to the potential predictability in the mid-latitudes during the summer. Koster et al. (2000) suggested that the enhancement in the ability to predict precipitation can only be seen in the transition zones between dry and humid climates, as latent heat is more sensitive to soil moisture and temporal variations in evaporation are large enough to impact the atmosphere in such locations. Alternatively, the findings of Yang et al. (2004), which were based on monthly mean analysis over the continental United States in summer, did not support this existence of definitive geographical preferences in the potential improvements of predictability of precipitation from month to month. In any event, the ability to improve prediction is limited due to the chaotic nature of the atmosphere and the fact that increased accuracy in the specification of soil moisture can only impact prediction to a certain extent (Yang et al. 2004).

2.2 Methods of Examination

In the event that actual surface observations of soil moisture of acceptable spatial and temporal frequency are available, data analysis can be used to examine the existence of feedback mechanisms. One such example is the Illinois Climate Network data set, comprised of 14 years worth of soil moisture data recorded biweekly across the entire state. Findell and Eltahir (1997) used this dataset to search for a correlation between soil saturation and precipitation in the state of Illinois. Using linear regression and the coefficient of determination as an indicator of the percentage of rainfall variability that could be attributed to the soil water initial condition, they found it difficult to identify the causal relationship between soil moisture and precipitation; however, they did find some evidence to indicate that a positive feedback was present. The poor spatial and temporal characteristics of the data still restricted them from drawing any strong conclusions from their analysis.

Using the same dataset, Salvucci et al. (2002) arrived at a conflicting conclusion, demonstrating that the results of an individual study are highly dependent upon the method of analysis. They performed a test for Granger causality, a method used to identify the presence of one and two-way coupling between terms in multivariate dynamical system where a substantial amount of noise is present. They were unable to find sufficient evidence to link soil moisture and precipitation in Illinois. They attributed the results of Findell and Eltahir (1997) to their method of filtering the data, which was achieved through linearly interpolating between soil moisture measurements at each station.

Due to the general lack of field measurements of soil moisture, most studies conducted on soil moisture-precipitation feedbacks have used numerical models. In place of observed soil moisture data, the estimates of soil moisture in these cases can be anything from remotely sensed data (Taylor and Ellis 2006), to values specified by the user (Pal and Eltahir 2001), to values generated from an antecedent precipitation index (Xue et al. 2003) depending on the intent of the study. Numerical modeling provides a way to simulate atmospheric processes in order to gain a better understanding of how these processes interact to produce short term weather, as well as climate.

Kustas and Albertson (2003) noted that while there have been efforts to assess the impact of surface heterogeneity on land-atmosphere feedbacks, they have been based primarily on conceptual/theoretical approaches using simple convective boundary layer simulations and sparse boundary layer flux observations. Such approaches are limited in that the fluxes traditionally have not been allowed to develop dynamically with surface and overlying air states. More recent studies have begun to use more complex models that remove many of the limitations associated with using a simple conceptual model. When choosing which type of model to use, the scale of the physical processes to be examined should be a determining factor.

General Circulation models (GCMs) are ideal for simulation of larger scale atmospheric processes due to their relatively coarse resolution and inability to explicitly resolve smaller scale features and processes. Their use, however, is not limited solely to the global scale, and studies have been done using GCMs to examine the impacts of varying levels of soil moisture heterogeneity (Koster et al. 2002). In one such study, Betts (2007) found a coupling between warm season soil moisture, liquid condensation level (LCL) height, relative humidity (RH), and precipitation at the daily timescale in the European Centre for Medium-Range Weather Forecasts reanalysis (ERA40), though they could not determine the direction of causality.

Due to the possibility of increasing predictability of weather and climate through improved representation of soil moisture, it is important to understand how current models simulate these processes in order to identify their limitations and potentially improve their accuracy. Due to the large domain involved these models have extremely coarse horizontal resolution, and as a consequence of using larger grid cells more averaging of variables occurs. At such large resolutions the model becomes less able to accurately represent surface characteristics at sub-grid resolutions. Important features, such as land cover variability, topographical features, and soil moisture anomalies, are filtered and possibly lost completely. The algorithms used to generate gridded data may lead to "smoothing" which acts to reduce variability (Koster et al. 2000). Topography, significant spatial heterogeneity in soil and vegetation properties, and the highly intermittent characteristic of precipitation fields result in large spatial variations in the soil moisture (Entekhabi et al. 1996). This high spatial variability of soil moisture will be lost when using a GCM.

Parameterization of physical processes can somewhat make up for the inability to capture them explicitly, but it is difficult to compensate for the loss of surface characteristics when the impact of small scale surface heterogeneity is of interest. While parameterization can approximate subgrid-scale processes, such as cumulus convection, microphysics, long and short wave radiation, and boundary layer turbulence, they cannot represent them with complete accuracy due in part to our lack of understanding of these processes and their interactions. Results are often highly dependent upon the parameterizations schemes that are chosen. When the model resolution is too coarse to capture the surface heterogeneity it may also prevent mesoscale circulations from developing in the model environment that would normally form as a result of variability in land surface properties. Using satellite derived soil moisture observations, Taylor et al. (2007) found that precipitation can produce enough spatial variability in soil moisture and heat flux to impact the low level wind field on scales of 10 km and higher. Lynn et al. (1995) found that mesoscale circulations that developed as a result of discontinuities in land cover can locally affect subgrid-scale processes significantly in GCMs and emphasized the development of parameterizations that would include their impact.

In their discussion of the impact of land-surface moisture variability on local shallow convective cumulus and precipitation in large scale models, Chen and Avissar (1994) pointed out the deficiencies in the ability of the parameterization schemes developed for use in large scale models to represent local shallow convective cumulus, which are affected by local land surface characteristics. They found that discontinuities in land cover acted to enhance shallow convective precipitation, but explicitly simulating shallow cumulus convection with reasonable accuracy requires high horizontal resolution, ideally smaller than 1 km. Additionally, failure to represent areas of saturated soil can interfere with the model's ability to accurately simulate important hydrologic processes, such as infiltration, evaporation, and runoff (Gedney and Cox 2003).

In order to circumvent some of the aforementioned issues, mesoscale or regional models are often used, as they are typically run with higher horizontal resolutions which allow them to better resolve smaller scale properties and atmospheric processes than GCMs. They are ideal for examining regional circulations, convection, and are often used to examine land-atmosphere interactions, though they still require some processes to be parameterized, including small scale turbulence, convective parameterization, and radiation physics. Due to the finer resolution, these models are better able to resolve topography and variability in surface features. Mesoscale and regional models still remain far from ideal in their representation of land cover, vegetation and soil moisture, but they are able to resolve more detail than GCMs. One potential downside to using a regional model rather than one of global extent is the loss of the ability to assess the impacts of teleconnections.

Many studies have used mesoscale models to examine the relationship between soil moisture and the atmosphere. Georgescu et al. (2003) used the Regional Atmospheric Modeling System (RAMS) to examine the impact of varying the initial spatial distribution of soil moisture on simulated precipitation and found evidence for the existence of a negative feedback in the Mississippi River Basin. They also examined the effects of differing convective schemes on their model results, finding a high sensitivity of model-generated precipitation to the choice of convective scheme. In another study, Xu et al. (2004) used the Fifth-Generation NCAR/PSU Mesoscale Model (MM5) coupled with the Oregon State University (OSU) land surface model to investigate the response of precipitation to soil moisture anomalies in the North American Monsoon region as well as the south-central United States. They detected a positive feedback between soil moisture and precipitation. Alonge et al. (2007), in their investigation into the impacts of soil moisture on the potential for deep convection in a semiarid environment in West Africa, found using a coupled land-atmosphere cloud resolving model and observation data from the Hydrological Atmosphere Pilot Experiment in the Sahel, that their wet regime created a boundary layer that was more favorable for deep convection. While convection began earlier in the dry regime it produced approximately 55% less precipitation.

When processes taking place on scales less than 1 km are of interest large eddy simulations (LES) can be used in the place of a mesoscale model. LES are used to study smaller scale processes (10 m to 1 km) by explicitly modeling the large scale turbulence within the atmospheric boundary layer (ABL). They are often used to study land-atmosphere interactions. Relative differences between surface properties and the properties of the overlying air lead to the development of land surface fluxes of energy and mass over heterogeneous landscapes, and LES has proven to be instrumental in examining the impacts of land surface heterogeneity on the ABL (Albertson et al. 2001) when combined with remotely sensed land surface conditions.

As precipitation resulting from soil moisture feedbacks comes from convection, the most appropriate scale at which to examine it is the mesoscale. Mesoscale models are designed to handle atmospheric processes and phenomena ranging from regional scales down to the microscale, as these small scale processes have been known to have significant impacts on storm-scale phenomena (Xue et al. 2003).

All of the aforementioned issues come together to raise several questions needing further investigation: 1) do modeled soil moisture and precipitation fields exhibit scale invariance, i.e. can they be used to predict properties at other spatial scales? 2) how does varying the mean soil moisture and model resolution impact the magnitude and frequency of precipitation events in a region through land-atmosphere feedbacks?

Soil moisture scaling has important implications for future work on land-atmosphere interactions, as having knowledge of soil moisture properties at any desired resolution would prove extremely valuable. The above questions seek to address the fact that characteristics of the land surface are lost at larger resolutions.

While the first question attempts to solve this problem, the second question tries to determine what impacts this actually has on model simulated precipitation.

2.3 Study Area

Understanding the impacts of soil moisture-precipitation interactions on regional climate in the Central Plains has important implications for agricultural practices. This study focused specifically on the Konza Prairie, located near Manhattan, KS (39^{o}05’N, 96^{o}35’W), within the Flint Hills region of northeastern Kansas. This land is owned by the Nature Conservancy and currently managed by Kansas State University as a National Science Foundation (NSF) Long-Term Ecological Research Station (LTER). Research conducted here primarily focuses on how climatic variability and local land use patterns (periodic fire and ungulate grazing) affects tallgrass prairie ecosystem structure and function (Fay et al. 2000).

Being located within the Flint Hills region the soils include deep silt loam and silty clay loam soils which are characteristically rich and thin. The subsurface is composed of alternating layers of limestone and shale, which give the landscape a terraced appearance (Davis et al. 1992). Vegetation over the Konza Prairie is predominantly native tallgrass prairie, consisting primarily of C_4 and C_3 grasses, including Indian grass (*Sorghastrum nutans (L.) Nash*), switchgrass (*Panicum virgatum L.),* little bluestem (*Schizachyrium scoparium Michx.*) and big bluestem (*Andropogon gerardii Vitman*) (Davis et al. 1992;Fay et al. 2000;Kaste et al. 2006).

Approximately 75% of the root biomass is located within the top 30 cm of the soil profile (Fay et al. 2003; Jackson et al. 1996).

The annual mean precipitation of 835 mm per year occurs primarily during the growing season, between May and September, with a mean growing season total of 635 mm. Being located on the Central Plains, the region experiences a temperate mid-continental climate with annual temperatures ranging from a low of -2.7 ^{o}C in January to a high of 26.6 ^{o}C in July (Fay et al. 2003).

2.4 Model Description

In order to investigate the scaling properties of soil moisture and precipitation and determine the impacts of varying mean soil moisture and resolution on convective precipitation, a suite of runs was conducted using the University of Oklahoma's Advanced Regional Prediction System (ARPS), which was developed at the Center for Analysis and Prediction of Storms (CAPS) in Norman, OK. ARPS is a three-dimensional, nonhydrostatic compressible model intended for use as a real-time forecasting model, as well as a tool for research. It includes data ingest, quality control, and objective analysis packages, single-Doppler radar parameter retrieval and data assimilation procedures, the prediction model, as well post-processing packages and validation tools (Xue et al. 2000, 2001).

Fifteen model runs were completed using varying spatial resolutions and levels of mean soil saturation (Figure 1) in order to examine the scaling properties of soil moisture and precipitation and to study how soil moisture-precipitation interactions vary as a function of mean soil saturation and resolution. The three initial soil moisture values used include field capacity (0.35 m^3/m^3), 50% of field capacity (0.13 m^3/m^3), and wilting point (0.09 m^3/m^3). Mean soil moisture values will hereafter be referred to as FC for field capacity, 50FC for 50% of field capacity, and WP for wilting point.

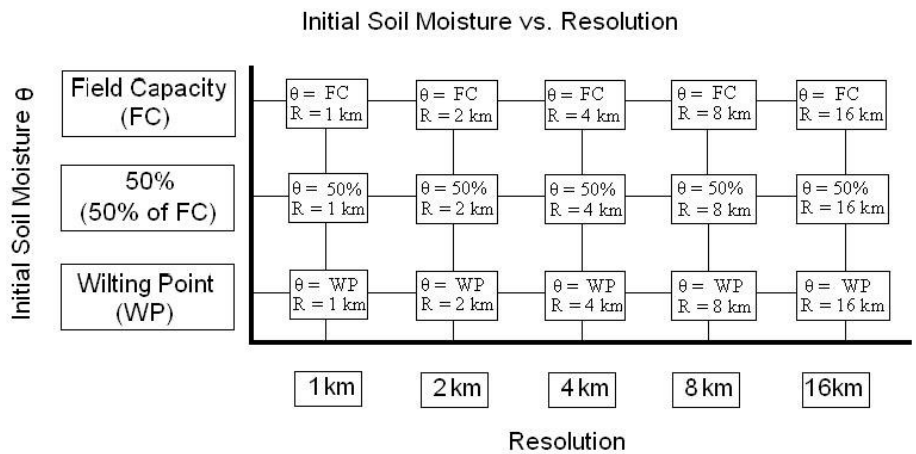

Figure 1. Initial Soil Moisture vs. Resolution. At each of the five given resolutions, the model was run using three levels of initial soil moisture: field capacity (FC), 50% of field capacity (50FC), and wilting point (WP)

All model runs were initialized using a standard mid-latitude summer sounding which was modified so that the wind direction at all levels was westerly. Soil and vegetation properties are homogeneous, with soil type being sandy loam and vegetation type grassland with a leaf area index (LAI) of 0.31. This allowed the vegetation's impact to be ignored as it remained constant through all runs.

As precipitation resulting from soil moisture feedback is associated with convection, and the maximum rainfall on the Konza Prairie occurs between May and September, summer was the ideal season to examine. ARPS was initially run over a period of 20 days, beginning on August 18th, using a resolution of 16 km. The first four days were regarded as spin-up and discarded, leaving 16 days which were then used to force a higher resolution nested grid. This time period was considered sufficient for observing land-atmosphere interaction and soil moisture evolution, as Brubaker and Entekhabi (1996b) state that a general time scale on the order of 10 days corresponds to local physical processes and land-atmosphere interaction at the regional scale. They found that 10 days was sufficient for recovery from a moist soil anomaly to normal conditions and that recovery typically occurred on the order of 14 days for dry soil anomalies, but could take as long as several tens of days.

Although ARPS has the ability to allow two-way interactive grid nesting, one-way interactive nesting was used for several reasons; the first being that this study is not trying to recreate an event that previously occurred where feedback from smaller scales to the synoptic scale would be important for accuracy. Second, as the interest was mesoscale convection and not in the affects of synoptic scale weather systems on the domain there was no real need to use two-way interactive grid nesting. Coarse resolution runs (16 km) were completed first and then used to force the inner, higher resolution grid at resolutions of 1, 2, 4, 8, and 16 km. The coarse grids were initialized with the same properties as the inner grids to maintain comparability between runs.

When using a model to examine soil moisture-precipitation feedbacks the location of the domain boundary has been found to alter the strength of the feedback mechanism (Seth and Giorgi 1998). Seth and Giorgi (1998) found that a smaller domain was better able to capture precipitation, but the sensitivity of precipitation to initial soil moisture was more realistic in a larger domain. In order to avoid errors associated with the location of the model boundaries the best course of action is typically to place the boundaries a significant distance away from the area of interest. The Konza Prarie occupies an area of approximately 12,000 km^2, while the outer domain covers an area of 4,194,304 km^2 and the inner domain an area of 16,384 km^2 (Figure 2).

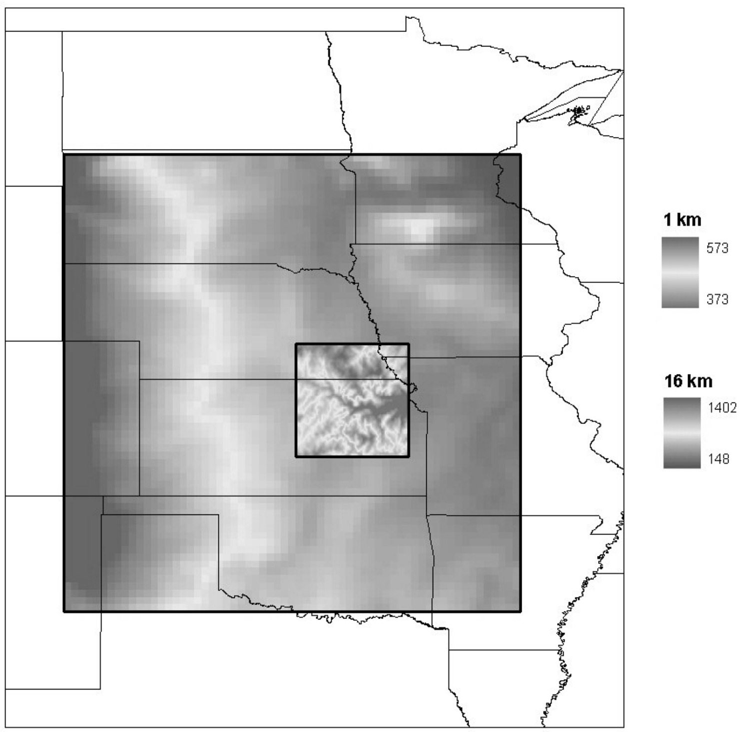

Figure 2. The large boxed area shows the geographical extent and topography of the outer domain (16 km resolution). The smaller box indicates the extent of the inner domain, overlaid with topography at 1 km resolution

The vertical grid was composed of 83 layers, with higher resolution at the surface (approximately 100 m), decreasing exponentially with distance from the surface, with a resolution of approximately 500 m at the top of the model domain. The stretching of the vertical grid allowed the model to better resolve land-atmosphere interactions, which was of greatest interest to this study, while not compromising computational efficiency by having unnecessarily high resolution at upper levels. Vertical resolutions were held constant throughout all model runs in the series to ensure comparability.

As precipitation processes cannot be explicitly resolved at coarser resolutions the Kain-Fritch WRF parameterization scheme was used in the 4, 8, and 16 km runs. This scheme was chosen because it is more suitable for higher resolution grids and has the ability to generate sources of rainwater and snow which are fed back to grid scale variables which then interact with ice microphysics processes (Xue et al. 2001).

2.5 Methodology

2.5.1 Scaling Analysis

As was previously mentioned, remotely sensed and modeled soil moisture typically are not directly comparable due to differences in resolution. Soil moisture variability is high over a range of scales and often shows as much variability over a distance of meters as it does over hundreds of kilometers, which is typical of scaling fields (Dubayah et al. 1997). A process is said to be scaling, or self-similar, if the statistical properties of the field do not vary as a function of scale, i.e. the process behaves similarly at both small and large scales (Bloschl 2001). Self-similarity of a field can be used to infer characteristics at smaller or larger scales (Halley et al. 2004).

By estimating the statistical moments, Dubayah et al. (1997) demonstrate how a coarse, remotely sensed soil moisture field can be used to predict model variability at resolutions other than the measurement scale. Numerous methodologies have been used to examine the scaling properties of a variable, with many focusing on how the variance changes as a function of resolution (Manfreda et al. 2007; Rodriguez-Iturbe et al. 1995), others the scaling of the coefficient of variation (Baldocchi et al. 2005), or how the statistical moments scale (Brunsell and Gillies 2003b; Dubayah et al. 1997; Peters-Lidard et al. 2001). The benefit to performing a scaling analysis on the statistical moments is that they provide information about the spatial structure of the field, whereas other methods only indicate the amount of variability in the field. If a scaling relationship does exist, each of the moments can be calculated for any other resolution.

For purpose of this study a scaling analysis was performed on 10 am to 2 pm temporally averaged soil moisture and cumulative precipitation for the 12 days using the first six statistical moments. Equation 4 gives the first moment (mean), equation 5 the second moment (variance), and Equation 6 is used to obtain all subsequent moments.

$$X^1 = \frac{1}{N}\sum x_i \tag{4}$$

$$X^2 = \frac{1}{N}\sum (x_i - \bar{x})^2 \tag{5}$$

$$X^n = \frac{\frac{1}{N}\sum(x_i - \bar{x})^n}{\sigma^n} \qquad (6)$$

where x_i is the pixel value, n is the order of moment, N is the number of points, $\bar{x}$ the spatial mean, and σ the standard deviation. The six moments are then plotted versus resolution, and the slope (β) calculated using linear regression (Brunsell and Gillies 2003b).

To determine whether or not a given field may be approximated by a linear scaling relationship, or fractal, a log-log plot of β versus order of moment must be constructed:

$$\log(\varphi) = \log(\alpha) + \beta * \log(x), \qquad (7)$$

where x is resolution, β is the scaling exponent, and α the intercept. How well the best fit line approximates the data is used as a criterion to make the determination. If multiple β values exist the field is said to be multiscaling and would be indicated by a convex or concave shape and non-linear change in β with order of moment (Dubayah et al. 1997).

The goal here was to investigate the possibility of scaling in soil moisture and precipitation fields and to examine how a coarse field can be used to predict model variability at other resolutions. This technique would help compensate for the model's inability to resolve key features of surface fields as resolution becomes coarser.

Cumulative precipitation for the 12 days was chosen over daily precipitation because in order to calculate each of the six statistical moments, for any given initial soil moisture, there must be precipitation occurring on each day at each model resolution. Without precipitation, moment calculations would result in zero making the analysis invalid for that day. For days when precipitation did occur at all resolutions the analysis was performed to allow for a comparison with the cumulative precipitation plot.

2.5.2 Comparison as a Function of Spatial Resolution

It was assumed that a higher resolution would correspond with higher accuracy in the representation of soil moisture variability and precipitation events due to the fact that surface characteristics and physical processes, such as convection, are better resolved. With this presiding assumption the Root-Mean Square Error (RMSE) was calculated between the 1 km runs and every other run:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}} \ . \tag{8}$$

where n is the number of points, and x_1 and x_2 are the variables between which the error is calculated. This is not to calculate a true error but to allow for a direct comparison between runs as a function of spatial resolution, showing whether or not other resolutions exhibit a consistent bias with respect to the 1 km run. The RMSE was calculated for both soil moisture and precipitation.

For each model run the temporal variance of precipitation and soil moisture were calculated at each pixel and then spatially averaged ($\overline{\sigma_T^2}$) to determine whether trends exist as a function of model resolution or initial soil moisture. As spatial resolution decreases the inability to explicitly capture physical processes may impact the model's ability to accurately resolve the temporal dynamics of the physical processes. This may potentially impact the frequency of precipitation events or temporal changes in the soil moisture field through wetting and/or drying processes.

A method for comparing spatial variability of soil moisture at differing resolutions is to look at the amount of statistical variability or dispersion present. The probability density function (pdf) of soil moisture was plotted for each run. As the soil moisture pdf is bounded by porosity and wilting point it theoretically cannot be normal, but in practice normality may be an acceptable assumption (Western et al. 2002). When the mean soil moisture approaches low or high values the normality assumption may become invalid; the pdf typically becomes skewed and has less variance. A positive skew (negative skew), or long upper tail (lower tail), generally occurs when the mean approaches the lower (upper) boundary (Western et al. 2002).

Plots of the soil moisture pdf allow for a visible examination of the amount of variance present, but for a quantitative comparison the variance to mean ratio (VMR) was also calculated:

$$VMR = \frac{\sigma^2}{\overline{x}}, \tag{9}$$

where σ^2 is the spatial variance and $\overline{x}$ the spatial mean. The VMR provides a measure of the dispersion, or variability, of a probability distribution. When the VMR is equal to 1 the spatial field is random, while a VMR < 1 indicates a regular distribution, and a VMR > 1 indicates that it is clumped (Baldocchi et al. 2005). In general the study is more interested in observing how the VMR of soil moisture changes over time as a function of initial soil moisture and resolution.

2.5.3 Soil Moisture-Precipitation Interactions

Areas characterized by high soil moisture will be associated with increased latent heat flux. This moisture will then be advected some distance downwind before falling again as precipitation, inducing a time lag between increased latent heat flux and subsequent precipitation and leading to a regional effect of the feedback mechanism. In order to investigate the temporal interactions between soil moisture and precipitation, lagged correlations were calculated to determine when the strongest relationship exists between them. Temporally lagged correlations are given by:

$$\hat{R}_{xy}(m) = \sum_{n=0}^{N-m-1} x_{n+m} y_n \,, \qquad m \geq 1 \tag{10}$$

$$\hat{R}_{xy}(m) = \hat{R}_{yx}(-m) \,, \qquad m < 0 \tag{11}$$

where x and y are stationary random variables, N is the number of points and m is the lag. Positive lags indicate that precipitation is leading soil moisture, while negative lags indicate that soil moisture is leading precipitation.

There will be a high correlation at the zero lag due to the influence of precipitation in determining soil moisture, but if feedback occurs there should be relatively strong correlations at other time lags. There are severe limitations to the use of linear correlations in the examination of a feedback, as causality cannot be inferred based on correlation. The point here is simply to identify whether or not a relationship exists.

The day on which the maximum lagged correlation occurs may vary as a function of initial soil moisture and resolution. For each model run the day of maximum lagged correlation, neglecting the zero lag, was found for each pixel and then spatially averaged. This analysis can potentially provide information regarding the temporal scales over which feedback may occur, which may differ for wet and dry soils as a result of the different processes responsible for feedback depending on the level of soil moisture.

2.6 Results

2.6.1 Precipitation

Scaling plots of β versus order of moment for cumulative precipitation look very similar for all levels of initial soil moisture (Figure 3). These plots demonstrate that the scaling properties are highly dependent on the methodology, as calculating only the variance or the coefficient of variation would result in significantly different scaling exponents. These plots do not show signs of multiscaling, although there is a strong linear relationship between the third through sixth moments. The mean and variance decrease considerably as a function of resolution, while the third and fourth moments do not. The fifth and sixth moments also show a significant decrease and it is important to consider when these moments begin to impact the spatial structure of the field and by what amount.

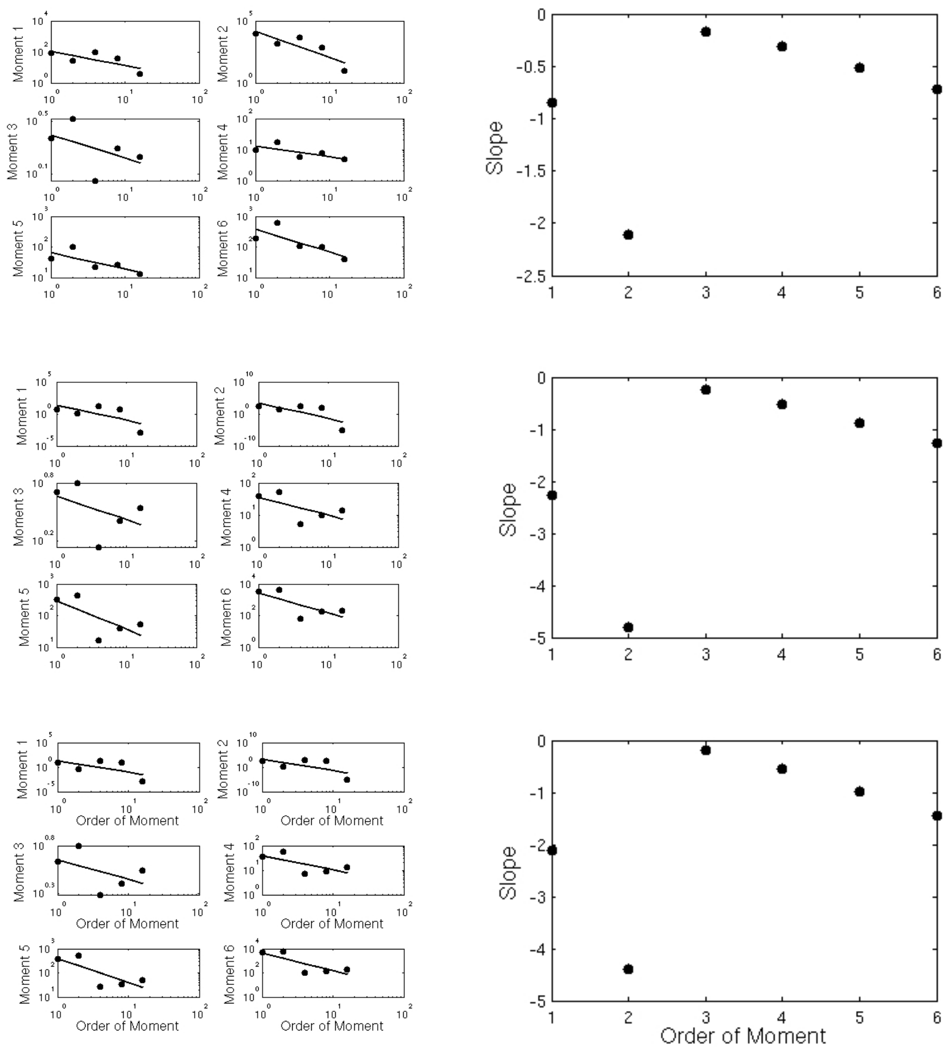

Figure 3. Scaling plots of cummulative precipitation for a) FC b) 50FC c) WP

In comparing the daily scaling plots (not shown) with cumulative precipitation plots, in general they exhibit the same characteristics, with the exception of day 1 in each of the three soil moisture levels. Day 1 plots show much stronger linear relationships, with R^2 values of 0.9879 (FC), 0.9789 (50FC), and 0.9917 (WP).

To determine the impacts of initial soil moisture and spatial resolution on total precipitation, precipitation for the entire domain was summed over the 12 day period for each model run (Figure 4). A comparison across initial soil moisture values shows that FC runs consistently have higher total precipitation amounts, regardless of resolution, which provides evidence for the existence of a positive soil moisture-precipitation feedback over the Konza Prairie. WP runs generally have precipitation totals greater or equal to 50FC. The fact that they exhibit equal totals at 16 km indicates that the 16 km resolution is not sensitive to the difference in initial soil moisture values between 50FC and WP. Comparing across resolutions, total precipitation decreases exponentially with resolution, with the exception of an increase between the 2 and 4 km runs.

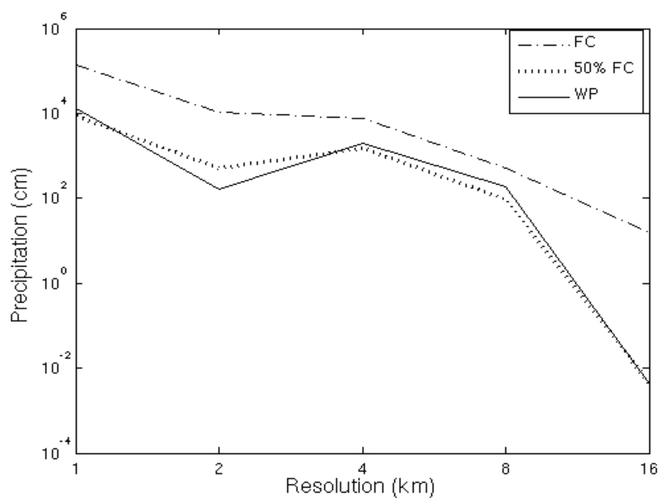

Figure 4. Precipitation summed over the domain for the 12 day period for each model run

When daily precipitation is summed over the domain, FC runs not only have the largest amount of total precipitation but they also generally have a higher number of precipitation events over the 12 day period. These events are almost always larger in magnitude than the 50FC and WP. Figure 5 shows the ratio of total number of days with precipitation events to the magnitude (cm) of the largest event at each resolution and initial soil moisture. The 50FC and WP 16 km runs have the lowest frequency of precipitation events, followed by the 8 km, and then 2 km 50FC and WP runs.

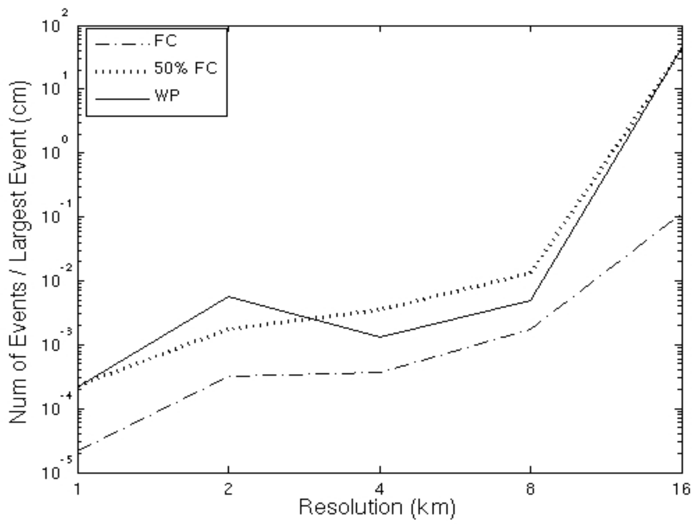

Figure 5. Ratio of the total number of days with precipitation events to the magnitude (cm) of the largest event at each resolution and initial soil moisture

In order to examine the temporal dynamics of precipitation as a function of mean soil moisture and resolution, the temporal variance of precipitation was calculated at each grid cell and then spatially averaged to allow for easy comparison between all 15 runs (Figure 6a). The FC runs consistently exhibit higher values than 50FC and WP regardless of resolution. There is a general decreasing trend from 4 km to coarser resolutions, with a significant reduction in each of the 16 km runs. It is worth noting that the values for the 1 km and 16 km 50FC and WP runs are exactly the same.

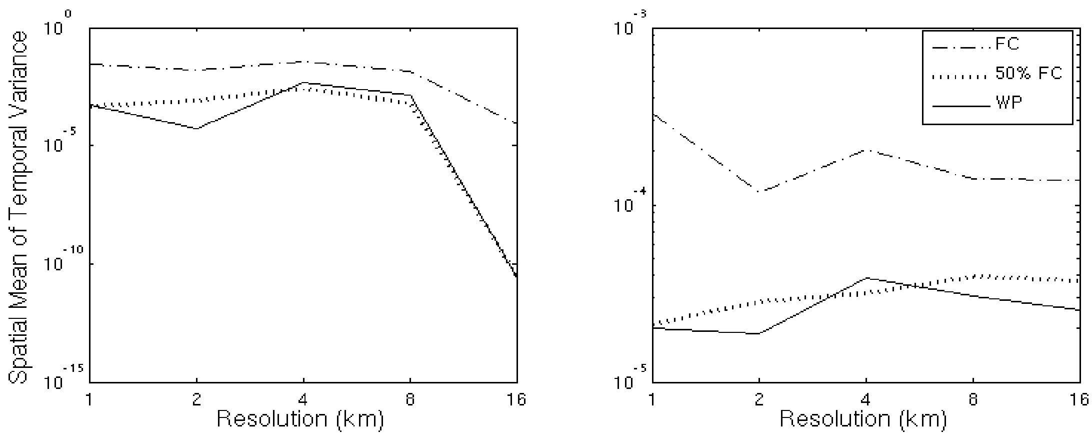

Figure 6. For each resolution the temporal variance was calculated for each grid cell in the domain and then spatially averaged a) precipitation b) soil moisture

To determine how each of the model resolutions compares with the 1 km runs, the RMSE was calculated for each initial soil moisture value (Figure 7a). Due to the ability to resolve smaller scale physical processes and heterogeneity in surface and atmospheric properties, 1 km was assumed to be the most accurate in its predictions. There is a much larger variation in RMSE as a function of resolution in the FC runs, while in both the 50FC and WP runs the RMSE remains relatively constant. The pattern of increase and decrease with resolution does not change as a function of initial soil moisture, with the 4 km runs having the highest RMSE.

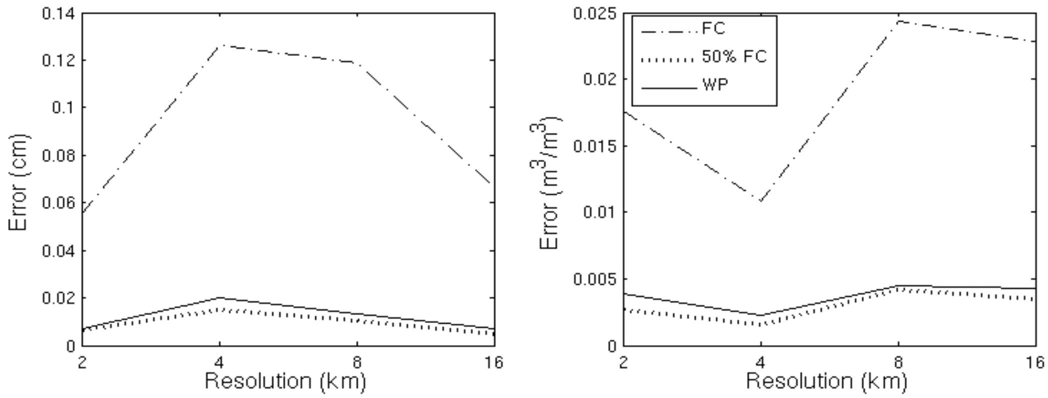

Figure 7. The RMSE calculated at each initial soil moisture and resolution, with 1 km runs representing truth a) precipitation b) soil moisture

2.6.2 Soil Moisture

To investigate the scaling properties of soil moisture and how they vary temporally, a scaling analysis was performed on 10 am to 2 pm temporally averaged soil moisture for each of the 12 days of model runs. Figure 8 shows an example of a log-log plot of β versus order of moment. In looking at the 12 plots for each soil moisture level none of them exhibit signs of simple scaling, as the amount of variability changes as a function of resolution.

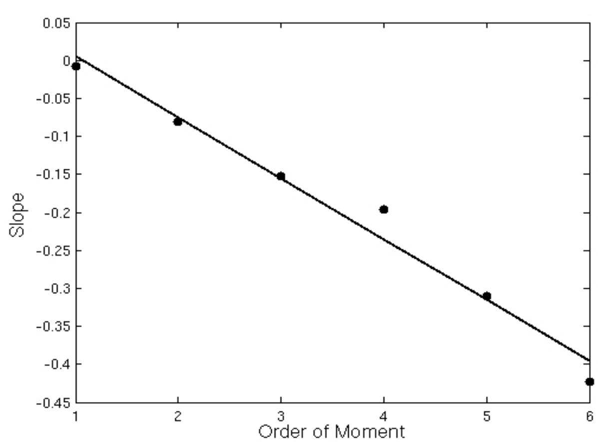

Figure 8. Slope versus order of moment for soil moisture from FC day 7. R^2 = 0.993

Timeseries of β and associated R^2 values are given in Figure 9. In general, fits are relatively good for β versus order of moment plots when the soil moisture is initialized at FC, indicated by high R^2 values (the lowest being 0.93). Fits are generally much poorer for 50FC and WP, with the exception of days 11 (R^2 of 0.96 for 50FC, 0.95 for WP) and 12 (R^2 of 0.99 for 50FC, 0.97 for WP), with day 12 possibly exhibiting signs of multiscaling for 50FC and WP. For all other days the fields appear to be scale dependent, and therefore cannot be used to predict statistical properties at other resolutions. The time evolution of β values for 50FC and WP behave extremely similar and are both distinctly different from FC. FC shows an increase in β through time in days 2 through 12.

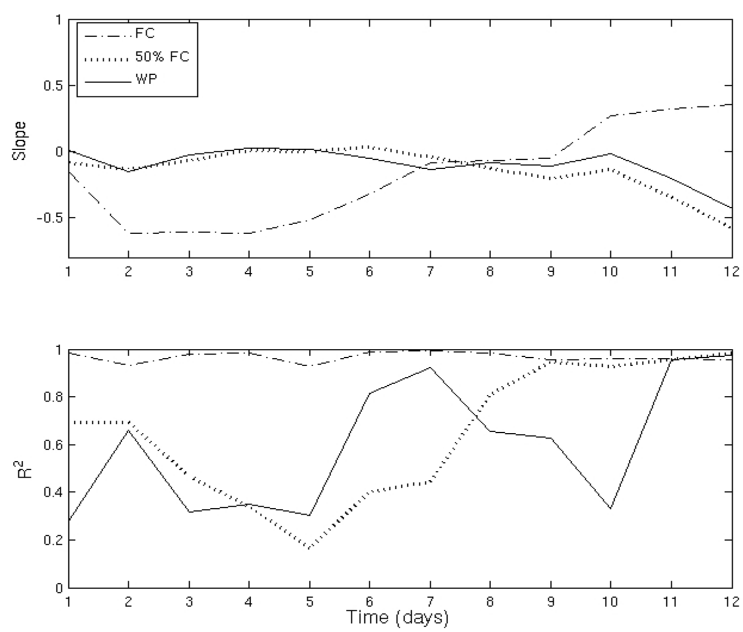

Figure 9. a) Timeseries of slope from soil moisture scaling plots for each initial soil moisture and b) associated R^2 values

Due to the fact that precipitation heavily influences the spatial and temporal heterogeneity of soil moisture, it was expected that the trends seen in $\overline{\sigma_T^2}$ of precipitation as a function of initial soil moisture and resolution would also be seen in the plot of $\overline{\sigma_T^2}$ of soil moisture (Figure 6b). Although this expectation holds for FC runs, 50FC and WP runs do not exhibit the same trend.

To provide a visual examination of spatial variance, soil moisture pdfs were plotted for each model run (Figure 10). The general shape of the density function remains the same regardless of initial soil moisture; however, density functions do show a decreasing trend in variance for all resolutions as the initial soil moisture decreases.

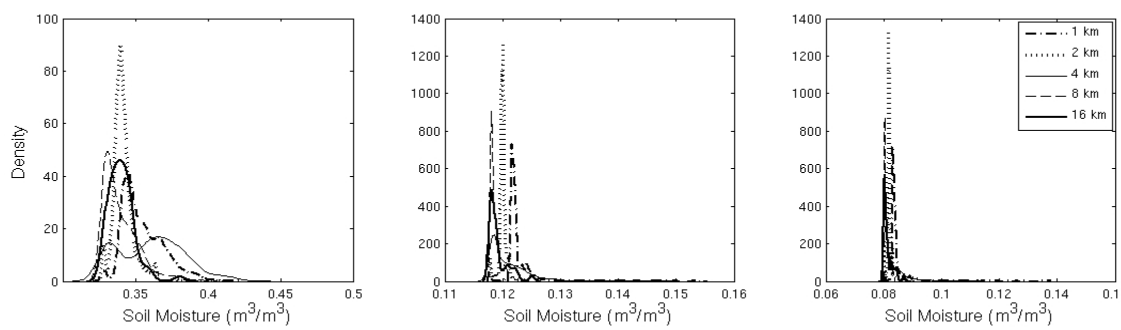

Figure 10. Probability density function of soil moisture for each model run a) FC b) 50FC c) WP

Timeseries of VMR (Figure 11) also show a general decrease with decreasing soil moisture. Values of VMR exhibit an overall increase with time for all resolutions at all initial soil moisture levels. The relationship between the different resolutions remains roughly the same as the initial soil moisture varies.

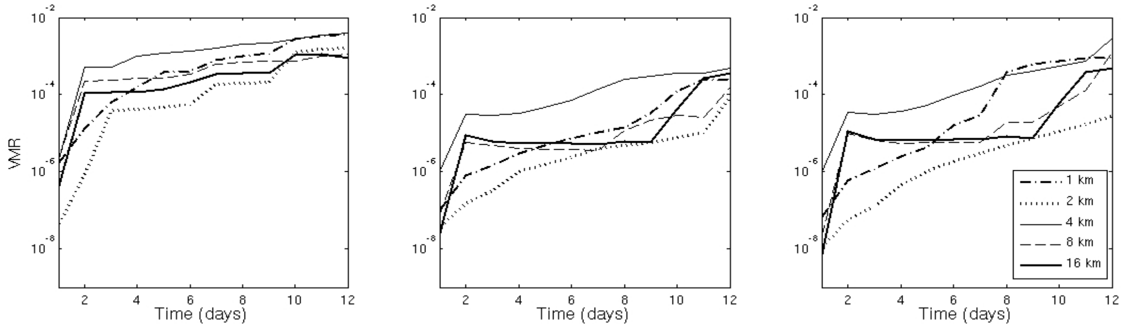

Figure 11. Timeseries of the ratio of spatial variance to spatial mean (VMR) for each resolution at each initial soil moisture a) FC b) 50FC c) WP

In order to provide a general comparison of the representation of soil moisture between runs, the RMSE was plotted (Figure 8b). FC runs consistently having the highest RMSE values, as was also true for precipitation. The main difference between RMSE for soil moisture and precipitation is that the 4 km runs have the lowest RMSE for all three soil moisture values. The general trend remains the same between the two variables, with FC having the highest error and 50FC the lowest.

2.6.3 Soil Moisture-Precipitation Interactions

To examine the temporal scales over which soil moisture-precipitation interactions occur, plots of temporally lagged correlation between 10 am to 2 pm temporally averaged soil moisture and total precipitation for each resolution at each initial soil moisture value were constructed (Figure 12). All of the correlations are positive, indicating that any feedback between soil moisture and precipitation must be positive. The highest correlations at each resolution generally occur at FC. The 1 km FC run has the overall highest correlation values, with moderate values extending out to around -7 days. These relatively high values, in at least the 1 and 2 km run FC runs, suggests a positive relationship between soil moisture and precipitation on the order of 5 to 10 days. Also worth noting, in the 1 km WP run the correlation remains almost constant from the zero lag out through -7 or -8 days. The low correlation values in the 50FC runs do not indicate a strong a relationship between soil moisture and precipitation, at least on this temporal scale.

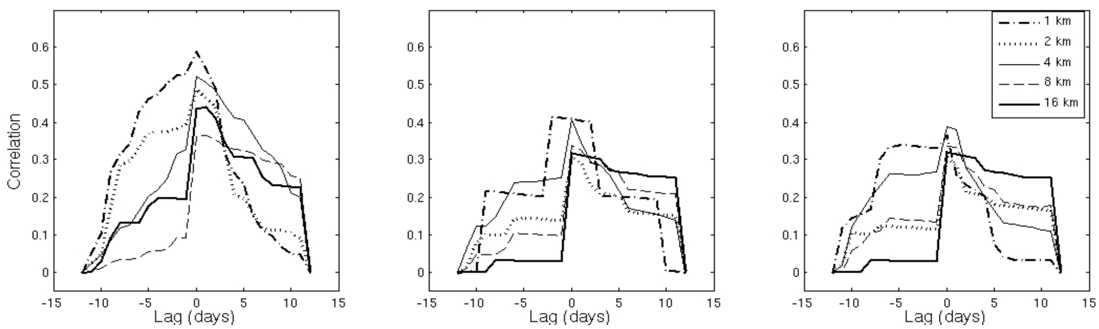

Figure 12. Temporally lagged correlation between total precipitation and 10 am to 2 pm temporally averaged soil moisture

The spatially averaged day of maximum temporally lagged correlation between total precipitation and 10 am to 2 pm temporally averaged soil moisture is shown in Figure 13. Error bars represent one standard deviation. The trends appear very similar in the 50FC and WP runs, the main difference being larger standard deviations in the 8 and 16 km WP runs. The main thing to note in these plots is that day of maximum correlation does not change much, if at all, in the 16 km runs as a function of initial soil moisture. There is a slight change in the 8 km runs, but in the 1, 2, and 4 km runs the change in day is much larger. The values are generally increasing in the negative direction beginning around 0 days for FC and shifting to around -5 days as soil moisture decreases.

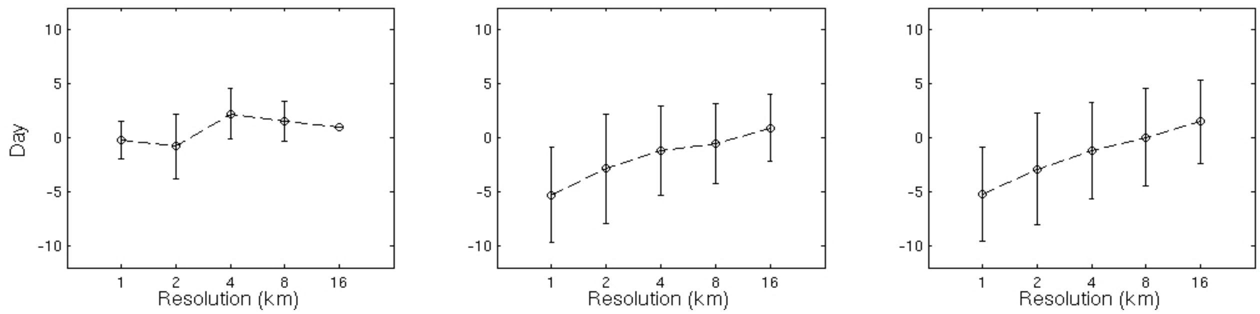

Figure 13. Day of maximum temporally lagged correlation between total precipitation and 10 am to 2 pm temporally averaged soil moisture was found at each pixel and then spatially averaged. Error bars show one standard deviation. a) FC b) 50FC c) WP

2.7 Discussion

2.7.1 Soil Moisture Scaling

Spatial patterns of soil moisture are influenced by soil properties, precipitation, evapotranspiration, and terrain through lateral flow. Each of these processes will be captured differently based on model resolution. The point here was to examine how soil moisture scales as a function of model resolution. Some care must be taken in drawing comparisons between other soil moisture scaling studies due to significant methodological differences. Other studies generally begin with one soil moisture field and aggregate this field to other resolutions to examine the scaling properties. The soil moisture data typically are remotely sensed or are obtained during large field campaigns where ideal days were chosen, with precipitation days often being avoided. Results from one given day may not apply to the next day and will be highly dependent on the method of averaging chosen. The goal was to examine how the scaling properties of soil moisture changed through time, as a function of individually modeled fields at differing resolutions. It is still possible to draw some comparisons between this and other studies but it will still be important to consider methodological differences which may impact the results.

Manfreda et al. (2007) used modeled soil moisture from the North American Land Data Assimilation System (NLDAS) at 0.125^o resolution, and after successively aggregating it to a resolution of 1.0^o, performed a scaling analysis on the variance. They found β values ranging from -0.32 to -0.12 in their top soil layer (10 cm). In a similar study, Rodriguez-Iturbe et al. (1995), using soil moisture data from the Washita '92 Experiment, which they aggregated from pixels of 200 x 200 m^2 up to 1000 x 1000 m^2, found β values between -0.21 and -0.28 for scaling plots of variance. In looking only at the slopes for the second moment (variance) from the 12 days of this analysis, only four days fall within the range of -0.14 to -0.39 from FC, five days fall within the range of -0.12 to -0.33 from 50FC, and only two days fall within the range of -0.12 and -0.33 from WP. It is important to note than many of these days are not consecutive and that the β values are, at times, highly variable from day to day.

Differences in the timing and magnitude of precipitation events between model resolutions will undoubtedly have significant impacts on the slopes. It has been shown during field campaigns, such as Washita '92, SGP '97, SMEX '02 and '04, that the level of soil moisture strongly influences the spatial variance of soil moisture patterns (Manfreda et al. 2007), which will be heavily influenced by precipitation. Examining soil moisture pdfs from 15 catchments around the world, Western et al. (2002) found that variance increases from near zero at WP, peaks at moderate values of soil moisture, and then decreases to near zero as the mean soil moisture approaches saturation. Although this dependence of variance on the amount of soil moisture will not impact scaling of variance in studies that rely on one field that has been aggregated to different resolutions, it will have an impact on this particular study where the amount of variance at a given resolution is completely independent of every other resolution.

2.7.2 Spatial Scaling of Total Precipitation

The idea of scaling in spatial precipitation fields has already been widely examined. Many studies have found that precipitation fields exhibit multiscaling characteristics, with non-linear change in β with order of moment (Gupta and Waymire 1990). Deidda (1999) specifically investigated the multiscaling properties of 6 hour precipitation fields obtained from a limited area model (LAM) with a horizontal resolution of 10 km and compared them to fields based on radar observations from the GATE campaign. His study found very good agreement between the modeled and radar fields and demonstrated that precipitation fields do exhibit multiscaling, but that it was more pronounced for shorter accumulation periods. This analysis, which was performed on total precipitation accumulated over the 12 day period for each of the three levels of initial soil moisture, did not find evidence of multiscaling. There may be many underlying reasons for this, including the accumulation timescale used and the fact that the representation of precipitation processes in numerical models is known to be problematic. At resolutions much larger than 1 km precipitation must be parameterized and current schemes do not accurately represent the physical processes involved in the occurrence of precipitation. Additionally, as was true for the soil moisture analysis, this study relies on precipitation fields at different resolutions obtained through independent model runs rather than obtaining fields through aggregation of one initial field. The plots do show a strong linear relationship between the third through the sixth order of moment. Relying only on how the variance scales with resolution, as many scaling studies have done in general, would result in distinctly different scaling properties. Also worth noting, in general daily precipitation fields exhibit extremely similar patterns in plots of β versus order of moment as cumulative plots, with the exception of day 1 for each of the three levels of initial soil moisture.

2.7.3 Soil Moisture-Precipitation Feedback

Determining the dominant resolutions at which interactions between soil moisture and precipitation can be captured has important implications for the improvement of weather and climate forecasting. As the scale of surface heterogeneity changes the dominant physical processes will also change. Presumably there will be some threshold of heterogeneity needed for the occurrence of a feedback between soil moisture and precipitation. The higher the resolution the more heterogeneity can be resolved by the model.

When examining the interactions between soil moisture and precipitation as a function of spatial scale, 1 km runs consistently have the largest amount of total precipitation and the highest frequency of precipitation events, though all of the FC runs have an equal number of events. Additionally, the magnitude of precipitation events is larger in 1 km runs regardless of the level of initial soil moisture. The relationship between soil moisture and precipitation also appears strongest in 1 km runs, which generally have the highest correlations (for negative lags), with the exception of several days in the 50FC run. Looking at cumulative precipitation amounts for each run, the 16 km 50FC and WP runs are exactly equal, which suggests that the 16 km resolution is not sensitive to differences between initial soil moisture in the 50FC and WP runs.

Feedbacks between soil moisture and precipitation can occur over moist and dry soils. Examining the series of 15 model runs shows that FC runs consistently have higher total precipitation amounts than the 50FC and WP runs, with the exception of the 8 km FC run, which provides some indication that a positive soil moisture-precipitation feedback may be occurring in these runs. This supports the results of Alonge et al. (2007), who found that dry soil regimes produced approximately 55% less precipitation than wet regimes. The relatively high, positive correlation values in the 1 and 2 km FC runs also suggests there may be a positive feedback occurring, but as previously emphasized causality cannot be inferred from linear correlations. It is also important to emphasize that for all runs correlation values are positive, indicating that any feedback occurring must be positive.

Summing precipitation over the domain at the daily timescale shows that FC runs also generally have a higher number of precipitation events over the 12 day period and that FC events are almost always larger in magnitude than 50FC and WP events. The temporal variance of soil moisture and precipitation were also consistently higher in FC runs by an exponential amount at all resolutions. Due to the fact that precipitation heavily influences the spatial and temporal heterogeneity of soil moisture, it was expected that the trends seen in $\overline{\sigma_T^2}$ of precipitation as a function of initial soil moisture and resolution would also be seen in the plot of $\overline{\sigma_T^2}$ of soil moisture. Although this holds for the FC runs it does not for the 50FC and WP runs. Examining pdfs of soil moisture and timeseries of VMR both show a general decrease in variance or dispersion with decreasing soil moisture at all resolutions.

2.7.4 Limitations

As with any study there are associated limitations and it is necessary to consider the results within the context of these limitations. Models are developed with a focus on a specific scale of interest. Processes occurring at this general scale are represented explicitly while those outside this scale of interest must be parameterized or greatly simplified. As a result, an issue of scale dependency in parameterization and model formulation limits the interpretation of scaling behavior of natural systems (Western et al. 2002). If the representation of physical processes within the model is not realistic an examination of scaling properties will only characterize the scaling behavior of the model rather than that of the process or variables of interest.

Precipitation frequency and amount are highly dependent on the choice of convective parameterization scheme. Additionally, precipitation amounts for the 1 and 2 km runs come solely from grid resolved precipitation while totals from 4, 8, and 16 km runs combine grid resolved with convectively parameterized precipitation. For these reasons the focus should not be on strict precipitation amounts but on how the amounts from different runs compare to one another.

The depth and number of soil layers can potentially have a large impact on soil moisture dynamics. For the sake of simplicity this study used only two soil layers, a top layer (20 cm) and a thicker layer below. The number of layers will impact wetting and drying processes including: evaporation, transpiration, infiltration, and runoff. In order to improve the study, ARPS would ideally be coupled to another model with the capability to improve the representation of the above hydrologic processes but also allow for groundwater dynamics and topographic redistribution of soil moisture.

Additionally the number of initial soil moisture values and model resolutions should be increased. This would help in the detection of thresholds in initial soil moisture or resolution that impact the relationship between soil moisture and precipitation.

2.8 Conclusions

Through the use of a mesoscale model it was found that the scaling properties of soil moisture are highly variable in time. This has important implications for the applicability of scaling properties in future studies, as what may be characteristic of one day cannot necessarily be applied to subsequent days. Scaling properties cannot be generalized, and as a result the analysis would have to be performed regularly to determine the scaling coefficients.

It was also found that cumulative precipitation fields did not exhibit signs of multiscaling, despite the general acceptance that precipitation can be described as such. Based on the study by Deidda (1999) this may be related to the long time scale of precipitation accumulation.

In terms of soil moisture-precipitation interactions, it has been demonstrated that soil moisture does impact the magnitude and frequency of precipitation events in the U.S. Central Plains. High soil moisture resulted in greater precipitation amounts and a higher frequency of events, suggesting the occurrence of a positive soil moisture-precipitation feedback. This has important implications for this region where agricultural production plays a large role in the economy, in addition to potential improvements in forecasting of regional weather and climate.

CHAPTER 3

ENERGY BALANCE PARTITIONING AND NET RADIATION CONTROLS ON SOIL MOISTURE-PRECIPITATION FEEDBACKS

3.1 Introduction

Land-atmosphere interactions play an important role in determining regional weather and climate. Although this idea has been widely accepted, an understanding of the physical processes and the scales over which these interactions occur remains somewhat limited. Improving the current understanding of these relationships has important implications for increasing predictability of local weather and climate. According to Barros and Hwu (2002), the basis of studies on land-atmosphere interactions is the idea that moisture and energy gradients across a landscape are associated with regional weather patterns over a wide range of spatial and temporal scales. Although soil moisture and vegetation impact the atmosphere through feedbacks with the land surface, the dominant processes driving these feedbacks have not been precisely determined and some disagreement still exists.

Previous research has shown evidence for the existence of a soil moisture-precipitation feedback (Eltahir 1998; Findell and Eltahir 1997; Pal and Eltahir 2001), which can be either positive or negative (Brunsell 2006). A positive feedback would be characterized by an increase in precipitation resulting from high soil moisture, or a continued suppression of precipitation resulting from anomalously dry soils. In the case of a negative feedback, increased precipitation would be associated with dry soils, while moist soils would act to suppress precipitation. In other words, a positive feedback acts to reinforce the initial change in the system while a negative feedback causes the system to diverge from the initial change.

By performing data analysis on observations of rainfall, temperature, and wet-bulb temperature from the Amazon Region Micrometeorological Experiment, Pal and Eltahir (1996) found that both the frequency and magnitude of localized convective storms increased with the surface wet-bulb temperature. As the amount of moisture in the soil increases, the wet-bulb depression decreases. Lower liquid condensation level (LCL) heights should correspond to smaller magnitude wet-bulb depressions, which according to Eltahir (1998), should enhance the likelihood for triggering moist convection and the occurrence of rainfall if all other factors remain the same.

Pal and Eltahir (2001) found evidence for the existence of a positive soil moisture-precipitation feedback in the U.S. Midwest. They showed that anomalously high soil moisture leads to an increase in the flux of high moist static energy air into the boundary layer from the surface through an increase in net surface radiation. An increase in the concentration of moist static energy occurs through a reduction in the height of the boundary layer, which occurs as a result of the anomalously moist soil. They attributed the increase in the frequency and magnitude of convective rainfall events to the increase in the amount of moist static energy per unit mass of air in the boundary layer.

Dong (2007) found a strong positive correlation between soil moisture and precipitation over grasslands at interannual time scales, while at the seasonal time scale they found a positive correlation between accumulations of cold season precipitation and springtime soil moisture, which became negatively correlated during summer. Although this may provide evidence for the existence of a feedback it is important to note that while correlations imply a relationship they cannot be used to infer causality.

Although all of the previously mentioned studies involve positive feedbacks, evidence also supports the existence of negative soil moisture-precipitation feedbacks. Negative feedbacks are associated with an increase in sensible heat flux over dry soils which can lead to an increase in turbulent mixing, boundary layer height, and convection (Findell and Eltahir 2003b). Findell and Eltahir (2003a), using a one-dimensional boundary layer model, found evidence for the existence of a negative soil moisture-precipitation feedback in the southwestern United States where the climate is dominated by a monsoon regime.

In another study, using data collected at the Blackwood Division of the Duke Forest near Durham, North Carolina and a simple slab model, Juang et al. (2007) found that conditions characterized by dry soil moisture and a dry atmosphere can induce convective precipitation. They suggested that a negative feedback may exist in the southeast region of the United States.

Cook et al. (2006), using the Community Climate System Model version 3 (CCSM3), found evidence for a negative feedback in southern Africa. They ran two simulations, a control case (CTRL) where soil moisture was allowed to interact dynamically with the atmosphere and a MOIST case where it was defined such that

ET would not be water limited. They saw a decreases in precipitation associated with their MOIST case when compared to their CTRL case.

The sign and magnitude of feedback varies spatially and temporally. A study involving twelve atmospheric general circulation model (AGCM) groups was coordinated by the Global Land-Atmosphere Coupling Experiment (GLACE) to detect regions of strong coupling between soil moisture and precipitation (Koster et al. 2004). They determined that the strongest coupling occurred in transition zones between wet and dry climates. They attribute this to the ability of boundary layer moisture to trigger convection in these areas, and the fact that evaporation is substantial enough yet still sensitive to the soil moisture state.

Knowing which physical processes are involved and identifying key features responsible for soil moisture-precipitation feedback is crucial for improving predictability of precipitation and other related variables and events. Pal and Eltahir (2001) emphasized the importance of the impacts of soil moisture on the energy and water budgets in determining the strength of soil moisture-precipitation feedback. Eltahir (1998) hypothesized the change in albedo and Bowen ratio (sensible heat/latent heat) as being the fundamental basis of the feedback. The foundation of this argument is that as soil moisture increases, the albedo decreases due to a darkening of the soil, which leads to an increase in net solar radiation. The Bowen ratio decreases as latent heat becomes larger than sensible, resulting in a decrease in surface temperature and an increase in the water vapor content of the boundary layer.

Therefore, when soil moisture is high, the decrease in albedo and Bowen ratio results in an increase in the net radiation at the surface (Eltahir 1998).

Teuling and Seneviratne (2008), using albedo estimates from the Moderate Resolution Imaging Spectrometer (MODIS) for the 2003 heat wave and drought over Europe, found that albedo responded oppositely to soil moisture anomalies in the visible and near-infrared portions of the spectrum. They determined that the impacts of dry soil alone would lead to higher albedos, however the response of vegetation to water stress resulted in opposite changes in spectral reflectance. For this specific case, their results did not support the existence of an albedo feedback induced by drought. Using eight years of Advanced Very High Resolution Radiometer (AVHRR) data, Brunsell (2006) found evidence to suggest that vegetation plays a dominant role in determining local feedbacks.

Spatial resolution plays an important role in almost any study as obtaining data at the appropriate resolution can sometimes pose a significant challenge. There are some ways to potentially overcome this issue, including the use of scaling coefficients calculated from spatial fields that exhibit statistical self-similarity. The idea of statistical self-similarity has been widely studied across a range of fields, including physics, ecology, hydrology, and atmospheric science. It has gained additional attention with the extensive use of remotely sensed data due to the potential for widespread application. By performing a scaling analysis it may be possible to infer variability at any other resolution if the field exhibits self-similarity, i.e. scale invariance. A process is said to be scaling, or self-similar, if the process behaves similarly at both small and large scales, i.e. the statistical properties of the field do not vary as a function of scale (Bloschl 2001).

The idea of spatial scaling is certainly not new and much work has already been done specifically on soil moisture and precipitation (Deidda 1999; Rodriguez-Iturbe et al. 1995; Waymire 1985; Western and Bloschl 1999). Research has already begun to take advantage of remotely sensed fields due to the availability of data where surface measurements either do not exist or are unavailable at consistent spatial and temporal scales. Field measurements of surface soil moisture, for example, cannot be taken over large areas or with the temporal frequency required for effective use. Although remote sensing has improved the spatial and temporal resolution of data for variables such as soil moisture, complications still arise as a result of resolution. Differences in resolution make it difficult to validate remotely sensed data with surface measurements or larger scale models (Brunsell and Gillies 2003a).

Statistical self-similarity can potentially be used to circumvent resolution issues associated with remotely sensed data. A process is defined as self-similar if:

$$\phi(x) = \lambda^{-\beta} \cdot \phi(\lambda \cdot x)\,, \tag{1}$$

where ϕ represents the field, x is the spatial scale, λ is the ratio of the large scale $\lambda \cdot x$ to the small scale x, and β is the scaling exponent (slope) (Bloschl 1996). If a field exhibits statistical self-similarity it can be used to infer model variability at any other resolution (Halley et al. 2004).

In determining the scaling properties of a field, some studies have focused on the variance (Baldocchi et al. 2005) and others on high-order statistical moments

(Brunsell and Gillies 2003b; Dubayah et al. 1997). Using higher-order moments provides more information on the statistical properties and structure of the field as opposed to the variance. A field ϕ is said to be spatially scaling with respect to moment q if the following relationship holds:

$$E[(\phi_\lambda)^q \propto \lambda^{K(q)} E[(\phi_1)^q], \quad (2)$$

where $K(q)$ is the scaling exponent associated with moment q (equal to β in equation 1 above) (Peters-Lidard et al. 2001). For a process or field to exhibit simple scaling a plot of β versus order of moment must be linear (Gupta and Waymire 1990). If the process is truly scale invariant then the amount of variability in the field does not change as a function of scale. For a multiscaling process the amount of variability changes as a function of scale which can be seen as a non-linear change in β with order of moment. A field or process may exhibit either scaling or multiscaling characteristics, or it may be scale dependent meaning that knowledge at one scale cannot be used to predict variability at other scales.

Chapter two already investigated the scaling properties of precipitation and soil moisture; however, it is well-known that soil moisture strongly influences other surface variables, including soil temperature and Bowen ratio, in a non-linear way. The second objective of this study was to examine the impacts of varying mean soil moisture on the scaling properties of 10 am to 2 pm temporally averaged soil temperature and Bowen ratio, with a specific emphasis on how these scaling relationships vary temporally, as this has important implications for the use of remotely sensed fields in future research.

The goal is to investigate the relative importance of energy balance partitioning and net radiation in soil moisture-precipitation feedbacks and to examine how the dominant physical process are impacted by changes in mean soil moisture and spatial resolution.

3.2 Model Description

In order to examine the physical processes involved in soil moisture-precipitation interactions and to investigate the impacts of mean soil moisture on the scaling properties of soil temperature and Bowen ratio, a series of model runs were conducted using the University of Oklahoma's Advanced Regional Prediction System (ARPS). ARPS is a three-dimensional, nonhydrostatic, compressible model which was developed at the Center for Analysis and Prediction of Storms (CAPS) to be used for real-time forecasting and to serve as a tool for research (Xue et al. 2000, 2001).

To examine the impacts of mean soil moisture and resolution on soil moisture-precipitation interactions, a suite of 15 model runs was conducted (Figure 14). The horizontal resolutions used in this study include 1, 2, 4, 8, and 16 km. At each of these resolutions initial soil moisture was varied from field capacity (0.35), to 50% of field capacity (0.13), to wilting point (0.09). This made it possible to examine how the dominant physical processes vary both as a function of mean soil moisture and resolution.

	Field Capacity (FC)	50% of Field Capacity (50FC)	Wilting Point (WP)
1 km	θ = FC, R = 1 km	θ = 50FC, R = 1 km	θ = WP, R = 1 km
2 km	θ = FC, R = 2 km	θ = 50FC, R = 2 km	θ = WP, R = 2 km
4 km	θ = FC, R = 4 km	θ = 50FC, R = 4 km	θ = WP, R = 4 km
8 km	θ = FC, R = 8 km	θ = 50FC, R = 8 km	θ = WP, R = 8 km
16 km	θ = FC, R = 16 km	θ = 50FC, R = 16 km	θ = WP, R = 16 km

Figure 14. Suite of 15 model runs conducted with varying resolutions and initial soil moisture values using the Advanced Regional Prediction System (ARPS)

A standard midlatitude summer sounding, modified to ensure westerly winds at all levels, was used to initialize all runs. Soil and vegetation properties are homogeneous across the domain, with soil type sandy loam and vegetation being grassland with an LAI of 0.31.

Convective processes cannot be explicitly resolved at resolutions much coarser than 1 km (Chen and Avissar 1994). As a result the Kain-Fritch Weather Research Forecasting (WRF) parameterization scheme was used in the 4, 8, and 16 km runs. This scheme was chosen because it is more suitable for higher resolution grids and has the ability to generate sources of rainwater and snow which are fed back to grid scale variables which then interact with ice microphysics processes (Xue et al. 2001).

As precipitation resulting from soil moisture feedbacks is convective in nature and synoptic impacts are not of interest in this particular study, one-way interactive grid nesting was chosen. Two-way nesting would be necessary to capture mesoscale impacts on the synoptic environment which would then feedback to modify the mesoscale environment. For the purposes of this study these mesoscale interactions are unnecessary due to the fact that the study is attempting to ascertain physical processes associated with soil moisture-precipitation feedbacks and not the accurate simulation of a particular synoptic case study.

Coarse runs for the one-way nesting were conducted over the outer domain (Figure 15), which covers an area of 4,194,304 km^2, using a horizontal resolution of 16 km over a period of 20 days beginning on August 18th. These runs were initialized using the same characteristics as the inner grid, which covers an area of 16,384 km^2, to maintain comparability between all runs. The first four days of each coarse resolution run were regarded as spin-up and discarded, leaving 16 days to force the inner grid at the 1, 2, 4, 8, and 16 km resolutions. The vertical grid was composed of 83 layers, with higher resolution at the surface (approximately 100 m), decreasing exponentially with distance from the surface, with a resolution of approximately 500 m at the top of the model domain.

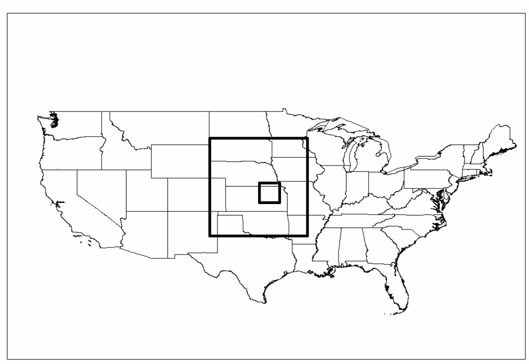

Figure 15. Model domain centered on the Konza Prairie in northeastern Kansas

3.3 Site Description

The model domain focuses on the U.S. Central Plains, which was selected due to its importance as an agricultural region. The center of the domain was specifically placed on the Konza Prairie, which covers an area of approximately 34.87 km^2 (Lett and Knapp 2005) in the Flint Hills of northeastern Kansas near Manhattan, KS (39°05'N, 96°35'W). The land is owned by the Nature Conservancy and managed by Kansas State University as a National Science Foundation (NSF) Long-Term Ecological Research Station (LTER). Much of the research conducted at Konza focuses on climate and the current management program includes periodic burning and the reintroduction of native grazers (i.e. buffalo) (Kaste et al. 2006).

The climate can be characterized as temperate mid-continental with cold, dry winters and warm, wet summers (Nippert et al. 2006) with annual temperatures ranging from a low of -2.7 °C in January to a high of 26.6 °C in July (Fay et al. 2003). Approximately 75% of the mean annual precipitation (835mm) falls during the growing season between April and September (Lett and Knapp 2005).

Being located within the Flint Hills region, the soils are rich and thin, overlaid on alternating layers of limestone and shale. The soil types vary in the area from Ustolls to Udolls including deep silt loam and silty clay loams soils. Steep-sided lowlands and flat upland ridges characterize the terrain at Konza (Lett and Knapp 2005). Native tallgrass prairie comprises the majority of the vegetation; with perennial warmseason grasses such as little blue stem (*Schizachyrium scoparium*

Michx), big bluestem (*Andropogon gerardii Vitman*), Indian grass (*Sorghastrum nutans (L.) Nash*), and switch grass (*Panicum virgatum L.*) dominating (Kaste et al. 2006).

3.4 Methodology

3.4.1 Net Radiation vs. Energy Balance Partitioning

In order to evaluate how net radiation (R_n) and energy balance partitioning change as a function of model resolution and mean soil moisture, the Root-Mean Square Error (RMSE) was calculated between the 1 km runs and every other resolution

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(x_{1,i} - x_{2,i})^2}{n}}\,, \tag{3}$$

where n is the number of points, and x_1 and x_2 are the variables between which the error is calculated. The 1 km runs were used as "truth" as they are able to resolve more of the small scale physical processes and capture more of the variability in surface properties which can potentially impact net radiation and partitioning into sensible and latent heat fluxes. Although the RMSE is typically used as an error estimate here it will be used as a metric to evaluate differences as a function of model resolution.

Previous studies have argued that soil moisture-precipitation feedbacks are driven by an increase in net radiation associated with a lowering of the albedo over moist soils (Eltahir 1998). In order to investigate the validity of this argument scatter plots of soil moisture versus net radiation were constructed. Additionally, scatter plots of soil moisture versus Bowen ratio were constructed to look for soil moisture impacts on surface energy balance partitioning, which is hypothesized to be the dominant process impacting the feedback mechanism (Brunsell 2006).

3.4.2 Lagged Correlations

It is hypothesized that changes in energy balance partitioning will impact precipitation more prominently than variation in net radiation through a soil moisture feedback. Chapter two found evidence for a positive soil moisture feedback in the Central Great Plains. Runs initialized at field capacity consistently exhibited higher total precipitation amounts and had a higher frequency of events. Lagged correlations were used to show the temporal scales over which the feedback mechanism occurs.

Here lagged correlations will be used to examine the temporal scales over which latent and sensible heat fluxes, Bowen ratio, and net radiation impact precipitation. Temporally lagged correlations are given by:

$$\hat{R}_{xy}(m) = \sum_{n=0}^{N-m-1} x_{n+m} y_n \,, \qquad m \geq 1 \tag{4}$$

$$\hat{R}_{xy}(m) = \hat{R}_{yx}(-m)\,, \qquad m < 0 \tag{5}$$

Where $\hat{R}_{xy}$ is the correlation, *x* and *y* are stationary random variables, *N* is the number of points and *m* is the lag. Positive lags indicate that precipitation is leading the other variable, while negative lags indicate that precipitation is being lead by the other variable.

The day at which the maximum lag correlation occurs is examined as a function of model resolution and mean soil moisture to determine the time scale associated with land-atmosphere feedbacks. Feedbacks involving dry versus wet soil may occur on different temporal scales. This is highly likely as the physical processes involved in the feedback differ as a function of soil moisture level as discussed in section 3.1 of this chapter. In order to determine whether there are consistent trends as a function of model resolution and mean soil moisture the day of maximum lagged correlation was found for each pixel, neglecting the zero lag, and then spatially averaged for each model run.

3.4.3 Information Content

As another method for assessing variability between individual model runs, entropy was calculated entropy:

$$H(x) = \frac{-\sum_{i=1}^{n} p_i(x) \log_2 p_i(x)}{\log_2(n)}, \tag{6}$$

where H is the entropy, x is the variable of interest, and $p_i(x)$ is the probability mass function, or the probability that x is exactly equal to some value (Shannon 1948). H is an information metric, i.e. a measure of the average information content (in bytes), which provides an indication of how much uncertainty is associated with a random variable (Brunsell and Young 2008; Brunsell et al. 2008). A higher H corresponds to less useable information. This presumably will vary as a function of model resolution, and also may vary as a function of initial soil moisture. It is expected that higher resolutions will correspond with lower values of *H* as they are able to capture more heterogeneity in surface characteristics and are better able to resolve smaller scale physical processes than coarser resolutions, resulting in a higher information content.

It is also possible to compute the amount of entropy contained within a system of two independent variables. The joint entropy of two variables is given by

$$JE(x, y) = -\sum_{i,j} p(i, j) \log_2 p(i, j), \tag{7}$$

where *JE* is the joint entropy and *p(x, y)* is the joint probability of *i* for the first variable and *j* for the second. The joint entropy must always be greater than or equal to the amount of entropy associated with the individual variables, as adding another variable cannot decrease the amount of information within the system. Joint entropy is calculated as an intermediate step to obtaining the mutual information content of the two variables.

The entropy and joint entropy can be used to calculate the mutual information content, or mutual dependence, of two variables:

$$I(x, y) = H(x) + H(y) - JE(x, y), \tag{8}$$

where *I* is the mutual information content, *H(x)* the entropy of *x*, *H(y)* the entropy of *y*, and *JE(x, y)* the joint entropy of *x* and *y*. This provides a measure of the amount of information known about one variable given the other (i.e. redundancy), or the decrease in uncertainty in one variable given the other.

The spatial entropy was calculated at an hourly timescale for soil moisture, precipitation, Bowen ratio, net radiation, and sensible and latent heat flux and then averaged to the daily timescale. The mutual information content was then calculated hourly and averaged to daily values for soil moisture and precipitation, soil moisture and Bowen ratio, and soil moisture and net radiation. Timeseries plots will provide an indication as to the strength of the relationship between these variables and how it varies temporally as a function of mean soil moisture and spatial resolution.

3.4.4 Turbulent Mixing and Boundary Layer Height

At coarser resolutions the model may be unable to capture mesoscale circulations resulting from heterogeneity in surface characteristics, which may play an important role in the dynamics of soil moisture-precipitation feedback mechanisms. As the main objective of this study was to examine the physical processes involved in the feedback and determine which have a dominant role, the relative impact of horizontal versus vertical motions is investigated. This presumably will vary as a function of model resolution, as mentioned above, but also as a function of mean soil moisture. Due to lower sensible heat fluxes FC runs are expected to have less turbulent mixing and as a result a lower boundary layer height. To verify this hypothesis the spatially averaged vertical profile of the ratio of 10am to 2pm temporally averaged vertical to horizontal turbulent mixing coefficients for momentum (km_v/km_h) was calculated and then the profiles for each of the 12 days were temporally averaged for each model run.

3.4.5 Spatial Scaling

In order to determine the variation in spatial scaling as a function of mean soil moisture and resolution, a scaling analysis is performed on model generated fields of 10 am to 2 pm temporally averaged soil temperature and Bowen ratio. Although different methodologies exist for determining the scaling properties, the statistical moments are calculated as they provide information on the spatial structure of the field. Other studies have chosen only to examine how the variance scales but calculating the moments will allow us to more fully characterize the statistical scaling relationships. If a scaling relationship does exist then it can then be used to calculate any of the statistical moments at any other resolution.

The analysis was performed on 10am to 2pm temporally averaged soil temperature and Bowen ratio by calculating the first six statistical moments. The first moment is given by Equation 9:

$$X^1 = \frac{1}{N}\sum x_i \tag{9}$$

the second moment by Equation 10:

$$X^2 = \frac{1}{N}\sum (x_i - \bar{x})^2 \tag{10}$$

and Equation 11 is used to obtain the third through sixth moments:

$$X^n = \frac{\frac{1}{N}\sum (x_i - \bar{x})^n}{\sigma^n} \quad , \tag{11}$$

where n is the order of moment, N is the number of points, $\bar{x}$ the mean, and σ the standard deviation. The six moments are plotted versus resolution on a log-log scale:

$$\log(\varphi) = \log(\alpha) + \beta * \log(\lambda), \tag{12}$$

where λ is spatial resolution, β is the scaling exponent (slope), and α the intercept, determined by linear regression (Brunsell and Gillies 2003b). β values are then plotted versus order of moment on a log-log scale.

In order to ascertain the model's capability to capture the dominant processes controlling soil moisture-precipitation feedbacks, soil temperature and Bowen ratio fields that have been obtained through individual model runs at varying resolutions are used, rather than beginning with one field and aggregating it to other resolutions. The majority of scaling analyses, regardless of the variable of interest, have been based on fields aggregated, or filtered, from an initial resolution. This will undoubtedly have a large impact on the scaling properties of the field.

In addition to quantifying the scaling coefficients at one point in time, the temporal variability in the spatial scaling relationship is examined. The interest lies in observing the scaling characteristics based on fields that are completely independent of one another and examining how these characteristics vary temporally. The ultimate goal is to determine whether there are scaling properties intrinsic to the field that will allow for the estimation of statistical properties at resolutions other than the modeled resolutions at different times. This has important implications for the use of remotely sensed data as input to numerical models and for the comparison of model output with remotely sensed fields.

3.5 Results

3.5.1 Net Radiation vs. Energy Balance Partitioning

Plots of RMSE for net radiation, latent, and sensible heat flux are shown in Figure 3. For net radiation (Figure 16a) there is an increasing trend in RMSE as a function of resolution. Mean soil moisture does not appear to have an impact on the RMSE. This does not hold for latent (Figure 16b) and sensible heat (Figure 16c), where clear trends are associated with mean soil moisture. FC runs have consistently higher RMSE values for latent heat and lower values for sensible heat. They also maintain an increasing trend with resolution. The 50FC and WP are distinctly different from the FC runs, but behave similarly to one another for net radiation, latent, and sensible heat. They are both associated with an increasing trend for sensible heat, but there is a step between 2 and 4 km for latent heat flux.

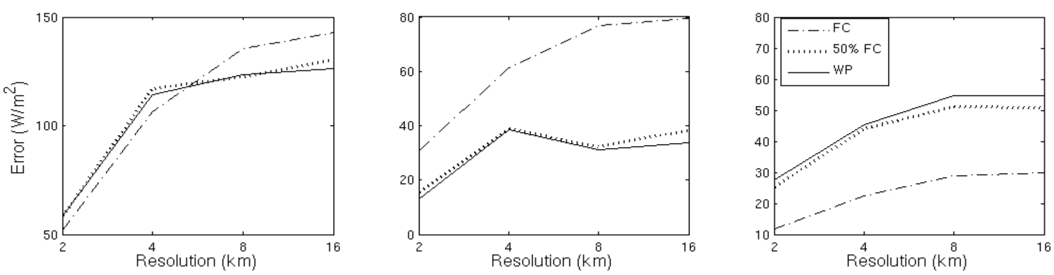

Figure 16. The Root-Mean Squared Error (RMSE) was calculated between 1 km runs and every other resolution for a) net radiation b) latent heat flux and c) sensible heat flux

Scatter plots of Bowen ratio versus soil moisture (Figure 17a) show a clear relationship, with Bowen ratio values decreasing as soil moisture increases. This is expected, with higher latent heat fluxes associated with higher soil moisture levels. This demonstrates that soil moisture does have a significant impact on energy balance partitioning. However, scatter plots of net radiation versus soil moisture (Figure 17b) do not show a clear relationship. Here an increase in net radiation does not appear to be associated with higher soil moisture values, which would be expected from a lowering of the albedo over moist soils.

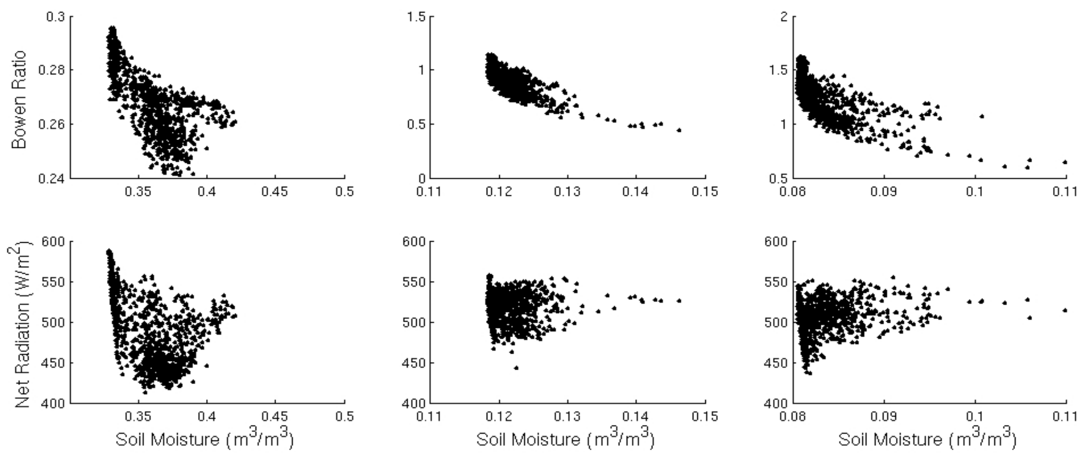

Figure 17. Scatter plots of soil moisture versus Bowen ratio (top) a) FC b) 50FC c) WP and soil moisture versus net radiation (bottom) d) FC e) 50FC f) WP for the 4 km runs

3.5.2 Information Theory Metrics

Timeseries plots of entropy at each initial soil moisture value and spatial resolution for latent heat and net radiation are shown in Figure 18. For latent heat, entropy values for FC runs are all clustered between 0.8 and 0.9, while the 50FC and WP runs show a larger range of values and more temporal variability. In the case of net radiation, 4, 8, and 16 km runs shows similar changes in entropy values over time regardless of initial soil moisture. The 1 km runs generally have the lowest values. For sensible heat (not shown), FC exhibits a clear increase in entropy values with resolutions, but for 50FC and WP the 4 km runs behave similarly to the 1 km run while the 2 km runs show similar characteristics to the 8 and 16 km runs. Plots of entropy for Bowen ratio (not shown) indicate a clear trend in H as a function of resolution for FC, with the 1 km run having the lowest values and 16 km the highest. This trend generally holds for 50FC and WP, with the 4 km run occasionally having lower values than the 2 km runs. Values of H are relatively similar for all resolutions at 50FC and WP, while FC runs show a greater range of values. The 4, 8, and 16 km 50FC and WP runs remain very similar to FC, with the main difference being the increase in entropy values in the 1 and 2 km runs.

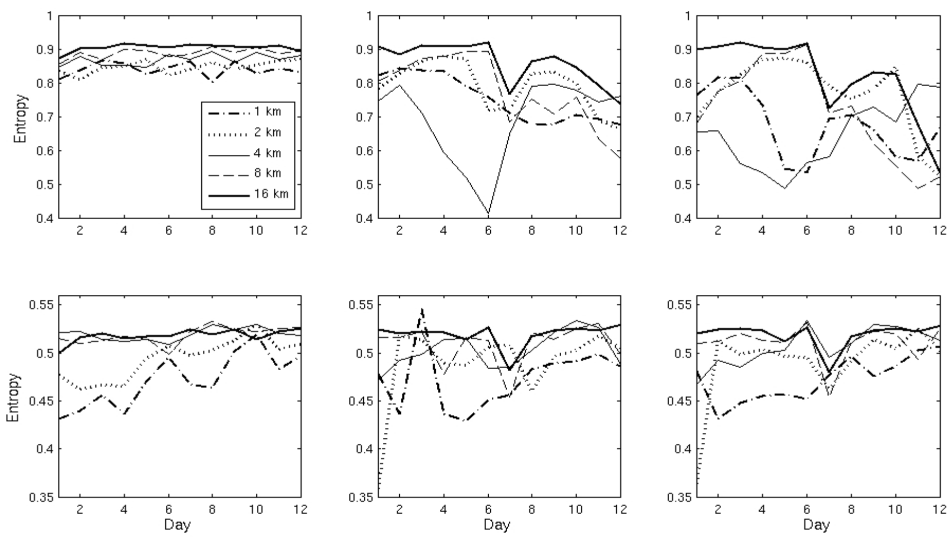

Figure 18. Timeseries of daily averaged entropy for latent heat flux (top) a) FC b) 50FC c) WP and net radiation (bottom) d) FC e) 50FC f) WP

Joint entropy was then calculated between soil moisture and Bowen ratio and soil moisture and net radiation. This allowed for the examination of the mutual information content (I). Figure 19a, b, and c show a timeseries of I for soil moisture and Bowen ratio. For FC the 1 and 2 km runs exhibit the lowest values of I with similar temporal trends. 50FC and WP plots look extremely similar, with no obvious trend as a function of resolution. The value of *I* for 1 km 50FC and WP runs generally decreases over time. Timeseries of *I* for soil moisture and net radiation (Figure 19d, e, and f) closely resemble those for soil moisture and Bowen ratio, with the main difference being lower values of *I* for all model runs.

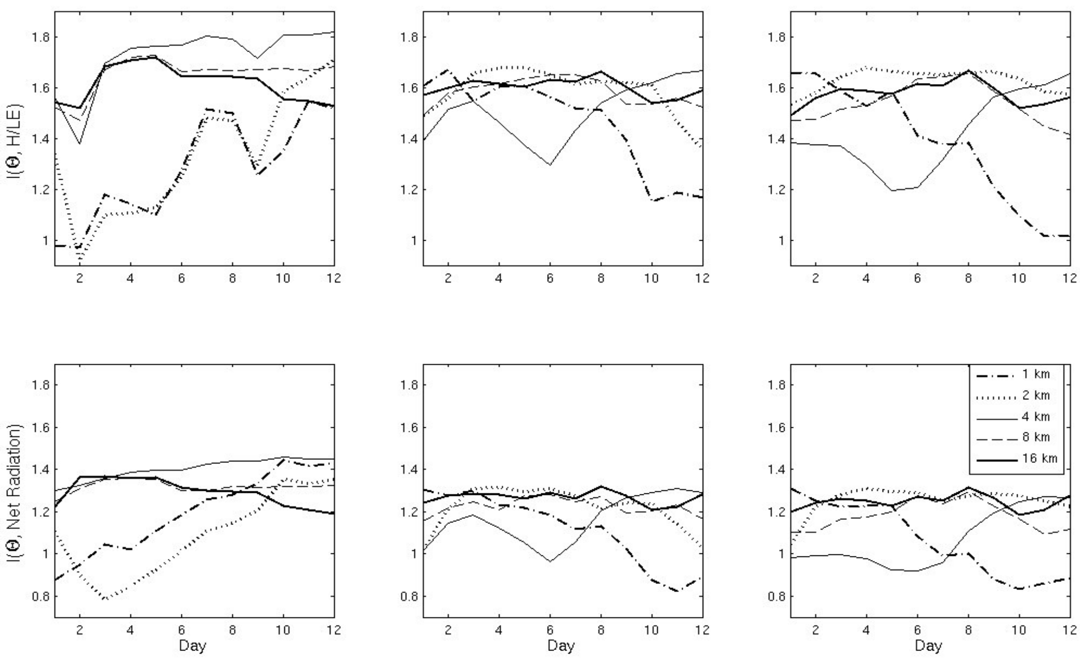

Figure 19. Timeseries plots of daily averaged mutual information content between soil moisture and Bowen ratio (top) a) FC b) 50FC c) WP (top) and between soil moisture and net radiation (bottom) d) FC e) 50FC f) WP

3.5.3 Lagged Correlations

Figure 20a, b, and c show the spatial average of day of maximum lagged correlation for Bowen ratio and precipitation as a function of spatial resolution. The 50FC and WP plots exhibit a distinct trend, with the day of maximum lagged correlation shifting from negative values in the 1 km runs to increasingly positive values as resolution become coarser. The spatial standard deviation also generally decreases as a function of resolution. The lag for the 1 km FC run is larger than that of the 50FC and WP runs and the decrease in standard deviation occurs much more rapidly with resolution, approaching zero.

The day of maximum lagged correlation between latent heat and precipitation (Figure 20d, e, f) changes sign for 50FC and WP runs as resolution increases, shifting from approximately -4 to +5. Spatial standard deviations are once again smaller for FC runs and there is also a shift in sign for day of maximum lagged correlation in FC runs. The trend is not as large or consistent as in 50FC and WP, with a positive trend from 1 to 8 km and then a slight decrease occurs at 16 km. Day of maximum correlation plots for sensible heat flux (Figure 20g, h i) are nearly identical to those of latent heat flux, however the shift between the 1 and 2 km runs for 50FC and WP is more dramatic for sensible heat flux.

Plots of day of maximum lagged correlation between net radiation and precipitation (Figure 20j, k, and l) show a large change in day as a function of resolution, with the largest changes occurring in the 50FC and WP runs. The 1 km runs also show a trend in day as a function of initial soil moisture. In looking only at the 1 km runs there is a shift from around -3 to -5 days in the FC run to around -6 or -7 days in the WP runs.

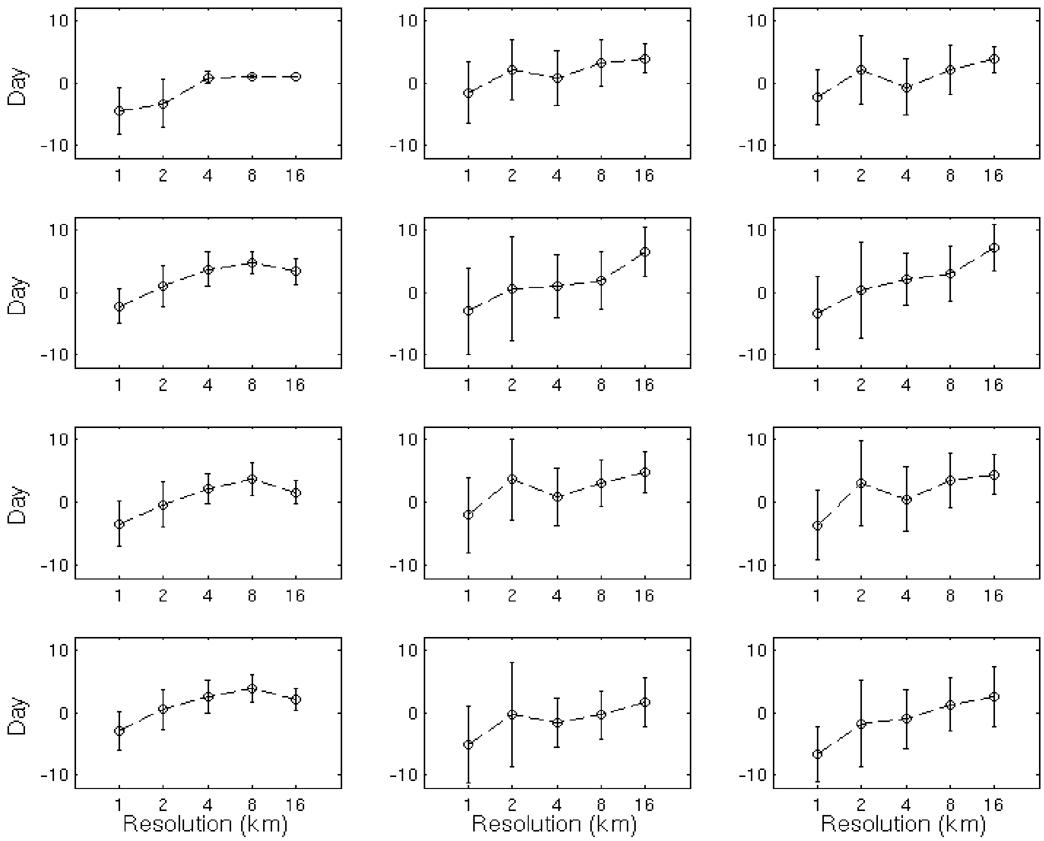

Figure 20. Spatially averaged day of maximum lagged correlation between daily total precipitation and 10 am to 2 pm temporally averaged Bowen ratio a) FC b) 50FC c) WP (top); latent heat flux d) FC e) 50FC f) WP (row 2); sensible heat flux g) FC h) 50FC i) WP (row 3); net radiation j) FC k) 50FC l) WP (bottom)

Lagged correlations between Bowen Ratio and precipitation (not shown) exhibit the highest correlations associated with FC. Values either remain similar or decrease as soil moisture decreases. For the 1 and 2 km FC runs correlation values oscillate but consistently remain between 0.3 and 0.5 to approximately -10 days. Correlation values for 4 km FC are above 0.5 for the first couple positive lags and then remain at or above 0.4 out to approximately +5 days.

For the lagged correlations between latent heat and precipitation (not shown), there were much higher values for FC than 50FC and WP. The 1 km FC once again has the highest correlation values, remaining at or above 0.4 out to approximately -7 to -8 days. As was also true for Bowen ratio, 50FC and WP plots are strikingly similar.

Lagged correlations between sensible heat flux and precipitation were also calculated (not shown). FC runs have higher correlation values, as was the case for latent heat flux, but values are generally lower than for latent heat flux. All correlation values for 50FC and WP are below 0.4.

Plots of lagged correlation between net radiation and precipitation (not shown) resemble those of latent heat flux, with relatively high correlation values for FC. Once again the 1 km FC run has the highest correlation, with values between 0.4 and 0.5 extending out to -5 lags. 50FC and WP runs are very similar; except for a peak in the correlation in the 1 km WP run at around -6 or -7 lags.

3.5.4 Turbulent Mixing and Boundary Layer Depth

Figure 21a provides an example of the spatially and temporally averaged vertical profiles of km_v/km_h. FC profiles are consistently characterized by a smaller ratio, as was hypothesized. Higher sensible heat flux in 50FC and WP runs leads to increased turbulent mixing with larger vertical motions. These profiles indicate a much larger boundary layer depth associated with 50FC and WP runs.

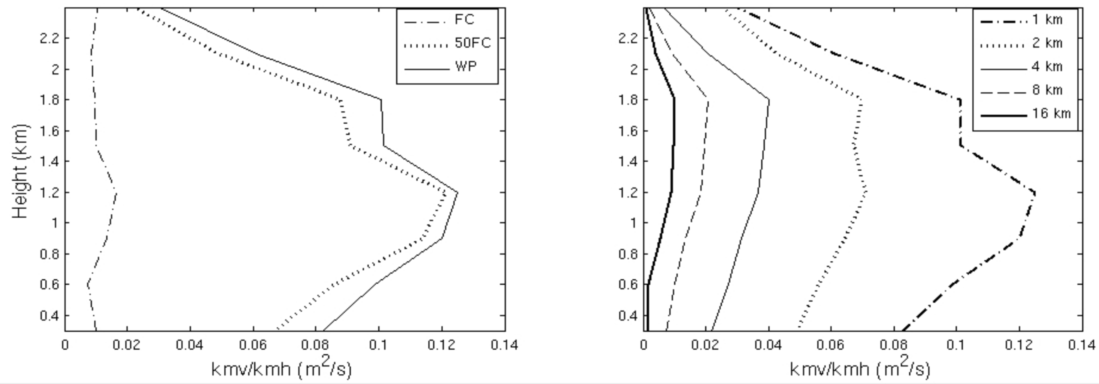

Figure 21. Spatially and temporally averaged vertical profiles of a) kmv/kmh for each mean soil moisture at 1km spatial resolution b) WP kmv/kmh at each spatial resolution

Resolution also has a significant impact on the ratio of km_v/km_h,. Figure 21b shows vertical profiles for each spatial resolution at WP. The ratio consistently decreases as the spatial resolution becomes coarser, which presumably will have a large impact on the dynamics of the soil moisture-precipitation feedback mechanism as the turbulent motions are not being captured as well at coarser resolutions. This will have an impact on the transport of moisture and boundary layer dynamics, which both play a role in the feedback. Although only WP runs are shown, the same trend exists in FC and 50FC runs as well.

3.5.5 Spatial Scaling

The scaling analysis was performed on 10am to 2pm temporally averaged Bowen Ratio using the first six statistical moments for each of the 12 days of model output. For FC there is a relatively strong relationship between the first moment and the third through sixth, while the second moment (variance) negatively affects the quality of the linear regression. In looking only at log-log plots of the variance versus resolution, in general strong linear relationships can be seen, suggesting that the second moment scales with resolution and could be used to predict the spatial variance at any other resolution.

Ignoring the second moment for 50FC and WP would not bring as significant of an improvement in linear regressions, as fits in general would not be as good as for FC. Additionally, on many days the log-log plots of variance versus resolution do not show fits as good as those seen in FC plots. Figure 22 shows timeseries of R^2 values and slopes from β versus order of moment plots. With the exception of the first two days, slopes are similar for all three levels of soil moisture. FC generally has the lowest R^2 values, though these reflect the poorness of fit associated with the outlying second moments.

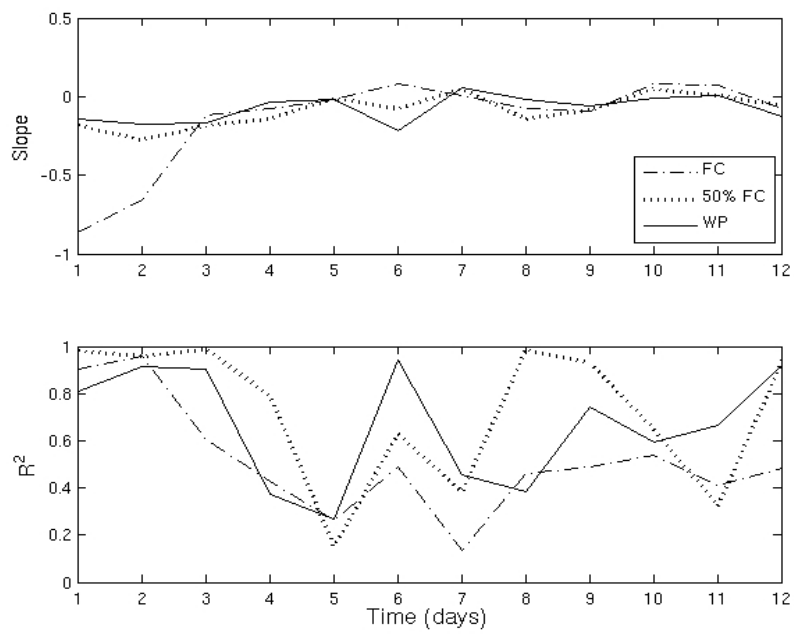

Figure 22. a) Timeseries of slope from β versus order of moment plots for Bowen ratio b) associated R^2 values

The plots of β versus order of moment for soil temperature do not exhibit signs of scaling or multiscaling, meaning that they cannot be used to infer variability at other resolutions. This is true for all levels of mean soil moisture. With the exception of several days for each mean soil moisture level, log-log plots of variance versus resolution show very good fits (Figure 23). This indicates that these plots can be used to predict the variance of soil temperature fields at any other resolution.

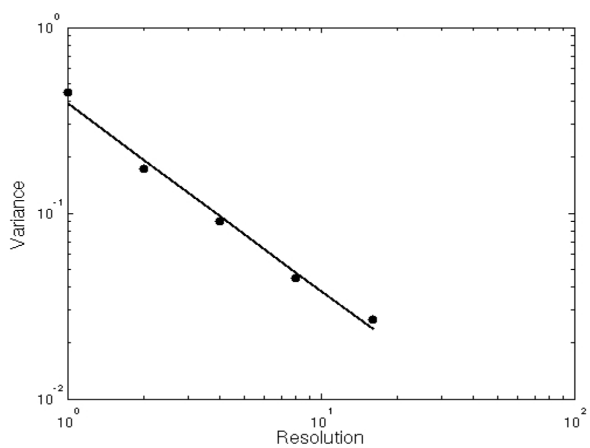

Figure 23. Scaling of the second moment (variance) for soil temperature from FC day 4

Looking at the R^2 values for FC (Figure 24) is extremely deceiving, as a significant amount of scatter can be found in these plots.

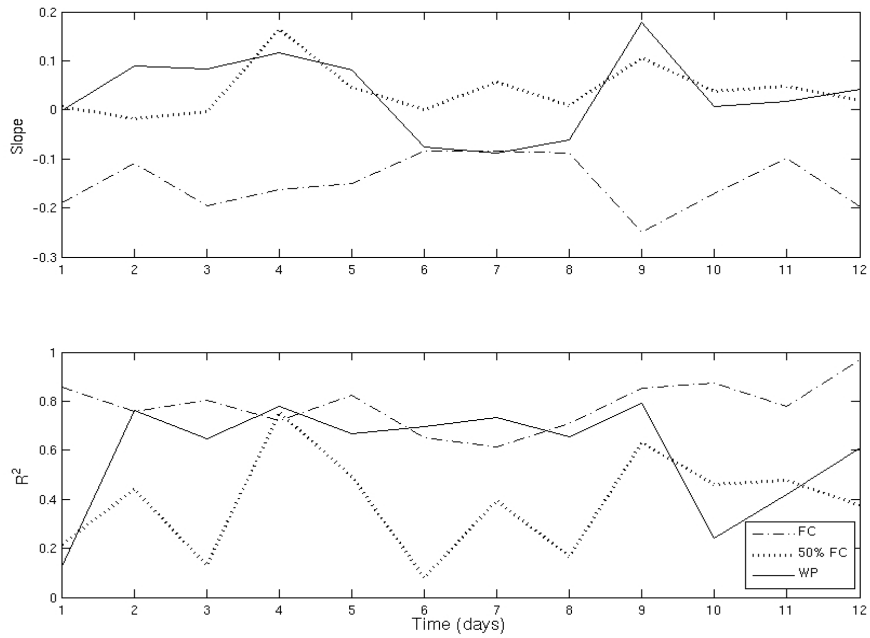

Figure 24. a) Timeseries of slope from β versus order of moment plots for soil temperature b) associated of R^2 values

3.6 Discussion

The objective of this study was to determine which physical processes play a role in soil moisture-precipitation feedbacks and to examine how they vary as a function of mean soil moisture and resolution. While some have argued the importance of an increase in net radiation resulting from a lowering of the albedo over moist soils, no evidence in the model has been found to support this. In fact, based on this series of model runs it has been shown that soil moisture did not have an impact on net radiation. Instead it is proposed that the difference in energy balance partitioning associated with soil moisture plays a dominant role in determining whether a feedback occurs.

FC runs were characterized by lower Bowen ratios resulting from increased latent heat flux. Lagged correlations between precipitation and latent heat flux exhibited the highest values when compared with sensible heat flux, Bowen ratio, and net radiation. FC runs were shown in Chapter two to have higher precipitation amounts in addition to a higher frequency of precipitation events when compared with 50FC and WP runs. In a comparison of mutual information content plots between soil moisture and Bowen ratio and soil moisture and net radiation higher levels of dependence between soil moisture and Bowen ratio are seen than with net radiation. An examination of turbulent mixing and boundary layer height showed smaller km_v/km_h ratios and lower boundary layer height for FC runs than 50FC and WP. Lower sensible heat fluxes associated with FC runs resulted in less turbulent mixing and as a result, shallower boundary layers.

In terms of resolution, using plots of entropy for Bowen ratio, latent and sensible heat flux, and net radiation it has been shown that 1 km runs consistently have a lower level of uncertainty associated with them. In general it has been found that using a finer resolution provides a greater information content, or less uncertainty. In plots of lagged correlation between precipitation and Bowen ratio, latent and sensible heat flux, and net radiation 1 km runs consistently had the highest correlation values regardless of mean soil moisture. Resolution also had a large affect on turbulent motions, which presumably will have a large impact on the dynamics of the soil moisture-precipitation feedback mechanism, as the turbulent motions are not being captured as well at coarser resolutions. This will undoubtedly affect the transport of moisture as well as boundary layer dynamics, which both play a role in the feedback.

Based on these findings, it appears that using a coarse resolution has important implications for the model's ability to resolve processes involved in soil moisture-precipitation feedbacks. This may result in inaccurate feedback magnitudes and may alter the spatial and temporal scales over which the feedback operates.

The scaling analysis performed on 10 am to 2 pm temporally averaged Bowen ratio showed that soil moisture appears to have a large impact on the scaling properties of the Bowen ratio. Ignoring the second moment in FC plots generally provided good fits between the remaining moments. Focusing only on the second moment shows that it does, however, scale with resolution. Although there were some days where these findings held true for 50FC and WP in general they cannot be applied. This has negative implications for the potentially widespread applicability of this methodology to remotely sensed fields. Scaling properties show a relatively large amount of temporal variability; therefore, generalizations about scaling coefficients cannot be made. This will undoubtedly place limitations on the usage, as the analysis would have to be performed with a relatively high temporal frequency.

Soil moisture did not seem to have a significant affect on the scaling properties of 10 am to 2 pm temporally average soil temperature. A scaling analysis of the first six moments showed that the fields do not exhibit self-similarity and therefore cannot be used to predict moments at other resolutions. With the exception of several days for each mean soil moisture value, the variance does scale with resolution and therefore could be used to predict variance at any other resolution. Further analysis is required to determine how temporally variable the scaling coefficients for variance are. This will potentially impact the applicability for future studies.

As with any study there are associated limitations which may impact the context in which the conclusions may be viewed. Numerical models are a simplified representation of reality limited by our understanding of physical processes, a lack of input data at ideal spatial and temporal resolutions, and technological resources. The results of this study are at least to some extent dependent on the choice of model and parameterization schemes. For example, it is widely recognized that precipitation is highly dependent on the choice of convective scheme. For this reason it is important to emphasize that the focus should not be placed on strict values of a variable but rather on how the values compare as a function of model resolution and mean soil moisture. A sensitivity analysis to parameterizations schemes would provide some indication as to the generality of these model results. Recommendations for future work include an increased number of mean soil moisture values and spatial resolutions.

3.7 Conclusions

Based on a series of regional model runs focusing on the Central Plains, it was found that energy balance partitioning played a significant role in the occurrence of soil moisture-precipitation feedback, while net radiation was not impacted by mean soil moisture. Turbulent motions and boundary layer depth were much larger over drier soils due to the larger sensible heat flux. Spatial resolution was found to have a large impact on the turbulence in the boundary layer, with coarser resolutions being unable to capture turbulent motions. This undoubtedly has an impact on the dynamics of soil moisture-precipitation feedback as the transport of moisture will affect the spatial and temporal scales over which feedback occurs. It was also found that higher resolution runs are generally associated with a higher information content. This is related to their ability to resolve finer scale processes and variability in surface and atmospheric fields than coarser resolutions.

The scaling analysis performed on soil temperature and Bowen ratio determined that mean soil moisture has a large impact on the scaling properties of Bowen ratio, while it did not appear to affect the scaling characteristics of soil temperature. There is the potential for large temporal variability in the scaling coefficients of both soil temperature and Bowen ratio, which may limit the large scale applicability of this methodology to remotely sensed fields.

CHAPTER 4

GENERAL SUMMARY AND CONCLUSIONS

4.1 CONCLUSIONS

The research presented in this thesis has focused on the impacts of varying mean soil moisture and model resolution on the occurrence of precipitation in the U.S. Central Plains. More specifically it has used a regional climate model to examine how the magnitude and frequency of precipitation events are impacted through land-atmosphere feedbacks, to determine the dominant physical processes driving the feedbacks and how they are impacted by changes in mean soil moisture and model resolution, and to examine the spatial scaling properties of modeled soil moisture, precipitation, Bowen ratio, and soil temperature fields.

Chapter one provided a brief overview of the issues being examined and some potential implications which serve as the motivation behind the study. Chapter two focused specifically on the interactions between soil moisture and precipitation and examined in detail the scaling characteristics of these variables, while chapter three investigated the physical processes involved in the feedback and how these are impacted by variations in mean soil moisture and model resolution.

In chapter two, evidence was presented to support the occurrence of a positive soil moisture-precipitation feedback in the U.S. Central Plains. High initial soil moisture was associated with greater precipitation amounts and a higher frequency of events. This implies that climate change in this region may have significant impacts on agricultural practices as decreased soil moisture may result in lower precipitation totals over longer temporal scales. This has potential ramifications for the ability of the region to maintain current crop yields, in addition to the potential for improvements in forecasting of regional weather and climate which can lead to improvements in agricultural forecasting. An examination of the scaling properties of soil moisture revealed high temporal variability. This has important implications for the use of remotely sensed data, as scaling properties from one day cannot necessarily be applied to subsequent days. Despite the general acceptance that precipitation can be described as multiscaling, this research found that cumulative precipitation fields did not exhibit signs of multiscaling, and therefore cannot be used to predict statistical properties at other resolutions.

Chapter three presented evidence to demonstrate that energy balance partitioning played a significant role in the occurrence of soil moisture-precipitation feedback, while soil moisture did not appear to have an impact on net radiation. Additionally it was found that drier soils were characterized by larger turbulent motions and boundary layer depth associated with a higher sensible heat flux. Turbulence in the boundary layer was significantly impacted by spatial resolution. Coarser resolutions were unable to capture turbulent motions, which will impact the dynamics of soil moisture-precipitation feedbacks as the spatial and temporal scales over which the feedback occurs will be affected by the transport of moisture. The scaling analysis performed on Bowen ratio and soil temperature determined that soil moisture had a significant impact on the scaling properties of Bowen ratio, while it did not appear to affect the scaling characteristics of soil temperature. Application of this methodology to remotely sensed fields may be limited, as with soil moisture, there is the potential for large temporal variability in the scaling coefficients of both soil temperature and Bowen ratio.

4.2 Recommendations for Future Research

The choice of convective parameterization scheme has a large impact on both the magnitude and frequency of precipitation events in a model. Performing a sensitivity analysis to parameterization schemes would allow for a wider acceptance of the particular results of this study. Additionally, increasing the number of mean soil moisture values and spatial resolutions would allow for the detection of threshold values which may determine when the model captures feedbacks between soil moisture and precipitation.

This research was conducted using only two soil layers, which will impact hydrologic processes such as evaporation, transpiration, infiltration, and runoff. The depth and number of soil layers can have a potentially significant impact on soil moisture dynamics. A coupled model should be used to improve the representation of the above hydrological processes and to incorporate the effects of groundwater dynamics and topographic redistribution of soil moisture. The incorporation of dynamic vegetation would also be beneficial as vegetation also plays a large role in precipitation feedbacks.

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REFERENCES

Albertson, J. D., W. P. Kustas, and T. M. Scanlon, 2001: Large-Eddy Simulation Over Heterogeneous Terrain with Remotely Sensed Land Surface Conditions. *Water Resources Research*, **37,** 1939-1953.

Alonge, C. J., K. I. Mohr, and W.-K. Tao, 2007: Numerical Studies of Wet Versus Dry Soil Regimes in the West African Sahel. *Journal of Hydrometeorology*, **8,** 102-116.

Baldocchi, D. D., T. Krebs, and M. Y. Leclerc, 2005: "Wet/dry Daisyworld": A Conceptual tool for Quantifying the Spatial Scaling of Heterogeneous Landscapes and its Impact on the Subgrid Variability of Energy Fluxes. *Tellus*, **57B,** 175-188.

Barros, A. P., and W. Hwu, 2002: A Study of Land-Atmosphere Interactions During Summertime Rainfall Using a Mesoscale Model. *Journal of Geophysical Research*, **107,** doi:10.1029/2000JD000254.

Betts, A. K., 2007: Coupling of Water Vapor Convergence, Clouds, Precipitation and Land-Surface Processes. *Journal of Geophysical Research*, **112,** 1-14.

Bloschl, G., 1996: *Scale and Scaling in Hydrology (Habilitationsschrift).* Wiener Mitteliungen, Wasser-Abwasser-Gerwasser, Band 132, Institute fur Hydraulik, TU Wien, 346 pp.

——, 2001: Scaling in Hydrology. *Hydrological Processes*, **15,** 709-711.

Brubaker, K., and D. Entekhabi, 1996a: Analysis of Feedback Mechanisms in Land-Atmosphere Interaction. *Water Resources Research*, **32,** 1343-1357.

——, 1996b: Asymmetric Recovery from Wet Versus Dry Soil Moisture Anomalies. *Journal of Applied Meteorology*, **35,** 94-109.

Brunsell, N. A., 2006: Characterization of Land-Surface Precipitation Feedback Regimes with Remote Sensing. *Remote Sensing of the Environment*, **100,** 200-211.

Brunsell, N. A., and R. R. Gillies, 2003a: Scale Issues in Land-Atmosphere Interactions: Implications for Remote Sensing of the Surface Energy Balance. *Agricultural and Forest Meteorology*, **117,** 203-221.

——, 2003b: Determination of Scaling Characteristics of AVHRR data with Wavelets: Application to SGP97. *International Journal of Remote Sensing*, **24,** 2945-2957.

Brunsell, N. A., and C. B. Young, 2008: Land Surface Response to Precipitation Events using MODIS and NEXRAD data. *International Journal of Remote Sensing*, **29,** 1965-1982.

Brunsell, N. A., J. M. Ham, and C. E. Owensby, 2008: Assessing the Multi-Resolution Information Content of Remotely Sensed Variables and Elevation for Evapotranspiration in a Tall-Grass Prairie Environment. *Remote Sensing of the Environment*, **In Press**.

Chen, F., and R. Avissar, 1994: Impact of Land-Surface Moisture Variability on Local Shallow Convective Cumulus and Precipitation in Large Scale Models. *Journal of Applied Meteorology*, **33,** 1382-1401.

Conil, S., H. Douville, and S. Tyteca, 2007: The Relative Influence of Soil Moisture and SST in Climate Predictability Explored within Ensembles of AMIP Type Experiments. *Climate Dynamics*, **28,** 125-145.

Cook, B. I., G. B. Bonan, and S. Levis, 2006: Soil Moisture Feedbacks to Precipitation in Southern Africa. *Journal of Climate*, **19,** 4198-4206.

Cosh, M. H., T. J. Jackson, P. Starks, and G. Heathman, 2006: Temporal Stability of Surface Soil Moisture in the Little Washita River Watershed and its Applications in Satellite Soil Moisture Product Validation. *Journal of Hydrology*, **323,** 168-177.

Davis, F. W., D. S. Schimen, M. A. Friedl, J. C. Michaelsen, T. G. Kittel, R. Dubayah, and J. Dozier, 1992: Covariance of Biophysical Data with Digital Topographic and Land Use Maps Over the FIFE Site. *Journal of Geophysical Research*, **97,** 19009-19021.

Deidda, R., 1999: Multifractal Analysis and Simulation of Rainfall Fields in Space. *Physics and Chemistry of the Earth*, **24,** 73-78.

Deidda, R., R. Benzi, and F. Siccardi, 1999: Multifractal Modeling of Anomalous Scaling Laws in Rainfall. *Water Resources Research*, **35,** 1853-1867.

Dong, J., W. Ni-Meister, and P. R. Houser, 2007: Impacts of Vegetation and Cold Season Processes on Soil Moisture and Climate Relationships over Eurasia. *Journal of Geophysical Research*, **112,** 1-11.

Drusch, M., 2007: Initializing Numerical Weather Prediction Models with Satellite-Derived Surface Soil Moisture: Data Assimilation Experiments with

ECMWF's Integrated Forecast System and the TMI Soil Moisture Data Set. *Journal of Geophysical Research*, **112,** D03102.

Dubayah, R., E. F. Wood, and D. Lavallee, 1997: Multiscaling Analysis in Distributed Modeling and Remote Sensing: An Application Using Soil Moisture. *Scale in Remote Sensing and GIS*, D. A. Quatrochi, and M. F. Goodchild, Eds., Lewis Publishers, 93-112.

Eltahir, E., 1998: A Soil Moisture-Rainfall Feedback Mechanism. Part I: Theory and Observations. *Water Resources Research*, **34,** 765-776.

Entekhabi, D., I. Rodriguez-Itrube, and F. Castelli, 1996: Mutual Interaction of Soil Moisture State and Atmospheric Processes. *Journal of Hydrology*, **184,** 3-17.

Fay, P. A., J. D. Carlisle, A. K. Knapp, J. M. Blair, and S. L. Collins, 2000: Altering Rainfall Timing and Quantity in a Mesic Grassland Ecosystem: Design and Performance of Rainfall Manipulation Shelters. *Ecosystems*, **3,** 308-319.

——, 2003: Productivity Responses to Altered Rainfall Patterns in a C4-Dominated Grassland. *Oecologia*, **137,** 245-251.

Findell, K. L., and E. A. Eltahir, 1997: An Analysis of the Soil Moisture-Rainfall Feedback, Based on Direct Observations from Illinois. *Water Resources Research*, **33,** 725-735.

——, 1999: Analysis of the Pathways Relating Soil Moisture and Subsequent Rainfall in Illinois. *Journal of Geophysical Research*, **104,** 31565-31574.

——, 2003a: Atmospheric Controls on Soil Moisture-Boundary Layer Interactions. Part II: Feedbacks within the Continental United States. *Journal of Hydrometeorology*, **4,** 570-583.

——, 2003b: Atmospheric Controls on Soil Moisture-Boundary Layer Interactions. Part I: Framework Development. *Journal of Hydrometeorology*, **4,** 552-569.

Fischer, E. M., S. I. Seneviratne, D. Luthi, and C. Schar, 2007: Contribution of Land-Atmosphere Coupling to Recent European Summer Heat Waves. *Geophysical Research Letters*, **34,** L06707.

Gameda, S., B. Qian, C. A. Campbell, and R. L. Desjardins, 2007: Climatic Trends Associated with Summerfallow in the Canadian Prairies. *Agricultural and Forest Meteorology*, **142,** 170-185.

Gedney, N., and P. M. Cox, 2003: The Sensitivity of Global Climate Simulations to the Representation of Soil Moisture Heterogeneity. *Journal of Hydrometeorology*, **4,** 1265-1275.

Georgescu, M., C. P. Weaver, R. Avissar, R. L. Walko, and M.-M. Gonzalo, 2003: Sensitivity of Model-Simulated Summertime Precipitation over the Mississippi River Basin to the Spatial Distribution of Initial Soil Moisture. *Journal of Geophysical Research*, **108,** doi:10.1029/2002JD003107.

Gupta, V. K., and E. Waymire, 1990: Multiscaling Properties of Spatial Rainfall and River Flow Distributions. *Journal of Geophysical Research*, **95,** 1990-2009.

Halley, J. M., S. Hartley, A. S. Kallimanis, W. E. Kunin, J. J. Lennon, and S. P. Sgardelis, 2004: Uses and Abuses of Fractal Methodology in Ecology. *Ecology Letters*, **7,** 254-271.

Harper, C. W., J. M. Blair, S. L. Collins, M. D. Smith, J. D. Carlisle, C. W. Harper, B. T. Danner, M. S. Lett, and J. K. McCarron, 2005: Increased Rainfall Variability and Reduced Rainfall Amount Decreases Soil CO2 Flux in a Grassland Ecosystem. *Global Change Biodiversity*, **11,** 322-334.

Jackson, R. B., J. Canadell, J. R. Ehleringer, H. A. Mooney, O. E. Sala, and E. D. Schulze, 1996: A Global Analysis of Root Distributions for Terrestrial Biomes. *Oecologia*, **108,** 389–411.

Jackson, T. J., P. E. O'Neill, and C. T. Swift, 1997: Passive Microwave Observation of Diurnal Surface Soil Moisture. *IEEE Transactions on Geoscience and Remote Sensing*, **35,** 1210-1222.

Jones, A. R., and N. A. Brunsell, 2008: A Scaling Analysis of Soil Moisture-Precipitation Interactions in a Regional Climate Model. *Theoretical and Applied Climatology*, (submitted).

Juang, J.-Y., A. Porporato, P. C. Stoy, M. S. Siqueira, A. C. Oishi, M. Detto, H.-S. Kim, and G. G. Katul, 2007: Hydrologic and Atmospheric Controls on Initiation of Convective Precipitation Events. *Water Resources Research*, **43,** doi:10.1029/2006WR004954.

Kaste, J. M., A. M. Heimsath, and M. Hohmann, 2006: Quantifying sediment transport across an undisturbed prairie landscape using cesium-137 and high resolution topography. *Geomorphology*, **76,** 430-440.

Kim, Y., and G. Wang, 2007: Impact of Initial Soil Moisture Anomalies on Subsequent Precipitation Over North America in the Coupled Land-Atmosphere Model CAM3-CLM3. *Journal of Hydrometeorology*, **8,** 513-533.

Knapp, A. K., and Coauthors, 2002: Rainfall Variability, Carbon Cycling, and Plant Species Diversity in a Mesic Grassland. *Science*, **298,** 2202-2205.

Koster, R. D., 2003: Observational Evidence that Soil Moisture Variations Affect Precipitation. *Geophysical Research Letters*, **30,** doi:10.1029/2002GL016571.

Koster, R. D., M. J. Suarez, and M. Heiser, 2000: Variance and Predictability of Precipitation at Seasonal-to-Interannual Timescales. *Journal of Hydrometeorology*, **1,** 26-46.

Koster, R. D., P. A. Dirmeyer, A. N. Hahmann, R. Ijpelarr, L. Tyahla, P. Cox, and M. J. Suarez, 2002: Comparing the Degree of Land-Atmosphere Interaction in Four General Circulation Models. *Journal of Hydrometeorology*, **3,** 363-375.

Koster, R. D., and Coauthors, 2004: Regions of Strong Coupling between Soil Moisture and Precipitation. *Science*, **305,** 1138-1134.

Kumar, P., and E. Foufoula-Georgiou, 1993: A Multicomponent Decomposition of Spatial Rainfall Fields 1: Segregation of Large and Small Scale Features Using Wavelet Transforms. *Water Resources Research*, **29,** 2515-2532.

Kustas, W. P., and J. D. Albertson, 2003: Effects of Surface Temperature Contrast on Land-Atmosphere Exchange: A Case Study from Monsoon 90. *Water Resources Research*, **39,** doi:10.1029/2001WR001226.

Kustas, W. P., T. J. Jackson, J. H. Prueger, J. L. Hatfield, and M. C. Anderson, 2003: Remote Sensing Field Experiments Evaluate Retrieval Algorithms and Land-Atmosphere Modeling. *American Geophysical Union*, **84,** 485-489.

Lett, M. S., and A. K. Knapp, 2005: Woody Plant Encroachment and Removal in Mesic Grassland: Production and Composition Responses of Herbaceous Vegetation. *The American Midland Naturalist*, **153,** 217-231.

Lynn, B. H., D. Rind, and R. Avissar, 1995: The Importance of Mesoscale Circulations Generated by Subgrid-Scale Landscape Heterogeneities in General Circulation Models. *Journal of Climate*, **8,** 191-205.

Manfreda, S., M. F. McCabe, M. Florentino, I. Rodriguez-Iturbe, and E. F. Wood, 2007: Scaling Characteristics of Spatial Patterns of Soil Moisture from Distributed Modeling. *Advances in Water Resources*, **30,** 2145-2150.

Menabde, M., D. Harris, A. Seed, G. Austin, and D. Stow, 1997: Multiscaling Properties of Rainfall and Bounded Random Cascades. *Water Resources Research*, **33,** 2823-2830.

Nippert, J. B., A. K. Knapp, and J. M. Briggs, 2006: Intra-annual Rainfall Variability and Grassland Productivity: Can the Past Predict the Future? *Plant Ecology*, **184,** 65-74.

Pal, J. S., and E. Eltahir, 1996: Relationship between Surface Conditions and Subsequent Rainfall in Convective Events. *Journal of Geophysical Research*, **101,** 26237-26245.

——, 2001: Pathways Relating Soil Moisture Conditions to Future Summer Rainfall within a Model of the Land-Atmosphere System. *Journal of Climate*, **14,** 1227-1242.

Peters-Lidard, C. D., F. Pan, and E. F. Wood, 2001: A Re-Examination of Modeled and Measured Soil Moisture Spatial Variability and its Implications for Land Surface Modeling. *Advances in Water Resources*, **24,** 1069-1083.

Raddatz, R. L., 2007: Evidence for the Influence of Agriculture on Weather and Climate through the Transformation and Management of Vegetation: Illustrated by Examples from the Canadian Prairies. *Agricultural and Forest Meteorology*, **142,** 186-202.

Rodriguez-Iturbe, I., P. D'Odorico, and A. Rinaldo, 1998: Possible Self-Organizing Dynamics for Land-Atmosphere Interaction. *Journal of Geophysical Research*, **103,** 23,071-023,077.

Rodriguez-Iturbe, I., G. K. Vogel, R. Rigon, D. Entekhabi, F. Castelli, and A. Rinaldo, 1995: On the Spatial Organization of Soil Moisture Fields. *Geophysical Research Letters*, **22,** 2757-2760.

Salvucci, G. D., J. A. Saleem, and R. Kaufmann, 2002: Investigating Soil Moisture Feedbacks on Precipitation with Tests of Granger Causality. *Advances in Water Resources*, **25,** 1305-1312.

Seth, A., and F. Giorgi, 1998: The Effects of Domain Choice on Summer Precipitation Simulation and Sensitivity in a Regional Climate Model. *Journal of Climate*, **11,** 2698-2712.

Shannon, C. E., 1948: A Mathematical Theory of Communication. *The Bell System Technical Journal*, **27,** 379-423.

Taylor, C. M., and R. J. Ellis, 2006: Satellite Detection of Soil Moisture Impacts on Convection at the Mesoscale. *Geophysical Research Letters*, **33,** doi:10.1029/2005GL02525.

Taylor, C. M., D. J. Parker, and P. P. Harris, 2007: An Observational Case Study of Mesoscale Atmospheric Circulations induced by Soil Moisture. *Geophysical Research Letters*, **34,** L15801.

Teuling, A. J., and S. I. Seneviratne, 2008: Contrasting Spectral Changes Limit Albedo Impact on Land-Atmosphere Coupling During the 2003 European Heat Wave. *Geophysical Research Letters*, **35,** doi:10.1029/2007GL032778.

Vachaud, G., A. P. Desilans, P. Balabanis, and M. Vauclin, 1985: Temporal Stability of Spatially Measured Soil-Water Probability Density Function. *Soil Science Society of America Journal* **49,** 822-828.

Vidale, P. I., D. Luthi, R. Wegmann, and C. Schar, 2007: European Summer Climate Variability in a Heterogeneous Multi-Model Ensemble. *Climatic Change*, **81,** 209-232.

Waymire, E., 1985: Scaling Limits and Self-Similarity in Precipitation Fields. *Water Resources Research*, **21,** 1271-1281.

Western, A. W., and G. Bloschl, 1999: On the Spatial Scaling of Soil Moisture. *Journal of Hydrology*, **217,** 203-224.

Western, A. W., R. B. Grayson, and G. Bloschl, 2002: Scaling of Soil Moisture: A Hydrological Perspective. *Annual Review Earth Planet Science*, **30,** 149-180.

Xu, J., W. J. Shuttleworth, X. Gao, S. Sorooshian, and E. E. Small, 2004: Soil Moisture-Precipitation Feedback on the North American Monsoon System in the MM5-OSU Model. *Quarterly Journal of the Royal Meteorological Society*, **130,** 2873-2890.

Xue, M., K. K. Droegemeier, and V. Wong, 2000: The Advanced Regional Prediction System (ARPS)- A Multi-Scale Nonhydrostatic Atmospheric Simulation and Prediction Model. Part I: Model Dynamics and Verification. *Meteorology and Atmospheric Physics*, **75,** 161-193.

——, 2001: The Advanced Regional Prediction System (ARPS)- A Multi-Scale Nonhydrostatic Atmospheric Simulation and Prediction Model. Part II: Model Physics and Applications. *Meteorology and Atmospheric Physics*, **76,** 143-165.

Xue, M., D. Wang, J. Gao, K. Brewster, and K. K. Droegemeier, 2003: The Advanced Regional Prediction System (ARPS), Storm-Scale Numerical Weather Prediction and Data Assimilation. *Meteorology and Atmospheric Physics*, **82,** 139-170.

Yang, F., A. Kumar, and K. M. Lao., 2004: Potential Predictability of U.S. Summer Climate with "Perfect" Soil Moisture. *Journal of Hydrometeorology*, **5,** 883-895.