Near-surface Atmospheric Response to Simulated Changes in Land-cover Vegetation Fraction, and Soil Moisture over Western Kentucky

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NEAR-SURFACE ATMOSPHERIC RESPONSE TO SIMULATED CHANGES IN LAND-COVER, VEGETATION FRACTION, AND SOIL MOISTURE OVER WESTERN KENTUCKY

A Thesis
Presented to
The Faculty of the Department of Geography and Geology
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Master of Science

By
Ronnie Leeper

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NEAR-SURFACE ATMOSPHERIC RESPONSE TO SIMULATED CHANGES IN LAND-COVER, VEGETATION FRACTION, AND SOIL MOISTURE OVER WESTERN KENTUCKY

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A series of land-use-land-cover-change (LULCC) based sensitivity experiments, including changes in vegetation type, fractional vegetation (FV), and soil moisture (SM), over Western Kentucky were conducted to investigate atmospheric response to land-use. The choice of land-use for this study was chosen in the context of Western Kentucky’s historical LULCC. For this study, vegetation types considered were grassland, forest, and bare soil with further variations in FV for grassland and forest at 25, 50, 75, and 100 % and systematic increases and decreases in volumetric SM of 0.05, 0.10, and 0.15 m$^3$ m$^{-3}$. To the author’s knowledge, this is the first assessment of its kind that incorporates these types of LULCC in a single study. In addition, typical anthropogenic land-use change often incorporates several types of LULCC. Moreover, this assessment provides a robust analysis of the impacts LULCC has on atmospheric processes over Western Kentucky.

To simulate the importance of land-use on atmospheric processes, a well known meso-scale model developed by the National Center for Atmospheric Research (NCAR) and the Pennsylvania State University (PSU) MM5 coupled with an intermediately complex land surface model (LSM) Noah was used. The purpose
of this research is to investigate the impact of multiple types of LULCC on planetary boundary layer (PBL) evolution, PBL stability, near surface 3D-wind fields, temperature, and moisture. Furthermore, it is anticipated that multiple types of LULCC will provide more insight into the complex nonlinear land-atmosphere interactions from atmospheric, air quality, and climatology perspectives.

Modeling analysis revealed the importance of land-use on atmospheric processes. Changes in all three types of LULCC (land-cover, FV, and SM) altered the distribution of surface energy and moisture, PBL structure, 3D-wind fields, and PBL stability. In general, it was found that LULCC that enhanced (diminished) ET rates reduced (increased) sensible heat flux, atmospheric temperature and, and PBL heights below (above) control (CTRL). For instance, the conversion of land-cover from CTRL to grassland reduced 2 m temperature and PBL heights by 0.60 °C and 228 m respectively compared to CTRL due to an evaporative advantage (lower stomata resistance). Multiple types of land-use change were found to either offset or enhance overall modeled response to LULCC. A reduction in FV to 25 % over grassland diminished ET despite the evaporation advantage of grassland and increased 2 m temperature and PBL heights with respect to CTRL by 3.3 °C and 504 m. These results significantly altered horizontal and vertical wind fields, affecting moisture advection and the development of meso-scale circulations. Compared to CTRL, these differences were enhanced over drier soils, but muted over moist soils. Moreover, the impact of LULCC on atmosphere evolution was not only dependent on the type of LULCC, but also on the current state of other unaltered land surface features such as vegetation type, FV, and SM.
Alterations to modeled PBL development, as a result of LULCC, can have important impacts on a region’s climatology and air quality. Simulated changes in typical PBL moisture and temperature through time can affect local and regional climatology. Depending on the type of LULCC, these alterations in climate may lead to localized cooling. In addition, it was further hypothesized that changes in PBL height can affect air quality. Given the capping inversion layer at the top of the PBL, changes in PBL heights can significantly affect air quality with lower (higher) PBL heights diminishing (enhancing) air quality. Moreover, this research prescribes the importance of considering LULCC in atmospheric assessments of climatology and air quality, including pollutant dispersion and trajectory modeling.
Chapter 1

Introduction

Global climate change is quickly becoming a serious issue, not only in the scientific community, but among everyday people around the globe. Consumers all over the world over are now more than ever conscious of their actions and environmental footprint. In response, serious efforts are currently underway to develop more fuel efficient cars, greener building codes, and sustainable development practices that will enhance air quality, preserve natural resources, and mitigate our anthropogenic impact on the environment. However, one of the most anthropogenically transformed features of our natural environment, often overlooked, is land-use. Anthropogenic land-use-land-cover-change (LULCC) is one of the most visible types of human environmental change from deforestation and urbanization to agriculture and mining. Alterations to Earth’s vegetative surface can lead to unintended environmental and atmospheric feedbacks, impacting regional sustainability, air quality, and climate (Ramenkutty et al. 2006). Therefore, understanding the complex land-atmosphere interactions is of critical importance to developing suitable practices for sustainable development.

Climate is sensitive to land-use as nearly all atmospheric energy and moisture is derived directly from the Earth’s surface. The sun, at an average temperature of 5527 °C, emits solar radiation in all directions at the speed of light (Pidwirny and Vranes, 2008). Within eight minutes of being released, this energy enters our atmosphere, and shines on the Earth’s surface, warming oceans and continents.
Apart from reflectance and scattering, the atmosphere is transparent to this short wave radiation as a majority of it is absorbed at the Earth’s surface. Land-cover plays a vital role in how this solar radiation is intercepted, incorporated into evapotranspiration processes (latent heat), and shared with the atmosphere through long wave radiation (sensible heat). Moreover, LULCC alters typical day-to-day land-atmosphere interactions by introducing new biological and physical vegetative properties that change how the atmosphere interacts with the surface. Three widely known types of LULCC that impact our atmosphere are changes land-cover, fractional vegetation (FV) or vegetation thickness, and soil moisture (SM) (Grasso, 2000). Depending on the type of LULCC and the magnitude of change, altered land-atmospheric interactions have been shown to affect convective turbulence, atmospheric moisture, subsurface moisture retention, PBL height and winds, Bowen ratio, cloud development, temperature, and precipitation (McPherson, 2007).

Humans have modified land-cover for various reasons throughout centuries, including: survival, economic gain, recreation, and aesthetic surroundings. Some of the first notable changes in land-cover occurred during the mid 3rd and 4th centuries over populated regions of the Roman Empire (Roman Architecture, 2008) and later in 12th century Mexico and 13th century South America with the rise of Aztec and Incan empires respectively (Aztec, 2008; Machu Picchu, 2003). Further north, Native Americans, prior to European settlement, regularly cleared large acres of forests (burning) throughout the Southeast (Sauer, 1937 and Dobler, 2007). Over Kentucky, these regular burnings were thought to convert forest to grasses and attract large hunting game, including buffalo, to this region (Sauer, 1937; Dobler, 2007; and
Further land transformations occurred throughout Kentucky’s history with the Jackson Purchase (Bladen and Klotter, 2008), advancements in agricultural practices with the Industrial Revolution, and mechanization of the Modern era. These advancements made altering land-use much easier and increased the rate of LULCC. Today, LULCC is a continuous process where land owners constantly alter the Earth’s surface from crop rotation to conservation efforts, and agricultural subsidy programs, such as the Conservation Reserve Enhancement Program (CREP) currently implemented in Kentucky. Furthermore, the main challenge of prescribing the influence of land-cover on the atmosphere is that land-use is in a constant state of flux with alterations to land-cover typically incorporating more than one type of LULCC.

A large number of modeling-based sensitivity studies have been conducted in the context of LULCC in the Great Plains of North America. This study investigates the sensitivity of warm season near-surface atmospheric response to changes in LULCC over Western Kentucky. This region sits east of the Great Plains and west of the Appalachian Mountains and is characterized by small changes in elevation and land-cover types consisting of forests and grasslands. The history of LULCC in Kentucky, as previously mentioned, provided the motivation for this sensitivity assessment and influenced the experimental design. Vegetation types considered in this LULCC study are forest, grass, and bare soil with successive changes in FV to 25, 50, 75, and 100% (no FV for bare soils) with systematic increases and decreases of initial volumetric SM content of 0.05, 0.10, and 0.15 m$^3$ m$^{-3}$. 
In order to simulate the importance of multiple types of LULCC, the National Center for Atmospheric Research (NCAR) fifth generation mesoscale model (MM5) is used for this study. MM5 is a numerical weather prediction (NWP) model developed for mesoscale atmospheric research that has had wide use in LULCC studies (e.g., Grossman-Clarke et al., 2005; Fu, 2003; McPherson and Stensrud, 2005; Narisma and Pitman, 2003; Quintanar et al., 2008). Each model run was initialized with the same set of initial conditions and simulated over a period of 11 days with a 4 day spin-up to allow the model to adjust to changes in LULCC; further details on experimental design are provided in Chapter 2. It is expected that simulated, combined modifications of vegetation type, FV, and SM will provide a better understanding of how LULCC affects planetary boundary layer (PBL) development and near-surface hydrological and energy exchanges, impacting climatology and air quality over Kentucky.
Chapter 2

Literature Relevant to the Study

The nonlinear, interactive relationship between land-use and the atmosphere has been well studied in terms of its influence on weather and climatology (Halldin et al. 1998; Pielke et al., 1999a; Fu 2003; Narisma and Pitman, 2003; Schneider and Eugster, 2005; Adegoke et al., 2006; Ramankutty et al. 2006; Pielke et al., 2007). Observational and modeling studies alike have shown that various land-uses respond differently to incoming solar energy and precipitation (Betts et al. 1996; Adegoke et al. 2006; McPherson 2007; Pielke et al. 2007). Observational datasets from the International H2O (IHOP-2002), Cooperative Atmosphere Surface Exchange Study (CASES-97) and other field campaigns associated with the boreal ecosystem-atmosphere study (BOREAS) and field experiments (FIFE) have revealed the strong influence vegetation has on the distribution of surface fluxes and moisture (Smith et al. 1994; Adegoke et al. 2006; Mengelkamp 2006; Betts et al. 2007; LeMone et al. 2007). Furthermore, modeling studies have also demonstrated the importance of land-use interactions on atmosphere evolution (Chang and Wetzel, 1991; Clark and Arritt, 1995; Shen, 1998; Pielke, 2001; Pielke et al., 2002; Adegoke et al., 2003; Narisma and Pitman, 2003; McPherson and Stunsurd, 2005; Gero et al, 2006; Niyogi and Xue, 2006).

Mengelkamp et al. (2006), in an intense observational field campaign over Germany, found statistically significant differences in observed surface energy fluxes, ET, and temperature over different land-uses. In addition, Betts et al. (2007) noted a reduction in measured surface radiation due to differences in vegetation albedo.
For instance, forest land-cover compared to grasses or agriculture absorbed 14 to 50 W m$^{-2}$ more radiation from the sun. In addition, LeMone et al. (2007) documented the importance of SM in observational studies of surface fluxes over various land-uses. Changes in surface heating and ET rates over a heterogenous land-cover can give rise to thermal/density gradients at the surface that are large enough to organize PBL wind fields into mesoscale circulations (Smith et al. 1994). These observational studies highlight the importance of land-atmosphere interactions on near-surface energy and moisture budgets.

McPherson (2007) noted that the strength of land-atmosphere interactions is sensitive to potential evapotranspiration and physical presence (vegetation roughness), impacting surface energy, moisture, and momentum. Oke (1987) shows that individual vegetation types respond differently to solar irradiance and available moisture at the surface as a result of differences in vegetative characteristics, such as albedo, stomatal resistance, rooting depth, and roughness length. Using observational and modeling techniques, Roy et al. (2007) showed that agricultural land-use, including irrigation, significantly modulated surface temperatures over India, as a result of increased evapotranspiration and subsequent reduction in partitioning of sensible heat flux. Reductions in sensible heat flux and temperature had been found to suppress cloud development (Lyons 2002) and delay the initiation of precipitation due to reduced convective mixing within the PBL (McPherson, 2007 and Pielke et al. 2007). Despite the initial delay in precipitation, increases in atmospheric moisture has been shown to enhance precipitation rates and moist static energy (latent heat), significantly effecting accumulated precipitation and the development of convectively driven storms (Pielke et al. 2007). In addition, sharp potential evapotranspiration contrasts between two distinct
vegetation types (ex. low versus high stomata resistance) has been found to establish thermal/density gradients at the surface and generate mesoscale circulations similar to land-sea breezes (Ookouchi et al. 1984 and Chen and Avissar 1994). Moreover, LULCC altering vegetation types has been shown to have profound effects on near-surface atmospheric processes, impacting PBL evolution, PBL wind fields, surface temperature and moisture, and development and timing of convection and precipitation.

Variations in FV have also been shown to influence the partitioning of available energy and moisture (Chang and Weztel 1991; Clark and Arritt 1995; Fu 2003, Barlage and Zeng 2004). FV is allowed to vary between 1 and 0, and is defined as the percent of green plant canopy absorbing solar radiation. For instance, a densely wooded forest that allows no sunlight to penetrate the canopy would be an example of 100% (1) FV (Fig. 1). Increased (decreased) FV reduces (increases) the amount solar radiation absorbed through the canopy for evaporative processes, impacting both energy and subsurface moisture available to the atmosphere. Chang and Wetzel (1991) demonstrated that changes in FV resulted in differential heating and enhancement of a stationary boundary front. It was further noted that higher FV caused early initiation of precipitation with higher rainfall intensities similar to changes in vegetation type.

Figure 1. Examples of 100% vegetation fraction on the left and 25% vegetation fraction on the right
(Clark and Arritt 1995). Zeng et al. (2003) prescribed that FV cover is one of the more important variables to be considered in land-surface/LULCC modeling.

SM has also been noted as a critical feature of the climate system that influences the distribution of moisture and energy at the surface through soil moisture-atmosphere feedbacks (McCumber and Pielke 1981; Chen and Avissar 1994; Mahmood 1996; Mahmood and Hubbard 2002, 2004, and 2007; LeMone et al. 2007). Changes to SM have been found to alter the diurnal PBL evolution (Zhang and Anthes 1982), surface Bowen ratio, convective available potential energy (CAPE) (Clark and Arritt 1995; Pielke 2001), cloud development (Findell and Eltahir 2003; Ek and Holtslag 2004), PBL wind field (Segal and Arritt 1992) and precipitation (Ookouchi et al. 1984; Pan et al. 1996). SM affects atmospheric processes through evapotranspiration. As subsurface moisture is evaporated, a portion of incoming solar energy is consumed (Pal and Eltahir 2001). This captured energy (latent heat flux), which is later released through condensation, has been shown by Pielke (2001) to fuel destructive storms in the Central Plains. Brubaker et al. (1993) prescribes that 10 to 30% of atmospheric water vapor is derived “directly” through local evapotranspiration (ET), and depending on atmospheric conditions can be as high as 40%. This local supply of atmospheric moisture is necessary for the development of clouds and precipitation in a dry atmosphere (Chen and Avissar 1994).

The initiation of subsurface moisture in atmospheric models continues to be an enormous challenge in numerical modeling studies (Koster and Saurez 2003; Mahmood and Hubbard 2007). Limited by the lack of high density networks observing soil profiles over much of the globe, proper initiation of SM in numerical models is often difficult.
Studies that have reasonably prescribed soil conditions in atmospheric models have noted improvements in simulated forecasts (Huang et al. 1996; Dirmeyer 2000; Hong and Kalnay 2000; Douville et al. 2001). Dirmeyer (2000) noted a reduction in the root-mean-square error of modeled near surface temperature and improved rainfall patterns with reasonable specification of root zone SM. Similarly, Schlosser and Milly (2002) and Huang et al. (1996) both found a strong correlation between underground water storage and modeled near-surface temperature and precipitation. Grasso (2000) also noted an improvement in modeled forecasts with proper specification of both volumetric SM and overlying vegetation.

While the impact of land-use on atmospheric processes has been well documented, the complex, nonlinear atmospheric response to LULCC is less understood. Research studies have shown that alterations to land-use may result in unintended consequences (Ramankutty et al. 2006). Marshall (2003) noted an increase in rare flash freeze events over Southern Florida, impacting orchards vital to the region’s economy, as a result of LULCC that drained natural marsh lands and removed an important nighttime energy source (water). In addition, Pielke et al. (1999b), using a regional atmospheric model, found a reduction in simulated rainfall over this same region by 11% as a result of LULCC between the 1900 and 1993, altering the spatial distribution of evapotranspiration patterns. Similarly, Pitman et al. (2004) explained up to a 50% reduction in observed precipitation over Southern Australia as a result of agricultural LULCC altering surface roughness and moisture convergence.

A limiting factor in typical LULCC studies is the focus on a single type of change; however, in reality LULCC often incorporates multiple types of LULCC
including land-cover, FV, or SM. Studies that are exceptions to this have shown improvements in the quality of model forecasts and accuracy of simulated temperature, atmospheric moisture, and dry line propagation (Chang and Wetzel 1991; Dirmeyer et al. 2000; Grasso 2000). Chang and Wetzel (1991) found model simulations initialized with proper representations of both SM and FV resulted in improved forecasts overruns that included just changes in SM or FV alone. Assessing the relationship between SM and evaporative fraction, Dirmeyer et al. (2000) concluded that evaporative fraction was sensitive to both SM and overlying vegetation. Furthermore, McPherson and Stensrud (2005) noted the importance of correctly identifying vegetation parameters, including FV and SM, to reasonably simulate surface energy exchanges and moisture flux. Hence, representation of the overlying land-use, including land-cover, FV, and SM is necessary to properly simulate atmospheric responses to LULCC.

A study region that has been continuously modified prior to European settlement and continues to this day is Western Kentucky (Sauer 1927; Division of Conservation 2009). Land-cover over Western Kentucky, originally forested, had large acres of it regularly burned (bare soil) by Native Americans to produce pastures (grassland) for large hunting game such as buffalo (Dobler 2007; Sauer 1927). Even into today, LULCC continues across this region through farm subsidy programs such as the conservation reserve enhancement program (CREP). This program is offered to local farmers through a partnership between the Commonwealth of Kentucky and the US Department of Agriculture (USDA) that supplements farmers to grow vegetation native to the region along the Green River watershed (Division of Conservation 2009). This program, which has been implemented since 2001, has allowed for re-growth of native vegetation to this
region potentially impacting currently US geological survey (USGS) prescribed FV estimates over portions of Western Kentucky, which last updated in 2001. In addition, this region is also characterized as heavily karst, which has been shown to affect ET rates and possibly root zone volumetric SM (Hess and White 1989). As such, this region provides a unique opportunity to investigate the sensitivity of combined simulated changes in vegetation type, FV, and SM on modeled near-surface atmospheric and hydrologic processes.

This study assesses the sensitivity of warm season (summer) near-surface atmospheric responses to combined changes in LULCC types over Western Kentucky. Types of LULCC considered for study are forest, grassland, and bare soils with FV at 25, 50, 75, and 100 % (no FV for bare soils) and systematic increases and decreases in volumetric SM of 0.05, 0.10, and 0.15 m$^3$ m$^{-3}$. This modeling based study consists of 56 different sensitivity tests including control (CTRL). Further details on experimental setup will be provided in Chapter 3.2. In order to simulate the importance of LULCC, the National Center for Atmospheric Research’s (NCAR) fifth generation mesoscale model (MM5) was used. The MM5 has been widely used in LULCC studies by Fu (2003), Narisma and Pitman (2003), Grossman-Clarke et al. (2005), McPherson and Stensrud (2005), and Quintanar et al. (2008). In addition, the model was verified against observational datasets in Chapter 4. As indicated above, it is expected that simulated combined modifications of LULCC types will provide a better understanding of LULCC on near-surface PBL development, hydrological components and the nonlinear response to multiple types of LULCC.
Chapter 3

Experimental Design

3.1 Model Description

The MM5 was utilized in this study to simulate systematic changes in vegetation type, FV, and SM. MM5 version 3 is a non-hydrostatic, atmospheric research model that is capable of resolving localized topographical, urban, and coastal impacts on synoptic scale systems through nested grids (Dudhia, 1993). This model simulates atmospheric processes by solving the four-dimensional (x,y,z, and t) primitive equations for a fully compressible atmosphere in a rotating frame of reference at user defined resolutions (Dudhia, 1993; NCAR 2006). MM5 also incorporates terrain-following vertical coordinates, real-time data assimilation, three-dimensional coriolis torque, and a suite of physics options including: cumulus parameterization, PBL, explicit moisture, and surface radiation schemes. To appropriately simulate land-atmosphere interactions, MM5 was coupled with the Noah land surface model (LSM).

The Noah LSM is a modification of the original Oregon State University LSM (OSULSM) and extended to include canopy resistance and surface runoff (Chen and Dudhia, 2001a). This community land-surface model is the result of a collaboration between Nation Center for Environmental Protection (NCEP), Oregon State University, Air Force, and the Hydrologic Research Lab; NOAH (Mitchell, 2001). This LSM has been tested against several other widely used LSMs, and reasonably reproduces observed energy fluxes, temperature, and atmospheric and subsurface moisture (Chen and Dudhia, 2001b). The Noah LSM is capable of simulating land-cover atmospheric interactions for a variety of vegetation types, FV, and SM conditions. Furthermore, this LSM can resolve
subsurface temperature and moisture at 0.1, 0.3, 0.6, and 1 meter depths; described as the depths that have the greatest impact on LULCC atmospheric interactions by Huang et al. (1996). The Noah LSM incorporates bio-physical vegetation parameters, including, roughness length, stomata resistance, root depth, leaf area index, and soil characteristics, into thermodynamic and hydrological models to simulate surface energy and moisture budgets (Fig. 2). The hydrological model is further impacted by vegetation fraction, as it partitions total evaporation between direct evaporation from the soil ($E_{dir}$), canopy transpiration ($E_t$), and canopy evaporation ($E_c$) (Chen and Dudhia, 2001a). Modeled canopy transpiration is removed from simulated SM content to conserve mass at each depth within the root zone. Integration of the SM prognostic equation over the four depths shows the removal of subsurface

![Figure 2. A graphic representation of the processes modeled within the Noah land surface model. Source: (Chen and Dudhia 2001).](image-url)
moisture taken-up for canopy transpiration and direct soil evaporation. Other components of this model include soil water diffusivity, hydraulic conductivity, and surface runoff.

3.2 Experimental Setup

For this study, MM5 was initialized with simple ice microphysics, Kain Fritsch cumulus parameterization, and the Eta PBL scheme with two nested domains at nine and three kilometer resolution for the outer and inner domains, respectively. Previously, Quintanar et al., (2008) conducted a series of experiments for domain sizes, and their impacts on accuracy of simulating a number of precipitation events under a variety of synoptic scale forcings for this study region. Based upon simulation results of these experiments and relatively stable synoptic conditions (with no precipitation) during this study period, it was determined that the adopted domain size would provide satisfactory results. Verification of CTRL model results (Chapter 4) also provided evidence that adopted domain sizes and selection of modeling physics options produced realistic simulations of land surface conditions. The outer and inner domains were centered at 37.5°N and -87.0°W at 9 and 3 km² resolutions with 35 x 41 and 49 x 64 grid-points respectively (Fig. 3). Twenty-three vertical levels were used as the primary focus was on near-surface and subsurface simulated results. Initial boundary conditions were forced using global final analysis data (FNL) provided by the National Centers for Environmental Protection (NCEP) at 1° x 1° resolution integrated over a time-step of 30 seconds. The selection of physic options, time-step, and resolution of model domains were made based upon a series of sensitivity tests that fit best against observations for the control run (not shown here).
The current land-cover consists of a mixture of forest, grassland, and cropland as represented by the USGS 24 land-use category dataset shown in (Fig. 4). As noted above, in order to capture the significance of LULCC on near-surface atmospheric and hydrological processes, a series of sensitivity experiments have been conducted. Simulated changes will include conversion of current vegetation (CTRL) to bare soil, grassland, and forest land-cover types. Subsequently, FV was modified (from current 85%) to 25, 50, 75, and 100% with further changes in initial volumetric SM including plus and minus 0.05, 0.10, and 0.15 m$^3$ m$^{-3}$. Changes in volumetric SM for this study will be referenced as WET05, WET10, and WET15 for increases in SM of 0.05, 0.10,
and 0.15 m$^3$ m$^{-3}$ respectively with a similar nomenclature (DRY05, DRY10, and DRY15) for decreases in SM. It is important to note that no FV experiments were considered for bare soil and CTRL simulations for a total of 56 different sensitivity experiments. These changes will be applied uniformly across the entire inner domain. All modeled results are compared to the CTRL run and presented as LULCC minus CTRL.

Figure 4. Inner domain current land-cover classification using USGS 24 classification. Source: Author.

Modeling scenarios were initialized with the same set of initial conditions, and simulated for a total of eleven days from the 15$^{th}$ to the 26$^{th}$ of June 2005. The initial four days of every experiment were excluded from model results to properly account for model spin-up with the final seven days used in the model analysis. During this period, synoptically weak high pressure conditions existed across much of the Ohio River Valley.
with typical dry, summer time temperatures near the lower 30s °C for highs and mid to upper teens (°C) for lows. Less than trace amounts of precipitation were recorded across the study region near the end of the modeling period. Weak synoptic conditions are favored in this study to maximize simulated LULCC atmospheric interactions, which can be overshadowed by large scale synoptic forcing.
Chapter 4

Model Verification

Simulation of CTRL conditions were verified with hourly observations taken from both Automated Surface Observing Systems (ASOS) and Soil Climate Analysis Network (SCAN) sites operated by the National Climatic Data Center (NCDC) and the Natural Resources Conservation Service (NRCS), respectively. The SCAN network additionally provided SM and temperature observations at five depths: 5, 10, 20, 50, and 100 cm. Four ASOS and two SCAN sites were located within modeled domains that had observations at appropriate time intervals from the 15th through the 26th of June 2005. Comparisons of modeled and observed data were conducted by using a series of statistical tests including the coefficient of determination ($r^2$), root mean square error (RMSE), $d$-index, and the mean absolute error (MAE). Weather stations included in this analysis were not equipped to observe the same set of meteorological observations. For example, SCAN sites were equipped to observe relative humidity while ASOS stations provided dew point temperature. Also, modeled SM results were only comparable with observations at two depths (0.1 and 1 m). The four ASOS stations included were Fort Campbell, Henderson, Glasgow, and Bowling Green and the two SCAN sites were Mammoth Cave and Princeton (Fig. 3).

Statistical results revealed that model simulations were aligned with and captured the trend in observed atmospheric conditions. Modeled relative humidity had $r^2$ of 0.58 and 0.56 for Mammoth Cave and Princeton, respectively (Table 1). MAE and RMSE ranged between 9-12% and 11-14%, respectively, for these locations. It was argued that the $d$-index provides a better evaluation of model performance since some of the above
measures are sensitive to outliers (Legates and McCabe 1999). The relative humidity $d$-index for Mammoth Cave and Princeton was 0.82 and 0.85, respectively.

**Table 1. SCAN Relative Humidity Model Validation Statistics**

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Mammoth Cave</th>
<th>Princeton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.58</td>
<td>0.56</td>
</tr>
<tr>
<td>RMSE (°C)</td>
<td>14.60</td>
<td>11.34</td>
</tr>
<tr>
<td>$d$ index</td>
<td>0.82</td>
<td>0.85</td>
</tr>
<tr>
<td>MAE (°C)</td>
<td>12.07</td>
<td>9.13</td>
</tr>
</tbody>
</table>

The $r^2$ values for modeled and observed dew point temperature at ASOS stations varied between 0.59-0.69 (Table 2). MAE and RMSE for dew point temperature at the ASOS sites were between 1.3-3.5 °C and 1.6-3.7 °C, respectively. On the other hand, the $d$-index ranged between 0.62-0.86. Upon further examination of simulated atmospheric moisture, it appeared that the model tended to over and under estimate lower and higher observed values, respectively, for atmospheric moisture measures (Fig. 5a-b).

**Table 2 ASOS Dew Point Temperature Model Validation Statistics**

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Bowling Green</th>
<th>Fort Campbell</th>
<th>Glasgow</th>
<th>Henderson</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.60</td>
<td>0.59</td>
<td>0.69</td>
<td>0.63</td>
</tr>
<tr>
<td>RMSE (°C)</td>
<td>1.69</td>
<td>1.65</td>
<td>3.78</td>
<td>3.03</td>
</tr>
<tr>
<td>$d$ index</td>
<td>0.86</td>
<td>0.85</td>
<td>0.62</td>
<td>0.73</td>
</tr>
<tr>
<td>MAE (°C)</td>
<td>1.31</td>
<td>1.32</td>
<td>3.5</td>
<td>2.61</td>
</tr>
</tbody>
</table>

Time series of modeled and observed relative humidity and dew point temperature suggests that the model satisfactorily captured the trend in atmospheric moisture (Fig. 5c-d). Relative humidity and dew point temperatures were modeled well during the early period of the simulation (June 15 through June 21). However, the model poorly simulated these quantities during trace precipitation events.

The model was a better predictor of 2 m temperature (Table 3). The $r^2$ and $d$-index for 2 m temperature for all sites ranged between 0.71-0.86 and 0.90-0.95, respectively. On the other hand, MAE and RMSE at all sites ranged between 1.4-2.0 °C.
and 1.9-2.8 °C, respectively. An example of the model’s performance in regard to simulated two meter temperature is shown in Fig. 6a-b. The model has a tendency to overestimate lower temperatures and is in agreement with Colle et al. (2003).

Modeled SM was compared to observations at 0.1 and 1m depths, as these were the only two coinciding depths of both observed and modeled SM. The $r^2$ ranged between 0.67 and 0.97 for both depths (Tables 4 and 5; Fig. 6c-d).

**Table 3** ASOS and SCAN Two Meter Temperature Model Validation Statistics

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Bowling Green</th>
<th>Fort Campbell</th>
<th>Glasgow</th>
<th>Henderson</th>
<th>Mammoth Cave</th>
<th>Princeton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.71</td>
<td>0.84</td>
<td>0.80</td>
<td>0.82</td>
<td>0.86</td>
<td>0.84</td>
</tr>
<tr>
<td>RMSE (°C)</td>
<td>2.87</td>
<td>1.92</td>
<td>2.24</td>
<td>2.39</td>
<td>2.49</td>
<td>1.99</td>
</tr>
<tr>
<td>$d$ index</td>
<td>0.91</td>
<td>0.95</td>
<td>0.94</td>
<td>0.94</td>
<td>0.94</td>
<td>0.95</td>
</tr>
<tr>
<td>MAE (°C)</td>
<td>1.99</td>
<td>1.45</td>
<td>1.69</td>
<td>1.89</td>
<td>2.02</td>
<td>1.54</td>
</tr>
</tbody>
</table>
At a depth of 0.1 m, the model had a moist bias and tended to overestimate SM. From the time-series graph (Fig. 6d) these differences were compounded. There are a number of possible explanations for this moist basis including subsurface processes not accounted for in the Noah LSM such as karst or lateral flow within the root zone that tend to make observations drier than modeled. In addition, there are also basis associated with the method of soil-moisture-probe installation at Princeton that can impact typical moisture flow within the soil around the probe that can impact observations. However, sensitivity tests between two simulations will have the same set of systematic model basis and presumably cancel each other with their overall differences not affected by this moist or other basis found in the model as suggested by Avissar and Pielke (1989).
### Table 4 SCAN 01.m Soil Moisture Model Validation Statistics

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Mammoth Cave</th>
<th>Princeton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.97</td>
<td>0.93</td>
</tr>
<tr>
<td>RMSE (°C)</td>
<td>21.61</td>
<td>3.07</td>
</tr>
<tr>
<td>$d$ index</td>
<td>0.29</td>
<td>0.68</td>
</tr>
<tr>
<td>MAE (°C)</td>
<td>21.32</td>
<td>2.39</td>
</tr>
</tbody>
</table>

### Table 5 SCAN 0.6m Soil Moisture Model Validation Statistics

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Mammoth Cave</th>
<th>Princeton</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R^2$</td>
<td>0.67</td>
<td>0.95</td>
</tr>
<tr>
<td>RMSE (°C)</td>
<td>6.92</td>
<td>4.81</td>
</tr>
<tr>
<td>$d$ index</td>
<td>0.00</td>
<td>0.20</td>
</tr>
<tr>
<td>MAE (°C)</td>
<td>6.78</td>
<td>4.74</td>
</tr>
</tbody>
</table>
Chapter 5

Results

5.1 Control Simulation

CTRL land-cover consists mainly of grasses (13%) and forests (74%) with the remaining inner domain’s vegetation composed of croplands and shrubs. The vegetation fraction during this summer period from June 15th to the 26th was nearly 85% with silt-loam as the dominant soil type. Modeled domain averages of latent and sensible heat fluxes were 198 and 42 Wm$^{-2}$ (Fig. 7a-b). Domain averages of relative humidity, ground surface, 2 m, and dew point temperatures were 64%, 25.9, 25.0, and 17.7 °C, respectively (Fig. 8a-e). Also, domain averaged PBL height was 401 m (Fig. 8e). Modeled results of 2 m temperature for the CTRL experiment were similar to summer time climatology averages for this region of 23 °C (Kentucky Climate Center 2008).
Figure 7. Diurnal area average of modeled latent heat flux (a) and sensible heat flux (b) for Control (square), bare soil (circle), grassland (diamond) and forest (triangle) experiments.
Figure 8. Diurnal area average of modeled (a) relative humidity (b) dew point temperature (c), ground temperature (d), two-meter temperature (e), and planetary boundary layer height for control (square), bare soil (circle), grassland (diamond), and forest (triangle).

5.2 Grassland Experiments

Domain averages of latent and sensible heat flux, relative humidity, and ground surface, two meter, and dewpoint temperatures, and PBL height over grassland were, 202 and 33 W m$^{-2}$, 68%, 25.4, 24.8 and 18.3 $^\circ$C, and 340 m, respectively (Fig. 7a-b, and 8a-e). Compared to CTRL (grass minus control), modeled latent heat flux, relative
humidity, and dewpoint temperature over grassland were elevated by 5 W m\(^{-2}\), 3.6%, and 0.53 °C, respectively. However, domain averages of sensible heat flux, ground surface and 2 m temperatures, and PBL height were reduced by 9 W m\(^{-2}\), 0.62 °C, 0.40 °C, and 63 m, respectively.

In addition, the average largest 24 hour difference in latent heat flux, relative humidity, and dewpoint temperature were greater than CTRL by 26 W m\(^{-2}\), 4.76 % and 0.78 °C, respectively. The average largest 24 hour difference in sensible heat flux, ground surface and 2 m temperature, and PBL height were less than CTRL (grass minus control) by 33 W m\(^{-2}\), 1.35 and 0.60 °C, and 228 m, respectively. The increase in atmospheric moisture and relative cooling of ambient temperature can be largely attributed to lower stomatal resistance for grass and corresponding higher evapotranspiration rates (Table 6). As a result, a small decrease in subsurface moisture was also reported (not shown).

<table>
<thead>
<tr>
<th>Land Use</th>
<th>Albedo</th>
<th>Roughness Length (m)</th>
<th>Root Zone</th>
<th>Stomata Resistance (s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grassland</td>
<td>0.19</td>
<td>0.08</td>
<td>3</td>
<td>40</td>
</tr>
<tr>
<td>Deciduous Forest</td>
<td>0.12</td>
<td>0.8</td>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>Barren Vegetated</td>
<td>0.12</td>
<td>0.01</td>
<td>1</td>
<td>999</td>
</tr>
</tbody>
</table>

In response to an evaporation-conducive environment over grassland, domain-wide spatial differences of PBL height similarly showed a systematic reduction in PBL heights over grassland compared to CTRL (Fig. 9a). The largest reduction of in PBL height was 300 m with much of the domain exhibiting a reduction between 100 to 250 m. Reductions in PBL height, as a result of increased evaporation, modified horizontal wind. From Fig. 9a, horizontal wind field differences showed a diverging pattern away from
grassland as a result of lowered PBL heights, which is in line with McPherson and Stensurd (2005) and Segal et al. (1988).

Figure 9. Difference fields of modeled Grassland PBL height with horizontal wind field (a) and \( \theta_e \) with vertical wind field (b) calculated at experiment minus control.

A south to north cross section showed elevated equivalent potential temperatures (\( \theta_e \)) of 2 °C compared to CTRL simulations (Fig. 9b). The increase in \( \theta_e \) (also known as moist static energy) over grassland land-cover is in line with simulated increases in latent heat flux and atmospheric moisture. Enhanced \( \theta_e \) extends to the top of the grassland PBL near 930 mb. Vertical wind profile shows primarily subsidence over the grassland region with maximum vertical wind speed differences (grass minus control) near the simulated domain border of 2 cm s\(^{-1}\). It was also found that near-surface wind fields encountered increased surface roughness outside of the region of LULCC (inner domain) that potentially increased drag and caused surface convergence and vertical motion. This, accompanied by descending motion over the grassland region as previously mentioned, completed a land-use induced mesoscale circulation evident in Fig. 9b with two complete circulations at either end of the cross section.
5.3 Grassland FV Experiments

FV experiments for grassland were conducted systematically at 25, 50, 75, and 100 %. Modeled latent and sensible heat fluxes were sensitive to changes in FV with domain averages of 140, 166, 189, and 210 and 70, 54, 40, and 28 W m\(^{-2}\) at 25, 50, 75, and 100 % respectively (Fig. 10a-b). In addition, domain averages of relative humidity and dew point temperature increased with increasing FV. These averages were 57, 59, 63, and 70 % and 16.7, 17.0, 17.6, and 18.6 °C (Fig. 11a-b). Due to reductions in modeled sensible heat flux, ground surface and 2 m temperatures and PBL height were diminished with increasing FV with domain averages of 28.3, 27.2, 26.1, and 25.0 °C and 26.6, 26.0, 25.3, and 24.5 °C, and 535, 479, 394, and 302 m for FV at 25, 50, 75, and 100 % respectively (Fig. 11c-e). As the amount of green plant canopy (FV) increased (decreased), atmospheric moisture proportionally increased (decreased).

In comparison to CTRL, modeled grassland results became increasingly moist and cooler with increases in FV. The largest average 24 hour latent heat flux, relative humidity, and dew point temperature were less than CTRL by 180, 98, and 21 W m\(^{-2}\), 9, 6, and 1%, and 1.9, 1.4, and 0.3 °C for FV at 25, 50, and 75%. At 100% FV, the largest average 24 hour differences for latent heat flux, relative humidity, and dew point temperature were 52 W m\(^{-2}\), 7%, and 1.2 °C greater than CTRL. For sensible heat flux, the largest average 24 hour differences were greater than CTRL by 86 and 36 W m\(^{-2}\) at 25 and 50% FV, but reduced to 8 and 47 W m\(^{-2}\) less than CTRL at 75 and 100% FV. Expectedly, the largest average 24 hour differences in ground and 2 m temperatures were less than CTRL by 3.3, 1.5, 0.2 and 1.7, 1.1, and 0.2 °C at 25, 50, and 75% FV, but were cooler than CTRL by 2.0 and 0.9 °C at 100% FV. Likewise, the largest average 24 hour
PBL height differences were greater than CTRL by 504 and 435 m at 25 and 50% FV, but less than CTRL by 36 and 376 m at 75 and 100% FV.

Figure 10. Diurnal area average of modeled latent heat flux (a) and sensible heat flux (b) for CTRL (solid line), grassland at 100% FV (circle), grassland at 75% FV (triangle), grassland at 50% FV (diamond), grassland at 25% FV (square), and 85% FV (dashed line) experiments.
Figure 11. Diurnal area average of modeled (a) relative humidity (b) dew point temperature (c), ground temperature (d), two-meter temperature (e), and planetary boundary layer height for control (solid line), grassland at 100% FV (circle), grassland at 75% FV (triangle), grassland at 50% FV (triangle), grassland at 25% FV (square), and grassland at 85% FV (dashed line) experiments.

PBL height and horizontal wind field differences with respect to CTRL showed the importance of FV (Fig. 12a-d). PBL heights across the domain were significantly greater than CTRL by 500 and 300 m for grassland experiments at 25 and 50 % FV. However, as FV increased to 75 and 100 %, PBL growth was diminished with heights less than CTRL by 200 and 500 m respectively. Horizontal wind field differences
initially show convergence over grassland at low FV (25 and 50%), but shifted to
divergence as FV increases as a result of a lowering PBL. Maximum wind speed
differences were greater than CTRL by 1.2, 0.7, 0.3, and 1 m s\(^{-1}\) for grassland
experiments at 25, 50, 75, and 100% FV respectively.

\(\theta_e\) and vertical wind field differences for grassland compared to CTRL were also
sensitive to changes in FV. At 25, 50, and 75% FV, \(\theta_e\) for grassland experiments were
less than CTRL by 4, 2, and 1 °C (Fig. 12e-g). As FV increased further to 100%, \(\theta_e\)
differences were greater than CTRL by 3 °C (Fig. 12h). Vertical wind field differences
were also sensitive to FV. Maximum vertical wind field differences were generally
located near the grassland edge with wind speeds greater than CTRL by 5 and 3 cm s\(^{-1}\)
(upward) at 25 and 50% FV to 1 and 2 cm s\(^{-1}\) (downward) at 75 and 100% FV. In
addition, meso-scale circulation development along the southern and northern edges of
the cross section seemed to be suppressed over dense vegetation (Figs. 12e-h). This is
likely due to diminished thermal/density gradients along the domain border associated
with increased FV and ET rates.
Figure 12. Difference fields of modeled PBL height, horizontal and vertical wind vectors, and $\theta_e$ were calculated as experiment minus control. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) grassland at 100% FV, (b) grassland at 75% FV, (c) grassland at 50% FV, and (d) grassland at 25% FV experiments. Simulation-averaged $\theta_e$ and arrows representing vertical wind vector differences for (e) grassland at 100% FV, (f) grassland at 75% FV, (g) grassland at 50% FV, and (h) grassland at 25% FV experiments.
5.4 DRY Grassland Experiments at 25% FV

Reductions in initial SM under grassland at 25% FV had a profound impact on simulated PBL processes. As can be seen from Figures 13a and b, surface fluxes were significantly altered as SM was reduced. Domain averages of latent heat flux were 120, 97, and 76 W m\(^{-2}\) for DRY05, DRY10, and DRY15, respectively. On the other hand, modeled sensible heat flux was 85, 101, and 115 W m\(^{-2}\) for these same experiments. Relative humidity and dew point temperature were only slightly diminished with domain averages of 54, 52, and 50 % and 16.2, 15.8, and 15.4 °C (Figs. 14a-b). Given the reduction of latent heat flux (44 Wm\(^{-2}\)) between the dry grassland experiments one would expect a similar reduction in relative humidity (4 %) and dew point temperature (0.8 °C). Upon further analysis, results showed moisture convergence over the simulated domain due to shifts in horizontal surface wind field that suppressed the atmospheric moisture response to reductions in root zone SM. This is similar to the findings of Douville et al. (2001) and Sud and Smith (1985). These results will be further discussed at the end of this section. Domain averages of ground and 2 m temperatures and PBL height were 29.1, 29.9, and 30.6 °C and 27.1, 27.6, and 28.0 °C, and 691, 640, and 589 m (Figs. 14c-e).

Dry grassland experiments at 25% FV with respect to CTRL were significantly drier and warmer, with higher PBL heights. The largest average 24 hour latent heat flux, dew point temperature, and relative humidity differences were less than CTRL (grassland minus CTRL) by 233, 290, and 345 W m\(^{-2}\), 12, 15, and 17 %, and 2.6, 3.0, and 3.6 °C. Also, sensible heat flux, ground and 2 m temperatures, and PBL heights for the dry grassland experiments were considerably higher than CTRL with the largest average 24
hour differences of 134, 178, and 212 W m$^{-2}$, 4.7, 6.0, and 7.0 and 2.2, 2.7, and 3.2 °C, and 619, 677, and 767 m respectfully.

Figure 13. Diurnal area average of modeled (a) latent heat flux and (b) sensible heat flux for Control (diamond), dry 0.05 grassland (circle), dry 0.10 grassland (square), and dry 0.15 grassland (triangle)
Figure 14. Diurnal area average of modeled (a) relative humidity, (b) dew point temperature, (c) ground temperature, (d) two-meter temperature, and (e) planetary boundary layer height for Control (diamond), dry 0.05 grassland (circle), dry 0.10 grassland (square), and dry 0.15 grassland (triangle).

Reductions in SM for grassland at 25% FV greatly enhanced turbulent mixing within the lower BL causing the PBL top to extend upward as described by Oke (1987). Figures 15a-c showed increasing PBL heights as SM was reduced. However, PBL growth was not uniform across the domain with PBL height differences ranging between 100 m less than CTRL to 1100 m greater than CTRL for the DRY experiments. In
addition, horizontal wind vector differences in comparison to CTRL were directed inward toward regions of higher PBL height (sensible heat flux), which is similar to Smith et al. (1994). Maximum horizontal wind speed differences were greater than CTRL by 1, 1, and 1.4 m s\(^{-1}\) for each reduction in SM respectively.

Due to reductions in subsurface moisture, \(\theta_e\) differences were less than CTRL from the surface up to 910 mb (Figs. 15d – f). \(\theta_e\) differences for the dry grassland experiments at 25% FV varied between 2 and 5 °C less than CTRL within the lower boundary layer. Also, vertical wind field differences primarily showed rising motion for all dry grassland experiments at 25% FV with developed circulations at both northern and southern edges along the cross section. The development of land breezes along vegetation boundaries has been described by Segal et al. (1988) and Ookouchi et al. (1984). They have attributed these circulations to sharp gradients in SM found along the domains border. It is hypothesized here that even over homogenous distributions of low FV, land-use thermal gradients may exist due to subtle elevation or SM differences that give rise to preferential boundary-layer circulations. These circulations may have also developed due to vigorous mixing within the PBL. In addition, maximum vertical wind speed differences were greater than CTRL by 7, 14, and 15 cm s\(^{-1}\) for DRY05, DRY10, and DRY15 experiments, respectively.
Figure 15. Difference fields of modeled PBL height and horizontal and vertical wind field vectors, and $\theta_e$ calculated at experiment minus CTRL. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) DRY05 grassland at 25% FV, (b) DRY10 grassland at 25% FV, and (c) DRY15 grassland at 25% FV experiments. Simulation-averaged $\theta_e$ with arrows representing vertical wind vector differences for (d) DRY05 grassland at 25% FV, (e) DRY10 grassland at 25% FV, and (f) DRY15 grassland at 25% FV experiments.

5.5 DRY Grassland Experiments at 50% FV

Reductions in initial SM over grassland at 50% FV were moderate when compared to simulated changes for grassland at 25% FV. Latent (sensible) heat flux was
diminished (increased) due to reductions in SM (Figs. 16a and b) with domain averages of 153, 136, and 117 (65, 77, and 91 W m\(^{-2}\)), respectively. Similar to DRY grassland experiments at 25% FV, atmospheric moisture sensitivity to reductions in SM was small compared to the sensitivity of modeled latent heat flux. Domain averages of relative humidity and dew point temperature were 56, 54, and 52 % and 16.5, 16.1, and 15.7 °C, respectively (Figs. 17a and b). Simulated ground and 2 m temperatures and PBL height were increased for DRY05, DRY10, and DRY15 experiments with domain averages of 27.9, 28.5, and 29.3 and 26.4, 26.8, and 27.2 °C and 528, 574, and 635 m, respectively (Figs. 17c-e).

Results compared to CTRL for the dry grassland experiments at 50% FV were more similar to CTRL than grassland at 25 % FV. The largest average 24 hour latent heat flux, dew point temperature, and relative humidity differences were less than CTRL by 137, 180, and 227 W m\(^{-2}\), 1.9, 2.5, and 3.2 °C, and 9, 12, and 15 %, respectively. The increase in FV also slightly diminished simulated differences between grassland at 50% FV and CTRL for temperature and PBL height. The largest average 24 hour sensible heat flux, ground and 2 m temperatures, and PBL height differences were greater than CTRL by 66, 107, and 154 W m\(^{-2}\), 2.7, 4.1, and 5.5 and 1.4, 1.9, and 2.5 °C, and 541, 592, and 700 m, respectively for DRY05, DRY10, and DRY15 experiments.
Figure 16. Diurnal area average of modeled (a) latent heat flux and (b) sensible heat flux for CTRL (diamond), DRY05 grassland at 50% FV (circle), DRY10 grassland at 50% FV (square), and DRY15 grassland at 50% FV (triangle).

PBL heights were primarily greater than CTRL across the inner domain for all dry grassland experiments at 50% FV (Figs. 18a-c). In other words, PBL height increased with respect to CTRL as SM was reduced. PBL height differences between the DRY
grassland at 50 % FV experiments compared to CTRL ranged between 100 m (DRY05) less than to 800 m (DRY15) greater than CTRL. Horizontal wind field differences showed converging wind vectors oriented toward the inner domain similar to the DRY grassland experiments at 25% FV (Figures 18a-c).

**Figure 17.** Diurnal area average of modeled (a) relative humidity, (b) dew point temperature, (c) ground temperature, (d) two-meter temperature, and (e) planetary boundary layer height for CTRL (diamond), DRY05 grassland at 50% FV (circle), DRY10 grassland at 50% FV (square), and DRY15 grassland at 50% FV (triangle).
Maximum horizontal wind speed differences were not as large as those over grassland at 25% FV, but were greater than CTRL by 0.8, 1, and 1.2 m s\(^{-1}\) for the DRY05, DRY10, and DRY15 experiments, respectively.

\(\theta_e\) differences for the DRY grassland experiments at 50% FV were less than CTRL (Figs. 18d – f). From the surface up to 900 mb, \(\theta_e\) differences ranged between 1 and 5 °C less than CTRL for the dry grassland experiments. Due to converging horizontal wind fields at the surface, vertical wind vector differences primarily showed rising motion near the cross sections southern and northern edges with a single region of subsidence along the cross section. It should also be noted that as SM was reduced, favorable locations for rising and subsiding motions varied as previously mentioned. Maximum vertical wind speed differences were greater than CTRL by 5, 5, and 4.5 cm s\(^{-1}\).
Figure 18. Difference fields of modeled PBL height and horizontal and vertical wind field vectors, and \( \theta_e \) calculated at experiment minus CTRL. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) DRY05 grassland at 50% FV, (b) DRY10 grassland at 50% FV, and (c) DRY15 grassland at 50% FV experiments. Simulation-averaged \( \theta_e \) with arrows representing vertical wind vector differences for (d) DRY05 grassland at 50% FV, (e) DRY10 grassland at 50% FV, and (f) DRY15 grassland at 50% FV experiments.

5.6 DRY Grassland Experiments at 75% FV

Over grassland at 75% FV, sensitivity to reductions in SM was further diminished when compared to DRY grassland experiments at 25 and 50% FV. Inner domain averages of latent and sensible heat flux for each decrease in initial SM were 181, 170,
and 151 and 46, 55, and 68 W m\(^{-2}\), respectively (Figs. 19a and b). Simulated domain averages of relative humidity, dew point temperature, ground and 2 m temperatures, and PBL heights were 60, 58, and 55%, 17.1, 16.7, and 16.1 °C, 26.5, 27.2, and 27.9 and 25.6, 26.0, and 26.4 °C, and 431, 483, and 546 m respectively (Figs. 20 a-e).

As expected, results for DRY grassland experiments at 75% FV were more similar to CTRL than DRY grassland runs at 25 or 50% FV. The largest average 24 hour latent heat flux, dew point temperature, and relative humidity differences were less than CTRL by 44, 78, and 131 W m\(^{-2}\), 0.9, 1.4, and 2.2 °C, and 4, 7, and 11 %, respectively for DRY05, DRY10, and DRY15 experiments. These results were followed by analysis of differences in sensible heat flux, ground and 2 m temperatures, and PBL height. These were greater than CTRL by 11, 40 and 83 W m\(^{-2}\), 0.7, 1.7, and 3.4 and 0.5, 0.9, and 1.6 °C, and 177, 374, and 434 m, respectively. Reduced model sensitivity to drier soils over more dense vegetation has been previously noted by Chen and Avissar (1994).

Across the inner domain, PBL height differences showed some sensitivity to reductions in initial SM. Successive reductions in available root zone SM increased PBL heights relative to CTRL (Figs. 15a-c). For the DRY experiments, simulated PBL height differences in comparison to CTRL ranged between 200 m less than CTRL to 600 m greater. Horizontal wind vector differences compared to CTRL were also small for the dry grassland experiments at 75% FV, but slightly increased as SM was reduced (Figs. 21a-c). Horizontal vector differences diverged (converged) near regions of lower (higher) PBL heights. Maximum horizontal wind speed differences were greater than CTRL by 0.7, 0.8, and 0.8 m s\(^{-1}\), respectively.
Figure 19. Diurnal area average of modeled (a) latent heat flux and (b) sensible heat flux for CTRL (diamond), DRY05 grassland at 75% FV (circle), DRY10 grassland at 75% FV (square), and DRY15 grassland at 75% FV (triangle)
Cross section results suggest that $\theta_e$ and vertical wind field differences were sensitive to reductions in SM. $\theta_e$ for the DRY05 grassland experiment was 1°C lower than CTRL (Fig. 21d). As SM was reduced further, $\theta_e$ was diminished up to 3°C from the surface up to 900 mb (Figs. 18e and f) compared to CTRL. For the DRY grassland...
experiments at 75% FV, maximum vertical wind speed difference was greater than CTRL by 2, 2, and 4 cm s\(^{-1}\) for DRY05, DRY10, and DRY15 experiments, respectively (Figs. 21d-f).

Figure 21. Difference fields of modeled PBL height and horizontal and vertical wind field vectors, and \(\theta_e\) calculated at experiment minus CTRL. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) DRY05 grassland at 75% FV, (b) DRY10 grassland at 75% FV, and (c) DRY15 grassland at 75% FV experiments. Simulation-averaged \(\theta_e\) with arrows representing vertical wind vector differences for (d) DRY05 grassland at 75% FV, (e) DRY10 grassland at 75% FV, and (f) DRY15 grassland at 75% FV experiments.
5.7 DRY Grassland Experiments at 100% FV

In general, grassland experiments at 100% FV were the least sensitivity to reductions in SM. Inner domain averages of latent and sensible heat fluxes were 206, 198, and 180 and 31, 37, and 50 W m$^{-2}$ for DRY05, DRY10, and DRY15 experiments, respectively (Figs. 22a-b). Domain average dew point temperature and relative humidity were 18.4, 17.8, and 16.9 °C and 68, 65, and 59 % for DRY SM experiments, respectively (Figs. 23a-b). Despite the insensitivity of modeled latent heat flux over grassland at 100% FV to reductions in SM, simulated atmospheric moisture (dew point and relative humidity) showed the greatest sensitivity to reduced SM at 100% FV than any of the other FV cases (25, 50, 75, and 85%); more on this later. However, increased FV did moderate atmospheric temperature and PBL height differences between dry grassland experiments and CTRL. Domain average ground and 2 m temperatures and PBL height for DRY05, DRY10, DRY15 were 25.3, 25.8, and 26.7 and 24.7, 25.1, and 25.6 °C and 320, 357, and 432 m, respectively (Figs. 23c-e).
Results for grassland experiments at 100% FV became more similar to CTRL for all DRY scenarios. The largest average 24 hour latent heat flux, relative humidity, and dew point temperature differences were greater than CTRL by 38 and 13 W m$^{-2}$, 5 and 1
%, and 0.9 and 0.3 °C for the DRY05 and DRY10, experiments. However, for the
DRY15, the largest average 24 hour differences were less than CTRL by 43 W m\(^{-2}\), 1.1
°C, and 5% respectively. On the other hand, the largest average 24 hour sensible heat
flux, ground and 2 m temperatures, and PBL heights were less than CTRL by 39 and 20
W m\(^{-2}\), 1.5 and 0.7 °C, 0.7 and 0.2 °C, and 332 and 195 m for the DRY05 and DRY10,
respectively. As SM reduced further by 0.15 m\(^3\) m\(^{-3}\) (DRY15), simulated sensible heat
flux, ground and 2 m temperatures, and PBL heights increased above CTRL by 26 W m\(^{-2}\),
1.1 °C, 0.6 °C, and 125 m.

PBL height difference for the DRY05 was primarily less than CTRL (Fig. 24a). However, as subsurface moisture reduced PBL heights were slightly elevated higher than
CTRL (Figs. 24b-c). PBL height differences for the dry experiments ranged from 450 m
less to 400 m greater than CTRL. Simulated horizontal wind field differences compared
to CTRL diverged from the domain center (Figs. 24a-c) for all DRY experiments.
Maximum horizontal wind speed differences were greater than CTRL by 0.6, 0.8, and 1
m s\(^{-1}\) for DRY05, DRY10, and DRY15 experiments, respectively.
Figure 23. Diurnal area average of modeled (a) relative humidity, (b) dew point temperature, (c) ground temperature, (d) two-meter temperature, and (e) planetary boundary layer height for CTRL (diamond), DRY05 grassland at 100% FV (circle), DRY10 grassland at 100% FV (square), and DRY15 grassland at 100% FV (triangle)
Figure 24. Difference fields of modeled PBL height and horizontal and vertical wind field vectors, and $\theta_e$ calculated at experiment minus CTRL. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) DRY05 grassland at 100% FV, (b) DRY10 grassland at 100% FV, and (c) DRY15 grassland at 100% FV experiments. Simulation-averaged $\theta_e$ with arrows representing vertical wind vector differences for (d) DRY05 grassland at 100% FV, (e) DRY10 grassland at 100% FV, and (f) DRY15 grassland at 100% FV experiments.

Vertical cross section of $\theta_e$ differences for DRY grassland experiments at 100% FV showed a moister lower boundary layer in comparison to CTRL for the DRY05, and DRY10 experiments (Figs. 24d and e). On the other hand, the DRY15 experiment
showed a drier lower boundary layer (Fig. 24f). It was also found that at 100% FV, $\theta_e$ differences for dry grassland experiments ranged from 4 °C less to 4 °C greater than CTRL between the DRY05 and DRY15 experiments. Vertical wind vector differences along the cross section mainly showed subsidence associated with lower PBL heights for all DRY grassland experiments at 100% FV (Figs. 24d-f). Also, descending motion near the cross section’s northern and southern edges can be attributed to diverging horizontal wind fields at the surface. Maximum vertical wind speed differences were greater than CTRL by 1.5, 2.5, and 3 cm s$^{-1}$, for DRY05, DRY10, and DRY15 experiments, respectively.

5.8 Moisture Convergence and Divergence

As noted by both Sud et al. (1985) and Douville et al. (2001), reductions in SM have been found to increase atmospheric moisture convergence. Douville et al. (2001) using a global circulation model (GCM) noted that reductions in SM over the India subcontinent and Africa resulted in moisture convergence over India. Keeping in-line with these results, moisture flux was analyzed for both DRY grassland experiments at 25% FV (Figs. 25a-c) and 100% FV (Figs. 25d-f) for the outer domain. Moisture flux, represented by vectors, indicated strong moisture convergence over DRY grassland experiments for 25% FV and a weak moisture divergence over DRY grassland experiments for 100% FV. In addition, moisture flux for these experiments closely followed surface horizontal wind fields, which were perturbed by changes in PBL height.
Figure 25. Difference fields of modeled PBL height and moisture flux vectors calculated as experiment minus CTRL for the outer domain. Modeled PBL height and arrows representing surface moisture flux vector differences for (a) DRY05 grassland at 25% FV, (b) DRY10 grassland at 25% FV, (c) DRY15 grassland at 25% FV, (d) dry grassland at 100% FV, (e) DRY10 grassland at 100% FV, and (f) DRY15 grassland at 100% FV experiments.

5.9 Forest

Domain averages of latent and sensible heat flux, relative humidity, and ground surface, 2 m and dew point temperatures over forest were, 192 and 47 W m$^{-2}$, 63%, and 26.4, 25.3 and 17.6 °C, respectively (Fig. 7a-b, 8a-f). Compared to CTRL, modeled
latent heat flux, relative humidity, and dewpoint temperature were only slightly diminished by 5 W m$^{-2}$, 0.8%, and 0.1 °C. Modeled sensible heat flux and ground surface and 2 m temperature over forest land-cover were slightly enhanced with respect to CTRL by 4 W m$^{-2}$ and 0.3 and 0.2 °C respectively. The increase in surface roughness and elevated sensible heat flux helped to raise PBL heights to 431m or 27m higher than CTRL.

The average largest 24 hour reduction in modeled latent heat flux was 21 W m$^{-2}$ compared to CTRL. Differences (forest minus control) in atmospheric moisture over simulated forest areas were modest when compared to CTRL. For example, relative humidity and dew point temperature show a 1.6 %, and 0.3 °C decrease, respectively. This study found the average largest 24 hour differences (forest minus control) of sensible heat flux, ground and 2 m temperature were only 17 W m$^{-2}$, 0.9 °C, and 0.3 °C greater than CTRL. Overall, results suggest that forest land-use modified near surface moisture content. However, compared to grass, the magnitudes of changes were muted. These marginal differences are associated with CTRL’s land-cover, which is mostly made up of forests as previously mentioned in addition to grass’s modeled evaporation advantage (lower stomatal resistance) over forest.

In line with previous results, alterations in PBL height with respect to CTRL were small (Fig. 26a). Maximum PBL height differences between forest and CTRL ranged from 150 to 200 m. However, much of the forested region showed increases in PBL height of less than 100 m. Horizontal wind field differences indicated weak convergence over the forest region linked primarily to the slight increase in PBL height, but also the increase in surface roughness. This is similar to the McPherson and Stensrud (2005)
suggestion that first order differences were attributed to the changes in PBL height. Maximum horizontal surface wind speed differences (forest minus control) were near 0.3 cm s$^{-1}$ greater than CTRL and concentrated over the northwestern corner and along the forested edge of the domain in vicinity of the larger forest PBL height difference.

The vertical cross sectional analysis of $\theta_e$ reveals almost no simulated change between forest and control runs (Fig. 26b). These results are similar with other simulated atmospheric fields between forest and control. Vertical wind field differences show regions of both subsidence and upward motion along the cross section at 1 cm s$^{-1}$ greater than CTRL.

**5.10 Forest FV Experiments**

FV experiments over forest land-cover affected modeled surface energy and moisture similar to grassland FV experiments. Domain averages of latent and sensible heat flux were 135, 158, 179, and 199 and 79, 67, 54, and 42 W m$^{-2}$ for forest experiments at 25, 50, 75, and 100% respectively (Fig. 27a-b). Alterations to FV also affected relative humidity, dew point temperature, ground and 2 m temperatures, and PBL heights. Domain averages of these variables were 56, 58, 60, and 65%, 16.8, 17.0,
17.2, and 17.9 °C, 28.9, 28.0, 27.0, and 26.1 and 26.9, 25.7, and 25.1 °C, and 556, 520, 472, and 404 m for FV at 25, 50, 75, and 100% respectively (Fig. 28a-f). Over all, increases in FV tended to enhance ET rates (latent heat flux) thereby reducing temperature and lowering of PBL heights.

In comparison to CTRL, forest land-use was less sensitivity to variations in FV than grassland. The largest 24 hour latent heat flux, relative humidity, and dew point temperature differences were less than CTRL by 200, 130, and 61 W m\(^{-2}\), 10, 8, and 4%, and 2.0, 1.5, 0.8 °C for FV at 25, 50, and 75%. At 100% FV, the largest average 24 hour difference was greater than CTRL by 7 W m\(^{-2}\), 1%, and 0.2 °C respectively. In addition, increases in FV suppressed modeled sensible heat flux, ground and 2 m temperature, and PBL heights with the largest average 24 hour differences greater than CTRL by 115, 74, 39 W m\(^{-2}\), 4.6, 3.2, and 1.8 and 2.0, 1.3, and 0.7 °C, and 473, 415, and 314 m for forest experiments at 25, 50, and 75% FV. However, the largest average 24 hour sensible heat flux, 2 m temperature, and PBL height differences were less than CTRL by 2 W m\(^{-2}\), 0.1 °C, and 44m with ground temperature greater than CTRL by 0.3 °C.
Figure 27. Diurnal area average of modeled latent heat flux for control (solid line), forest at 100% FV (circle), forest at 75% FV (triangle), forest at 50% FV (diamond), forest at 25% FV (square), and forest at 85% FV (dashed line) experiments.
Figure 28. Diurnal area average of modeled (a) relative humidity (b) dew point temperature (c), ground temperature (d), two-meter temperature (e), and planetary boundary layer height for control (solid line), forest at 100% FV (circle), forest at 75% FV (triangle), forest at 50% FV (diamond), forest at 25% FV (square), and forest at 85% FV (dashed line) experiments.

PBL height differences across the modeled domain became more similar to CTRL as FV increased. Simulated PBL height differences over forest were greater than CTRL by as much as 600, 500, and 300 m for FV experiments at 25, 50 and 75 % respectively. At 100% FV, modeled differences varied between 60 m greater to 120 m less than CTRL.
Similar to grassland FV experiments, horizontal surface wind field differences were largest near regions with sharp contrasts in PBL heights between forest and CTRL. Maximum horizontal wind speed differences were greater than CTRL by 2.0, 1.3, 1.0, and 0.5 m s\(^{-1}\) for each increase in FV respectively (Figs. 29a-c).

\(\theta_e\) differences along the south to north cross section over forest land-use similarly diminished as FV increased. \(\theta_e\) differences ranged from the surface up to 900 mb with values less than CTRL by 4, 3, and 1 °C for FV experiments of 25, 50, and 75 % respectively (Figs. 29d-e). At 100% FV, \(\theta_e\) is slightly higher than CTRL by 0.4 °C (Fig 29f). In addition, vertical wind field differences at 25% FV showed primarily rising motion within the PBL along the cross section. However, as FV increased to 100% vertical wind field differences varied between intermitted regions of rising and subsiding motion. Maximum vertical wind field differences were greater than CTRL by 6, 5, 3, and 0.8 cm s\(^{-1}\) for each increase in FV from 25 to 100% FV.
Figure 29. Difference fields of modeled PBL height, horizontal and vertical wind vectors, and $\theta_e$ were calculated as experiment minus control. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) forest at 100% FV, (c) forest at 75% FV, (e) forest at 50% FV, and (g) forest at 25% FV experiments. Simulation-averaged $\theta_e$ and arrows representing vertical wind vector differences for (b) forest at 100% FV, (d) forest at 75% FV, (f) forest at 50% FV, and (h) forest at 25% FV experiments.
5.11 DRY Forest Experiments at 25% FV

Simulated surface fluxes for forest land-use at 25% FV were highly sensitive to reductions in initial SM. Coupling reduced subsurface moisture with low FV, significantly diminished the availability of subsurface moisture for evapotranspiration. Domain average latent and sensible heat fluxes were 116, 91, and 67, and 92, 110, and 125 W m$^{-2}$ for the DRY05, DRY10, and DRY15 experiments, respectively (Figs. 30 a-b). Domain averaged relative humidity and dew point temperature was 54, 51, and 49% and 16.3, 15.9, and 15.5 °C (Figs. 31a-b). Modest variability in atmospheric moisture was similar to DRY grassland experiments at 25 % FV and indicated moisture advection into the modeled domain as a result of altered surface winds. Domain average ground and 2 m temperatures and PBL height were all elevated (Figs. 31 c-e). They were 29.7, 30.6, and 31.3 and 27.3, 27.8, and 28.3 °C, and 600, 656, and 705 m, respectively, for DRY05, DRY10, and DRY15 respectively.
Figure 30. Diurnal area average of modeled (a) latent heat flux and (b) sensible heat flux for CTRL (diamond), DRY05 forest at 25% FV (circle), DRY10 forest at 25% FV (square), and DRY15 forest at 25% FV (triangle)

In comparison to CTRL, dry forest experiments at 25% FV were significantly drier and warmer with elevated PBL heights. The largest average latent heat flux, relative humidity, and dew point temperature differences were much less than CTRL. These differences were 249, 317, and 377 W m$^{-2}$, 13, 16, and 18 %, and 2.5, 3.0, and 3.4
°C lower for the DRY05, DRY10, and DRY15 experiments respectively. Sensible heat flux, ground and 2 m temperatures, and PBL height were expectedly greater than CTRL with the largest average difference of 156, 203, and 239 W m$^{-2}$, 6.0, 7.5, and 8.6 and 2.4, 2.9, and 3.4 °C, and 565, 650, and 761 m, respectively for DRY05, DRY10, and DRY15.

PBL height and horizontal wind field differences with respect to CTRL revealed their sensitivity to reductions in subsurface moisture. PBL height differences varied across the domain (Figs. 32a-c) due to randomly generated turbulent eddies as described by Chen and Avissar (1994) which lead to greater PBL growth. PBL height differences for the dry experiments ranged between 100 m less to 1100 m greater than CTRL. Horizontal wind field differences were directed toward the domain center and increased as SM was reduced. Maximum horizontal wind speed differences were greater than CTRL by 0.6, 0.8, and 1.4 m s$^{-1}$ for DRY05, DRY10, and DRY15, respectively.
A cross section of $\theta_e$ differences showed a reduction compared to CTRL over drier soils (Figs. 32d-f). For the DRY forest experiments at 25% FV, $\theta_e$ differences within the lower boundary layer (up to 850 mb) ranged between 2 and 5 °C less than CTRL. Similar to DRY grassland experiments at 25% FV, modeled meso-scale
circulations developed both at either ends of the cross section. Along the cross section, it was found that reductions in SM enhanced vertical wind speed differences with vertical speeds greater than CTRL by 12, 15, and 18 cm s$^{-1}$ for DRY05, DRY10, and DRY15 experiments, respectively.
Figure 32. Difference fields of modeled PBL height and horizontal and vertical wind field vectors, and $\theta_e$ calculated at experiment minus CTRL. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) DRY05 forest at 25% FV, (b) DRY10 forest at 25% FV, and (c) DRY15 forest at 25% FV experiments. Simulation-averaged $\theta_e$ with arrows representing vertical wind vector differences for (d) DRY05 forest at 25% FV, (e) DRY10 forest at 25% FV, and (f) DRY15 forest at 25% FV experiment

5.12 Dry Forest Experiments at 50% FV

Surface fluxes were less sensitive to reductions in SM for forest experiments at 50 % FV than 25 %. Domain averaged latent and sensible heat fluxes were 145, 124, and 99, and 76, 90, and 106 W m$^{-2}$, for the DRY experiments respectively (Figs. 33 a-b).
Domain averaged relative humidity and dew point temperature were 56, 53, and 51 % and 16.6, 16.1, and 15.7 °C for the DRY experiments (Figs. 34 a-b). Also, ground and 2 m temperatures and PBL heights were 28.6, 29.4, and 30.2 and 26.7, 27.1, and 27.6 °C,
and 550, 603, and 655 m, respectively for DRY05, DRY10, and DRY15 experiments (Figs. 34c-e). Similar to grassland results, increases in FV slightly offset the impact of reductions in initial SM as suggested by Chen and Avissar (1994).

Figure 34. Diurnal area average of modeled (a) relative humidity, (b) dew point temperature, (c) ground temperature, (d) two-meter temperature, and (e) planetary boundary layer height for CTRL (diamond), DRY05 forest at 50% FV (circle), DRY10 forest at 50% FV (square), and DRY15 forest at 50% FV (triangle)

Compared to CTRL, simulated results were significantly drier and warmer. The largest average 24 hour latent heat flux, relative humidity, and dew point temperature
differences were all less than CTRL by 167, 220, and 287 W m$^{-2}$, 10, 13, and 15 %, and 1.9, 2.6, and 3.1 °C, respectively. As expected, simulated sensible heat flux, ground and 2 m temperatures, and PBL heights were greater than CTRL with the largest average differences of 107, 153, and 205 W m$^{-2}$, 4.4, 6.0, and 7.6 and 1.8, 2.4, and 3.0 °C, and 441, 585, and 654 m for each DRY experiment respectively.

The influence of drier soils on PBL development and horizontal wind fields can be seen in figures 35a-c. In comparison to CTRL, maximum PBL height differences increased across the model domain in conjunction with increasing sensible heat flux and enhanced turbulent mixing over drier soils. Drier soils were also found to alter surface wind fields. For the DRY experiments, PBL height differences ranged between 100 and 900 m greater than CTRL. Horizontal wind vector differences directed toward the domain center increased in magnitude as PBL height differences grew. Maximum horizontal wind speed differences were greater than CTRL by 0.6, 0.8, and 0.8 m s$^{-1}$ for the DRY05, DRY10, and DRY15 experiments respectively.

Differences for DRY forest experiments at 50% FV along a south to north cross section showed lower $\theta_e$ compared to CTRL from the surface up to 900 mb (Figs. 35d-f). Reductions up to 5 °C in $\theta_e$, when compared to CTRL, were modeled as SM was lowered. Vertical wind differences along the cross section showed intermitted regions of rising and subsiding motion analogous to convective mixing, which increased in strength over drier soils (Figs.35d-f). Maximum vertical speed differences along the cross section were greater than CTRL by 7, 6, and 18 cm s$^{-1}$ for each reduction in initial SM respectively.
Figure 35. Difference fields of modeled PBL height and horizontal and vertical wind field vectors, and $\theta_e$ calculated at experiment minus CTRL. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) DRY05 forest at 50% FV, (b) DRY10 forest at 50% FV, and (c) DRY15 forest at 50% FV experiments. Simulation-averaged $\theta_e$ with arrows representing vertical wind vector differences for (d) DRY05 forest at 50% FV, (e) DRY10 forest at 50% FV, and (f) DRY15 forest at 50% FV experiments.

5.13 Dry Forest Experiment at 75% FV

At 75% FV, reductions (increases) in latent (sensible) heat flux were not as large as the simulated changes for the DRY forest experiments at 25 or 50% FV. Domain averages of latent and sensible heat flux were 172, 155, and 131 and 60, 72, and 89 W m$^{-2}$.
for the DRY05, DRY10, and DRY15 experiments (Figs. 36a-b). Relative humidity and
dew point temperature were lowered (Figs. 36a-b) along with simulated ground and 2 m
temperatures while PBL height increased (Figs. 36c-e) as SM reduced. Domain averages
of relative humidity, dew point temperature, ground and 2 m temperatures and PBL
height were 59, 56, and 53%, 16.9, 16.5, and 16.0 °C, 27.5, 28.2, and 29.1 °C, and 26.0,
26.4, and 29.6 °C, and 507, 554, and 614 m respectively for the DRY05, DRY10, and
DRY15 experiments.
Figure 36. Diurnal area average of modeled (a) latent heat flux and (b) sensible heat flux for CTRL (diamond), DRY05 forest at 75% FV (circle), DRY10 forest at 75% FV (square), and DRY15 forest at 75% FV (triangle)
Figure 37. Diurnal area average of modeled (a) relative humidity, (b) dew point temperature, (c) ground temperature, (d) two-meter temperature, and (e) planetary boundary layer height for CTRL (diamond), DRY05 forest at 75% FV (circle), DRY10 forest at 75% FV (square), and DRY15 forest at 75% FV (triangle)

Despite the higher FV, DRY forest experiments at 75% FV were relatively drier and warmer than CTRL. Maximum simulated 24 hour differences of latent heat flux, dew point temperature, and relative humidity were less than CTRL by 87, 134, and 196 W m$^{-2}$, 6, 9, and 13 %, and 1.2, 1.8, and 2.6 °C, respectively for each reduction in SM.
As expected, simulated sensible heat flux, ground and 2 m meter temperatures, and PBL height were all greater than CTRL with the largest average 24 hour difference of 58, 98, and 158 W m\(^{-2}\) and 2.6, 4.1, and 6.2 °C and 1.0, 1.8, and 2.6 °C, and 447, 469, and 596 m, respectively for the DRY05, DRY10, and DRY15 experiments.

Across the domain, PBL height differences (Figs. 38a-c) increased in comparison to CTRL with reductions in SM. However, increases in PBL height were not uniform with differences ranging between 100 m less to 750 m greater than CTRL for the DRY experiments. Visual inspection of Figures 38a-c suggests that horizontal wind vector differences were correlated with greater PBL growth. Oriented primarily inward toward the domain center, horizontal wind speed differences were greater than CTRL by 0.5, 0.6, and 1 m s\(^{-1}\) for the DRY05, DRY10, and DRY15 experiments respectively.

\(\theta_e\) and vertical wind fields throughout the PBL were also sensitive to reductions in SM over forest land-use for 75% FV. \(\theta_e\) differences along the cross section ranged between almost no change to 4 °C less than CTRL for the DRY experiments (Figs. 38d-f). As previously mentioned, higher vegetation density (75% FV) offset \(\theta_e\) differences compared to CTRL over drier soils. Vertical wind field differences and mixing along the cross section were enhanced as SM was reduced. Intermittent patterns of rising and subsiding motion (turbulent mixing) began to develop and strengthen over drier soils. Maximum vertical wind speed differences were greater than CTRL by 4, 6, and 8 cm s\(^{-1}\), for the DRY05, DRY10, and DRY15 experiments, respectively.
Figure 38. Difference fields of modeled PBL height and horizontal and vertical wind field vectors, and $\theta_e$ calculated at experiment minus CTRL. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) DRY05 forest at 75% FV, (b) DRY10 forest at 75% FV, and (c) DRY15 forest at 75% FV experiments. Simulation-averaged $\theta_e$ with arrows representing vertical wind vector differences for (d) DRY05 forest at 75% FV, (e) DRY10 forest at 75% FV, and (f) DRY15 forest at 75% FV experiments.

5.14 Dry Forest Experiment at 100% FV

Surface fluxes for DRY forest experiments at 100% FV were only slightly impacted by reductions in SM. Domain averaged latent and sensible heat fluxes were
194, 182, and 160 and 45, 54, and 71 W m\(^{-2}\) for the DRY05, DRY10, and DRY15 experiments (Figs. 39a and b). Chen and Avissar (1994) suggested that fully vegetated surfaces moderate the impact of reduced SM on surface fluxes. It was

![Figure 39. Diurnal area average of modeled (a) latent heat flux and (b) sensible heat flux for CTRL (diamond), DRY05 forest at 100% FV (circle), DRY10 forest at 100% FV (square), and DRY15 forest at 100% FV (triangle)]
also found that atmospheric moisture for forest land use was more sensitive to reductions in SM at 100% FV than FV at 25, 50, or 75% due to moisture divergence as previously mentioned. Domain average relative humidity and dew point temperature were 63, 60, and 57% and 17.6, 17.1, and 16.4 °C, respectively for DRY forest experiments (Figs. 40a and b). Ground and 2 m temperatures and PBL heights were elevated with reductions in SM with domain averages of 26.3, 27.0, and 27.9 °C and 25.3, 25.7, and 26.2 °C and 422, 473, and 552 m, respectively for DRY05, DRY10, and DRY15 experiments (Figs. 40c-d).

Compared to CTRL, DRY forest experiments at 100 % FV were more similar than other DRY forest experiments (25, 50, and 75 % FV). Simulated latent heat flux, relative humidity, and dew point temperature differences were less than CTRL with the largest average 24 hour difference of 12, 52, and 117 W m$^{-2}$, 1, 5, and 9 %, and 0.3, 1.0, and 1.8 °C. Sensible heat flux and ground and 2 m temperatures, and PBL height differences for each reduction in SM were greater than CTRL by 14, 45, and 102 W m$^{-2}$, 0.8, 2.1, and 4.0 and 0.3, 0.9, and 1.9 °C, and 103, 247, and 463 m respectively.
Figure 40. Diurnal area average of modeled (a) relative humidity, (b) dew point temperature, (c) ground temperature, (d) two-meter temperature, and (e) planetary boundary layer height for CTRL (diamond), DRY05 forest at 100% FV (circle), DRY10 forest at 100% FV (square), and DRY15 forest at 100% FV (triangle).

PBL height differences for the DRY05 at 100% FV varied little across the domain (Fig. 41a). However, as SM was reduced, PBL heights increased across the domain (Figs. 41b and c) with simulated PBL height differences ranging between 100 m less to 500 m greater than CTRL. In addition, the heterogeneous growth of the boundary layer
altered simulated horizontal wind fields. Horizontal wind vector differences were strongest in the vicinity of greater PBL growth with respect to CTRL. Maximum horizontal wind speed differences were greater than CTRL by 0.3, 0.6, and 0.5 m s\(^{-1}\) for the DRY05, DRY10, and DRY15 experiments respectively.

\(\theta_e\) differences for the DRY05 forest experiment at 100\% FV had a mix of higher and lower values compared to CTRL from the surface up to 880 mb. As SM was reduced further, \(\theta_e\) differences were more uniformly lower than CTRL for the DRY10 and DRY15 forest experiments (Figs. 41d-f). Boundary layer \(\theta_e\) differences ranged between 0.5 °C greater to 3.0 °C less than CTRL between the DRY05 and DRY15 experiments, respectively. Vertical wind speed for the DRY05 and DRY10 experiments were both 2 cm s\(^{-1}\) greater than CTRL (Fig 41d). However, differences were amplified to 3 cm s\(^{-1}\) as vertical mixing increased for the DRY15.
Figure 41. Difference fields of modeled PBL height and horizontal and vertical wind field vectors, and $\theta_e$ calculated at experiment minus CTRL. Model-averaged PBL heights with arrows representing surface wind vector differences for (a) DRY05 forest at 100% FV, (b) DRY10 forest at 100% FV, and (c) DRY15 forest at 100% FV experiments. Simulation-averaged $\theta_e$ with arrows representing vertical wind vector differences for (d) DRY05 forest at 100% FV, (e) DRY10 forest at 100% FV, and (f) DRY15 forest at 100% FV experiments

5.15 Bare Soil Experiment

The removal of vegetation across the modeled domain as in the bare soil experiment significantly altered surface fluxes with domain averages of latent and
sensible heat flux at 99 and 79 W m$^{-2}$ (Figs. 7a-b). Despite the reduction in modeled ET, simulated latent heat flux is still greater than sensible energy as a result of direct evaporation from the soil. Further inspection of initial SM content over the modeled domain reveals that antecedent subsurface conditions are nearly saturated, allowing for evaporation from the soil to be maintained. In addition, nighttime radiative cooling over bare soil reduces surface temperature and creates a negative sensible heat flux where atmospheric energy is shared with the surface. Modeled domain averages of relative humidity, dewpoint temperature, ground surface and 2 m temperatures, and PBL height were 54 %, 16.2 °C, 30.4 and 27.3 °C, and 588 m, respectively (Fig.8a-f).

Compared to CTRL, bare soil land-use was considerably drier and warmer. The largest average 24 hour latent heat flux, relative humidity, and dew point temperature differences were less than CTRL by 303 W m$^{-2}$, 13 %, and 2.9 °C. In addition, the largest average 24 hour sensible heat flux, ground and 2 m temperature differences were greater than CTRL by 111 W m$^{-2}$, 7.2 and 2.9 °C respectively. The increase in sensible energy and ambient temperature elevated modeled PBL heights with the largest average 24 hour difference greater then CTRL by 897 m.

Figure 42a shows PBL heights over bare soil were generally greater than CTRL across the modeled domain. PBL heights across the model domain ranged between 100 to 550 m greater than CTRL. Similar to findings in other research, increases in sensible heat flux elevate PBL heights through increased vertical mixing within the PBL (e. g., McPherson and Stensrud, 2005). Horizontal wind field differences in Figure 42a show mainly convergence over the modeled domain (wind field directed inward) similar to
grassland and forest experiments at 25% FV. Maximum wind speed differences were greater than CTRL by 1 m s\(^{-1}\).

**Figure 42.** Bare soil difference fields of modeled PBL height wind horizontal wind vectors (a) and \(\theta_e\) with vertical wind vector (b) calculated as experiment minus control.

\(\theta_e\) and vertical wind field differences along a south to north cross section (Fig. 42 b) showed a drier PBL with regions of rising and subsiding motion. \(\theta_e\) differences from the surface up to 900 mb in some locations were less than CTRL by 6 °C. Vertical wind field differences showed two defined regions of rising motion along the southern and northern edges that are part of modeled meso-scale circulations with regions of subsidence and vertical motion along the interior of the domain. Maximum vertical wind speed differences were greater than CTRL by 4 cm s\(^{-1}\).

### 5.16 Dry Bare Soil Experiments

Simulated surface fluxes over bare soil were sensitive to decreases in initial SM. Domain averaged latent (sensible) heat flux was reduced (increased) with decreasing SM (Figs. 43a-b). As SM was reduced by 0.05, 0.10, and 0.15 m\(^3\) m\(^{-3}\), domain averages of latent and sensible heat fluxes were 77, 52, and 31, and 94, 113, and 129 W m\(^{-2}\). The reduction in available subsurface moisture has reduced simulated atmospheric moisture...
and increased temperature and PBL heights. Domain averaged relative humidity, dew
point temperature, ground and 2 m temperatures, and PBL height (Figs. 44a-e) were 51,
49, and 47 %, 15.8, 15.4, and 15.1 °C, 31.4, 32.3, and 33.2 and 27.8, 28.3, and 28.7 °C,
and 642, 702, and 760 m for the DRY05, DRY10, DRY15 experiments.

Reductions in simulated initial SM over bare soil maximized differences between
bare soil and CTRL. The largest average 24 hour latent heat flux, relative humidity, and
dew point temperature difference for the DRY05, DRY10, and DRY15 experiments,
were less than CTRL by 359, 421, and 470 W m$^{-2}$, 15, 17, and 19%, and 3.4, 3.8, and 4.3
°C, respectively. Simulated sensible heat flux, ground and 2 m temperatures, and PBL
heights over bare soil for these same experiments were greater than CTRL by 152, 196,
and 240 W m$^{-2}$, 8.9, 10.4, and 11.9 °C and 3.4, 3.8, and 4.0 °C, and 982, 1061, and 1101
m, respectively.
Figure 43. Diurnal area average of modeled (a) latent heat flux and (b) sensible heat flux for CTRL (diamond), DRY05 bare soil (circle), DRY10 bare soil (square), and DRY15 bare soil (triangle).
Figure 44. Diurnal area average of modeled (a) relative humidity, (b) dew point temperature, (c) ground temperature, (d) two-meter temperature, and (e) planetary boundary layer height for CTRL (diamond), DRY05 bare soil (circle), DRY10 bare soil (square), and DRY15 bare soil (triangle).

It also was found that PBL height and horizontal wind field differences varied in response to decreases in initial SM. Simulated PBL heights over bare soil were greater than CTRL with increasing differences within the inner domain as the soil became drier (Figs. 45a-c). PBL heights for the DRY bare soil experiments ranged between 100 to 1100 m greater than CTRL. As a result of elevated PBL heights, horizontal wind vector
differences were oriented toward the domains center and increased in magnitude with reductions in SM. Maximum horizontal wind speed differences were greater than CTRL by 1.2, 1.8, and 1.8 m s$^{-1}$ for the DRY05, DRY10, and DRY15 experiments respectively.

Lower $\theta_e$ differences were found from the surface up to 900 mb and ranged between 3 and 6 °C less than CTRL (Figs. 45d-e). Vertical wind field differences along the cross section primarily showed rising motion over the domain extending past the PBL top with the strongest vertical wind speeds differences near the domain border (Figs. 44d -e). Maximum upward wind speed differences were greater than CTRL by 10, 12, and 18 cm s$^{-1}$, respectively for the DRY05, DRY10, and DRY15 experiments. For the DRY10 and DRY15 bare soil runs, strong vertical mixing within the PBL organized into a convective circulation similar to that found over both DRY grassland and forest at 25 % FV.
5.17 Wet Experiments

Increases in SM over grassland and forest from 25 to 100 % FV and bare soil land-uses had negligible effects on simulated near-surface atmosphere (Tables 7-9). For instance, the range in simulated dew point temperature over wet grassland experiments at
25% FV was only 0.07 °C. Simulated sensible heat flux for forest at 100 % FV only changed by 1.3 W m\(^{-2}\) between the WET05 and WET15 simulations. The model’s insensitivity to increases in SM for this study was due to an already moist root zone. FNL prescribed SM across the domain was 0.36 m\(^3\) m\(^{-3}\), which is very close to SM capacity of silt loam at 0.47 m\(^3\) m\(^{-3}\). In other words, initial SM conditions for this modeling period were already near saturation, as previously mentioned. As suggested by McPherson (2007) and Oke (1987), increases in SM only elevates transpiration and evaporation rates up to a point where further increases have little or no effect, as was found in our experiments. These results identify the importance and need for observational knowledge of the initial soil profile of temperature and moisture in numerical modeling applications in order to properly simulate atmospheric conditions. These results are in line Dirmeyer et al. (2000).

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Table 8. Modeled diurnal area average of WET Forest Experiments.

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<th>Sensible Heat (Wm$^{-2}$)</th>
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<th>Ground Temp. (°C)</th>
<th>Two m. Temp. (°C)</th>
<th>PBL Height (m)</th>
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<td>68</td>
<td>59</td>
<td>17.2</td>
<td>28.2</td>
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Table 9. Modeled diurnal area average of WET Bare Soil Experiments.

<table>
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<tr>
<th>Land-use</th>
<th>SM</th>
<th>Latent Heat (Wm$^{-2}$)</th>
<th>Sensible Heat (Wm$^{-2}$)</th>
<th>Rel. Humid. (%)</th>
<th>Dew Point (°C)</th>
<th>Ground Temp. (°C)</th>
<th>Two m. Temp. (°C)</th>
<th>PBL Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare Soil</td>
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<td>70</td>
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<td>56</td>
<td>16.5</td>
<td>29.7</td>
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<td>540</td>
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</table>
5.18 LULCC and LCL Heights

Alterations in the distribution of moisture and energy at the surface have been found to impact the lifted condensation level (LCL). The LCL is the lowest height at which clouds form or the height an air parcel must rise in order to become saturated and condense. In this research, it was noted that changes in land-cover, FV, and or SM that lead to reduced (increased) transpiration from the surface elevated (lowered) LCL heights similar to PBL heights (Table 10). Compared to CTRL, the largest simulated increase in LCL heights were expectedly found over bare soil land-cover with reduced root zone soil moisture with a height of 470 m higher. Conversely, the lowest LCL height for the DRY experiments compared to CTRL was found over grassland land-cover at 100 % FV with a height of 248 m lower. The significance of altering LCL heights is that it effects the initiation and timing of cloud cover that can impact a system’s evolution and other processes by shielding incoming solar radiation and the release of latent energy. While this study is conducted under very benign synoptic conditions, further research will look into the impact LULCC has on cloud development system evolution.

<table>
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<tr>
<th>Land Use</th>
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<th>CTRL SM</th>
<th>DRY05</th>
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Chapter 6

Summary and Conclusions

This research investigated the sensitivity of atmospheric responses to combined modeled changes in vegetation type, FV, and volumetric SM. To the author’s knowledge, this is the first study that has coupled systematic changes in these three types of LULCC. It was found that changes in vegetation type, FV, and SM altered simulated surface energy and moisture budgets, PBL structure, 3D-wind fields, and through time climatology. In addition, altered PBL wind fields modified PBL stability, initiated meso-scale circulations, which can have important implications on air quality, and pollution trajectory studies.

LULCC that transforms vegetation type over Western Kentucky altered simulated PBL evolution based upon differences in vegetation characteristics, such as stomata resistance, rooting depth, and roughness length. For instance, grassland land-cover had an evaporative advantage over forest, despite shallower roots, due to a lower stomata resistance. This reduced modeled sensible heat flux, air temperature, PBL heights and convective mixing, while increasing latent heat flux and atmospheric moisture compared to CTRL. Rougher forest land-use slightly enhanced convective mixing (forced convection) and reduced horizontal wind field differences from surface drag compared to CTRL. In addition, forest’s developed (deeper) roots mitigated the impact of drier soils with access to deeper moisture within the root zone. Additionally, bare soil conditions, highlighted the importance of vegetation cover on PBL development. Despite enhanced convective mixing well into the free atmosphere and higher PBL heights, the contrast between bare soil and vegetation organized convection into circulation cells that has been
connected the development of deep convection and precipitation as described by Ookouchi et al. (1984) and Chen and Avissar (1994). These circulation cells were also modeled for other types of LULCC and were suppressed with increases in FV and SM.

Alterations in FV were also found to alter transpiration rates. Increases (decreases) in FV enhanced (diminished) transpiration rates, which impacted near-surface energy and moisture budgets. FV experiments at 25 % for both grassland and forest land-uses, despite the evaporative advantage of grassland and deeper rooting depth of forest, reduced atmospheric moisture levels to conditions comparable of bare soil. These results lead to higher PBL heights and altered vertical mixing similar to bare soil with the development of meso-scale circulations along the sharp contrast in FV at the domains border. In addition, increases in FV enhanced atmospheric moisture and lowered PBL heights, altering horizontal wind fields (divergence) compared to CTRL. Similar to McPherson and Stensurd (2005), horizontal wind field differences compared to CTRL were sensitivity to PBL growth. In addition, some of the largest modeled changes in horizontal wind field occurred in the vicinity of maximum PBL height change. These results were found to impact moisture advection with lowered (risen) PBL heights, inducing moisture divergence (convergence) over the region of LULCC.

Root zone volumetric SM also impacted simulated ET rates overall types of land-uses and FV percentages considered in this research. Reductions in volumetric SM diminished the availability of subsurface moisture for transpiration processes by stressing the overlying vegetation and causing stomata closure. Moreover, reductions in volumetric SM diminished ET and enhanced PBL growth, altering PBL wind fields as previously described. In addition, reduced volumetric SM was found to have a larger
simulated impact on atmospheric processes than increases in volumetric SM.

Considering the initially moist soil conditions, further increases in volumetric SM had little impact on modeled results, which are in line with McPherson (2007) and Oke (1987). Moreover, these results identify the importance of how land-use is altered compared to its initial state. In other words, increases in SM for an already moistened soil has little impact on atmospheric processes. These results can be extended to other changes in land-use including vegetation type and FV. Furthermore, the impact of LULCC on atmosphere evolution is not only dependent on the type of LULCC, but the current state of other unaltered land surface features (vegetation type, FV, and SM) in addition to how different the new land-use is to the previous land-cover.

Modeling multiple types of LULCC showed that atmospheric responses to land-use were sensitive to the other types of land-use change, as previously mentioned. For instance, modifications of vegetation type or FV that yielded higher evapotranspiration rates was offset by drier soils similar to Chen and Avissar (1994). In addition, atmospheric response to changes in vegetation type that enhanced evapotranspiration rates, such as forest to grass, may be augmented or neutralized with further changes in FV or root zone SM. In general, LULCC that reduced (increased) modeled evapotranspiration rates, such as changes in vegetation type with higher (lower) stomata resistance or reductions (increases) in FV and SM, tended to enhance (diminish) convective mixing within the PBL and elevate (reduce) PBL heights as described by Oke (1987). Furthermore, these results note the importance of accurately prescribing the current state of the land-surface, including vegetation type, FV, and SM in conjunction with LULCC to properly simulate atmosphere evolution and through time climatology.
Changes in PBL height and 3D-wind fields can also have important impacts on air quality and pollution trajectory. From Oke (1987), the PBL top acts as a lid to convection and mixing with the free atmosphere from above due to a slight temperature inversion. As such, reductions in PBL growth can greatly reduce air quality by increasing the concentration of atmospheric pollutants within a shallower boundary layer of air (low PBL). This is similar to early morning poor air quality over Los Angeles, California or Houston, Texas when the lower atmosphere is loaded with atmospheric pollutants before the PBL is fully developed. Conversely, LULCC that increases atmospheric mixing with higher PBL growth can improve air quality by reducing the concentration of pollutions in a larger volume of air. However, increases in convective mixing and changes in horizontal wind field would likely alter the transport and dispersion of these pollutants. Moreover, it is suggested here that LULCC should be included in air quality assessments and the dispersion and trajectory of atmospheric pollutants.

Clearly, proper specification and initialization of the land-cover, including vegetation type, FV, and SM in future modeling studies must be addressed in order to improve modeling accuracy in both atmospheric and climatology models. These findings also illustrate the need for a high quality, spatially dense observational meteorological networks that include among other atmospheric variables SM. Such networks, like the Kentucky Mesonet, would fill the often missing observed SM datasets and improve atmospheric and climatology studies when used in conjunction with proper specification land-use (vegetation type, FV, and SM). In addition, this research prescribes the
importance of considering LULCC in assessments of climatology, air quality and pollutant dispersion and trajectory modeling.
Bibliography


