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# Observational and modeling studies of the impacts of agriculture-related land use change on planetary boundary layer processes in the central U.S.

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**Abstract**

The impact of agricultural land use change on atmospheric boundary layer processes, the associated feedbacks and their regional scale impacts, are examined with particular emphasis on the central United States. Specifically, the role of contrasting forested and agricultural land covers in the initiation and subsequent evolution of summertime cloud patterns in the U.S. Midwest; and the impact of agricultural practices, including irrigation, on the surface climate of the U.S. High Plains are discussed in detail. Satellite-based observational results of previous work summarized in this paper indicate that the timing and intensity of cloud development appears to be influenced by both synoptic flow regimes and agricultural land use type. For example, under conditions characterized by high pressure with surface winds generally less than 5 m $s^{-1}$, peak cloud development occurred almost two hours earlier over cropland than over the forest or boundary locations in Michigan. Cloud masses were also considerably taller over cropland in the mid-afternoon than over forest and land cover transition zones. The modeling results discussed here for a model domain centered over Nebraska indicate significant differences in the surface energy fluxes between the irrigated (control) and non-irrigated (dry) simulations. Surface latent heat flux was higher by 36% and dewpoint temperature higher by 2.3 °C in the control simulation. Also, surface sensible heat flux of the control simulation was 15% less and the near-ground (2 m) temperature was 1.2 °C less compared to dry run, indicating irrigation-induced surface cooling effect. Recent investigations on crop–climate interactions in which crop and ecological models were coupled to regional climate models show that incorporating important perturbations such as prolonged droughts and the resulting changes in soil and plant nutrient conditions remains one of the biggest challenges in developing effective and realistic ecological-climate integrated modeling systems.


*Keywords:* Crop–climate interactions; Convective clouds; Regional climate modeling; Agricultural land use

## 1. Introduction

The central United States (U.S.) is one of the most agriculturally productive areas in the world and supports a wide range of agro-businesses that are economically vital to the U.S. Together, the High Plains

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and Midwest states account for more than 75% of the total land area under grain cultivation and about 45% of U.S. cattle inventory (National Agricultural Statistics Services (NASS) of the United States Department of Agriculture (USDA) USDA/NASS—U.S. 2002 Agricultural Census). Following the westward expansion of European settlement over the past 100–150 years, this region experienced massive land use changes from the conversion of the native vegetation to farmlands. By some estimates, over 90% of the tall grass prairie native to the eastern section of the High Plains has been converted to managed agriculture, including irrigation (Samson and Knopf, 1994). In the Midwest, the change has been dominantly from the conversion of forested areas into cropped regions (Iverson and Risser, 1987). A distinct feature of this Midwest land cover transformation are the narrow and often extensive transition boundaries separating cooler, moist forested areas from relatively warm and drier cropped areas (Carleton and O'Neal, 1995).

Large scale anthropogenic modification of vegetation alters various physical properties of the land surface (e.g., albedo, surface roughness, leaf area index, and rooting depth) which have been shown to influence climate over a range of spatial and temporal scales (Pielke and Avissar, 1990; Adegoke and Carleton, 2000). In addition, agriculture-related land cover conversion affects landscape heterogeneity, which observational and modeling studies show could affect the development of small cumulus clouds and potentially induce mesoscale circulations. The latter are important because they can significantly enhance the rainfall associated with synoptic scale cyclonic systems. For example, Marotz et al. (1975) showed that cloud fields in Kansas during the warm season are differentiated between irrigated and non-irrigated areas. Other studies have also shown that shallow cumulus clouds tend to form earlier and became more numerous over a landscape of wheat stubble than over adjacent landscapes of pasture and row crops in Oklahoma (Rabin et al., 1990; Wetzel et al., 1996). Similarly, differences in cumulus convection (amount, timing) occur between cropped and forested areas in the Midwest (Carleton et al., 2001). Using data from Oklahoma Mesonet Network, McPherson et al. (2004) investigated the impact of winter wheat on surface climate in Oklahoma and found a summer (winter) warming (cooling) in the winter wheat region relative to the surrounding area. Modeling studies support these findings and also show that local wind circulations as intense as the land–sea breeze can develop. Thunderstorm severity can be enhanced in the horizontal wind convergence region that develops because of the differential heating between areas of forest that are not moisture stressed and the adjacent dry, vegetated land (Segal et al., 1988; Pielke and Zeng, 1989). Similarly, Weaver and Avissar (2001) reported simulated vertical velocities of 1–2 m $s^{-1}$ due primarily to landscape heterogeneity associated with winter wheat farming in Oklahoma. These vertical velocities were shown to coincide with satellite observations of cumulus clouds, implying that the enhanced vertical velocities could have been strong enough to induce convective cloud formation.

The primary mechanism by which land surface modifications and changes influence climate is through controlling the transfer of heat and moisture into the planetary boundary layer (Pielke, 2001). The horizontal contrasts in vegetation and phenological stage, surface and soil moisture conditions, and evapotranspiration (ET) between cropped areas and adjacent land covers, can each affect boundary layer processes such as surface energy partitioning. For example, when the soil is wet from recent rainfall energy exchange between the surface and the overlying atmosphere will mostly be in the form of latent heat. Conversely, energy transfer will be primarily in the form of sensible heat under dry soil conditions. These bio-physical processes alter surface temperature patterns by strengthening the horizontal temperature gradient and may impact the convective available potential energy (CAPE) or other measures of cumulus cloud activity such as satellite-observed outgoing longwave radiation (OLR) (Raymond et al., 1994; Carleton et al., 1994, 2001; Segal et al., 1995; Chase et al., 1999; Pielke, 2001; Hanesiak et al., 2004). The lower albedo and infrared emission values of vegetated surfaces imply an increase in net radiation absorbed at the surface compared to adjacent cleared or deforested areas. This increased available energy results in elevated rates of evaporation and transpiration and, to a much lesser extent, photosynthesis. The higher ET rates result in a moister lower atmosphere with higher equivalent potential temperature.

Furthermore, the increased aerodynamic roughness of forested areas can reduce low-level wind speeds, increase the intensity of turbulence and, subsequently, favor the formation of convective clouds over vegetated areas (Rabin et al., 1990; Wetzel, 1990; Carleton et al., 2001). A comprehensive review of both the physics and relevant published work on the influence of surface vegetation changes on cumulus cloud development can be found in Pielke (2001). While this paper draws on insights from previous published work relevant to this topic, we focus primarily on our recent observational and modeling studies in the central U.S. The paper is organized into two sections. In the first section we explore the role of contrasting forested and agricultural land areas in the formation of convective clouds in the Midwest. In the second section we focus on simulations of the impact of U.S. Plains agriculture, especially irrigated agriculture, on PBL processes notably surface energy partitioning and near-ground temperature using the Colorado State University (CSU) Regional Atmospheric Modeling System (RAMS). In this study the central U.S. is defined to include the extensive flatlands of the High Plains states of Nebraska, the Dakotas, Kansas and northern Oklahoma; the humid lowlands of the Midwest (i.e., central and northern Illinois, Indiana and Ohio); and the surrounding areas of rolling topography that support mostly natural (i.e., forest) growth. The latter occur especially in the southern parts of Missouri and Indiana.

## 2. Observational studies

The possible role of contrasting forested and agricultural land covers in the formation of convective clouds in the Midwest, especially during extreme climatic events such as the 1988 drought, has been investigated by a number of researchers. Examples include the studies by Carleton et al. (1994), Rabin and Martin (1996) and O'Neal (1996), in which both conventional land use data and satellite observations of surface and cloud conditions were used to investigate interactions between convective cloud development and features such as land cover and surface moisture status in the Midwest. The patterns of cumulus convection determined from the analysis of satellite imagery in these studies show a strongly diurnal cycle and apparent associations with land cover types. Other studies (e.g., Travis, 1997; Brown and Arnold, 1998) suggest that during the warm mid-summer months, convective cloud masses tend to be organized along wind convergence boundaries (central Wisconsin) and boundaries of land cover (e.g., between forests and agricultural land) and even soil order (Illinois). These boundaries are important because they may enhance the convergence of near-surface winds thereby increasing the likelihood of moist convection during synoptically ''weak flow'' situations. Deep convection is a major contributor to the warm season precipitation regime of the central U.S., particularly the Midwest region (Winkler et al., 1988; Easterling, 1989), and occurs as air mass showers and thunderstorms associated with weak flow patterns, and thunderstorms organized as either mesoscale systems or in association with baroclinic features (e.g., Fritsch et al., 1986; Moller et al., 1994; Hanesiak et al., 2004).

While these studies provided many useful insights into the land surface-convective cloud coupling over the Midwest, they were mostly based on composites of a few case study days for one or two growing seasons. A comprehensive study based on systematic analyses of multi-year data was needed to determine whether the convective cloud–land surface associations reported in those previous studies are evident over longer-term periods, under the usual range of climate conditions (i.e., non-drought, non-flood). The first attempt at conducting such a comprehensive study (Adegoke, 2000) produced several interesting findings, some of which were reported in Adegoke and Carleton (2000), Carleton et al. (2001) and Adegoke and Carleton (2002). The discussion in the following paragraphs is based, in part, on these analyses of land surface-convective cloud associations during the summer months (June, July and August) for the 1991–1998 period. The study integrated high-resolution multi-year satellite data with detailed land use-land cover (LULC) datasets and sought answers to the following questions: What associations exist between broad Midwest land cover categories (e.g., cropland and forest) and convective clouds (determined from hourly GOES satellite imagery) under conditions of weak, moderate and strong synoptic flow? How do the boundaries between farmlands and forested areas affect convective cloud formation under the various synoptic flow conditions?

### 2.1. Cloud–land cover relationships

The retrieval of satellite cloud data and the determination of cloud associations with land cover characteristics involved several steps. First, the hourly GOES IR and VIS satellite images were geometrically registered to the same projection (Albers Equal Area Projection) as the Midwest LULC map described in the preceding section. To compensate for the effects of varying solar elevation angle ($\zeta$), the VIS brightness counts were converted to albedo ($\alpha$), using the Garand (1988) algorithm:

$$\alpha = \frac{aB^2 + b}{I_0 \cos \zeta}$$

where $a$, $b$ and $I_0$, are calibration constants for the GOES-7 and GOES-8 sensors. Then hourly cloud IR and VIS pixel data were extracted for 40-km square grids centered over cropland, forest and transitional (boundary) representative sites in Illinois, Indiana and Missouri respectively. The boundary locations were included to investigate the possible effect of abrupt surface discontinuities on convective cloud initiation. Summary statistics representing mean cloud amounts (from the VIS), and mean cloud top temperatures (CTT) (from IR) were calculated for each synoptic flow type and stratified according to land cover (i.e., cropland, forest and boundary). Hourly VIS brightness and CTT data composites for all ''best weak flow'' days for target sites in three Midwest states (Michigan, Indiana and Missouri) are shown in Fig. 1. The VIS data (Fig. 1a–c) show that cloud development peaked about one and half to two hours earlier, and also persisted longer, over cropland than over the forest or boundary locations; at least, in Michigan. Also, cloud masses in Michigan were considerably taller (i.e., lower CTT) over cropland (Fig. 1d) in the mid-afternoon than over the boundary (Fig. 1e) or forest (Fig. 1f) land cover types. The mid-afternoon (12 p.m.–3 p.m. local time) mean albedo value was about 20–25% greater over cropland in Michigan than the adjacent boundary and forest areas. The pattern of land cover-cloud associations in

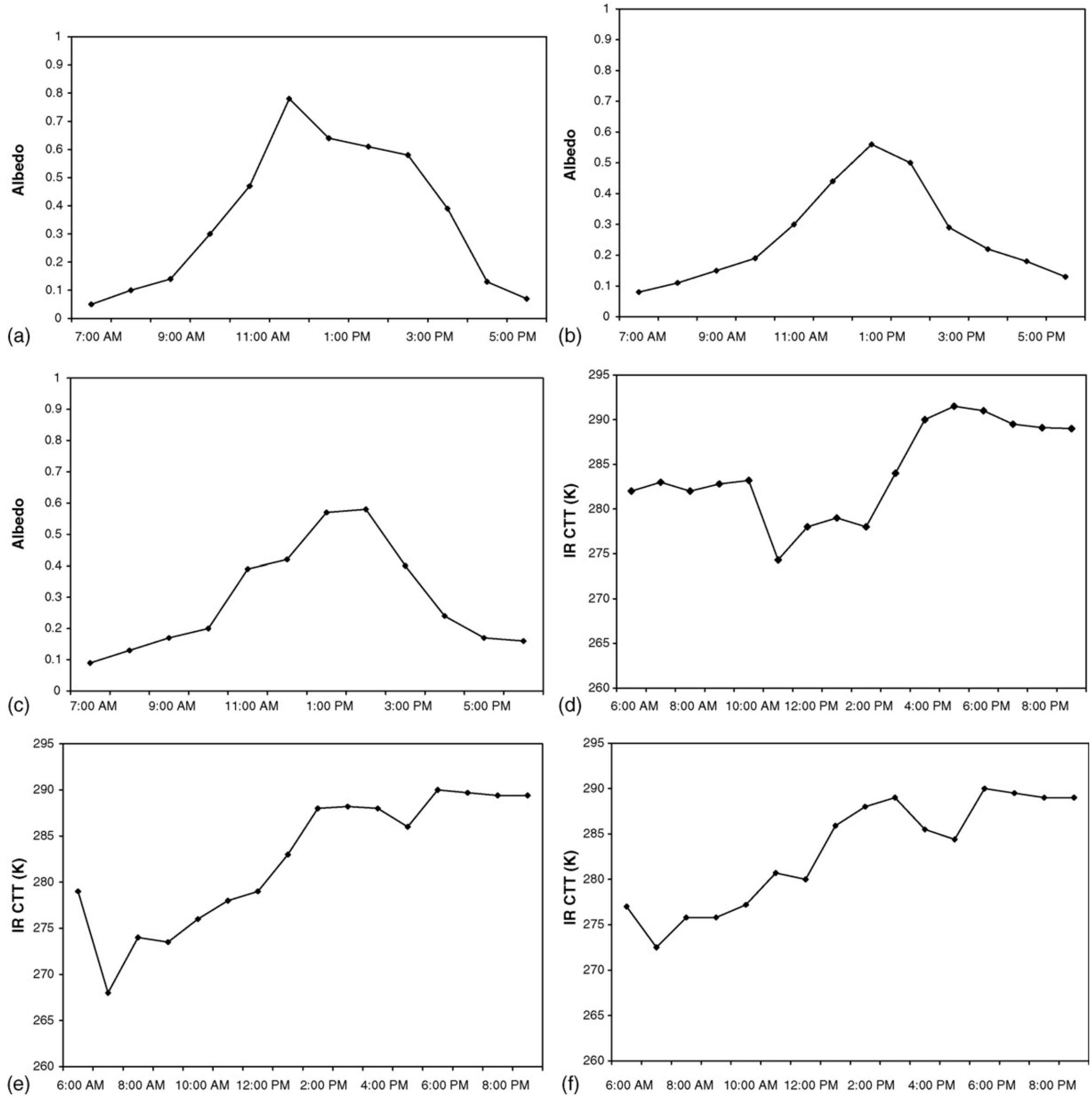


Fig. 1. ''Best weak flow'' day mean hourly albedo (VIS) and infra red cloud top temperature (IR CTT) (K) composites over cropland (a and d), boundary (b and e) and forest (c and f) in Michigan (adapted from Adegoke, 2000).

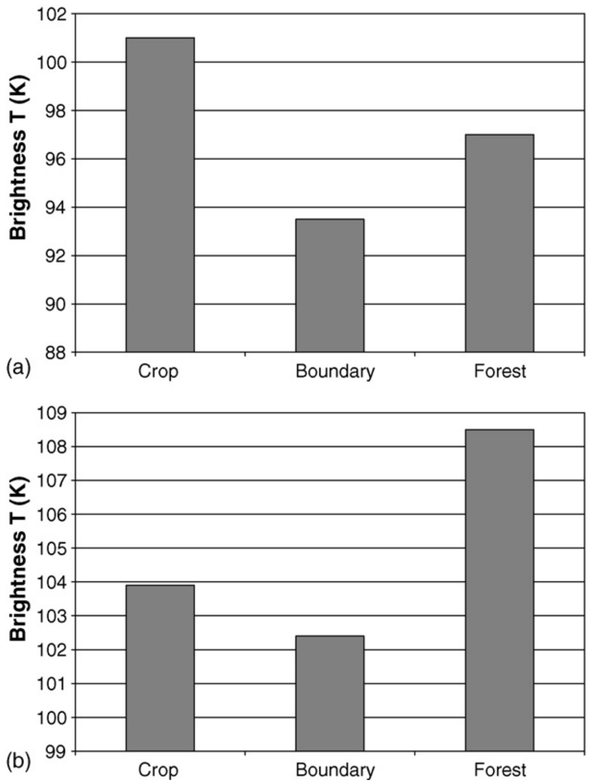


Fig. 2. ''Best weak flow'' day mean maximum brightness (K) composites for Michigan (a) and Missouri (b) (adapted from Adegoke, 2000).

Michigan contrasts with the situation in Missouri. In Missouri, cloud development (depicted by the higher average maximum VIS brightness) is more pronounced over the forest location (Fig. 2). The observed lag in the time of cloud formation over more forested locations and the apparent difference in the cloud response patterns for Michigan and Missouri appear to be partly due to differences in the PBL moisture and temperature characteristics of the two sites. Analyses of thermodynamic and moisture indices derived from radiosonde data indicate that the lower atmosphere is drier in Michigan compared to Missouri, where cloud growth tend to be more vigorous over forest areas (Table 1). These findings seem to confirm the hypothesis that clouds form earlier and persist longer over drier (cropped) areas under relatively dry atmospheric conditions, and later over moister (forest) areas when the convective potential of the PBL is greater and the atmosphere is less dry.

In contrast to the ''best weak flow'' composites, the ''weak flow'' days were characterized by greater convective activity (i.e., cumulus cloud cover) over boundary areas in all three states (not shown). The mean mid-morning to mid-afternoon VIS albedo value over the three boundary areas is 0.72, while similar mean values for cropland and forest are 0.59 and 0.61 respectively (i.e., a difference of between 18 and 25% in the albedo values between the boundary, cropland and forest areas). This result is important in that it provides empirical evidence over several summer seasons that confirms earlier theoretical and observational studies. The latter suggested that surface discontinuities, such as organized land-cover boundaries, could enhance convective cloud formation similar to a sea-breeze-like circulation forced by differential heating (Pielke et al., 1991; Rabin et al., 1990). The difference in cloud response to land cover forcing between the ''weak flow'' and ''best weak flow'' days may be due, in part, to the slightly more vigorous synoptic environment (e.g., faster mid-troposphere winds) during ''weak flow'' as opposed to ''best weak flow'' days. Hourly VIS and IR data for ''strong flow'' day composites did not indicate any cloud pattern differentiation by land cover type or surface boundaries. The late-morning to mid-afternoon thermally forced peak in the cloud VIS albedo values over cropland in Michigan (evident in the mean statistics of the ''best weak flow'' cases) is absent, as would be expected, in the ''strong flow'' composites.

In summary, the satellite-based observational results first reported in Carleton et al. (2001) and summarized here indicate that under ''best weak flow'' conditions (defined as days characterized by high pressure aloft and at the surface with winds generally less than 5 m $s^{-1}$), clouds attained peak development almost two hours earlier over cropland than over the forest or

Table 1
Thermodynamic indices for composite ''best weak flow'' days: 12Z radiosonde data

| | CCL (mb) | CCL-EL (mb) | $K$-index | $T_c$ (°C) | Mean $T_v$ (°C) | Mean $T - T_v$ (°C) | RH (%) | Mean $W$ (cm) |
|---|---|---|---|---|---|---|---|---|
| Michigan | 749 | 480 | 12 | 32 | 16 | 3.7 | 68 | 0.18 |
| Missouri | 827 | 528 | 29 | 26.8 | 20.5 | 2.7 | 78 | 0.33 |

CCL: convective condensation level by surface heating; CCL-EL: depth (mb) of the positive layer; $K$-index: stability measure useful for prediction non-severe convective showers; $T_c$: temperature required for free convection from the surface; mean $T_v$: mean virtual temperature for surface-850 mb layer; mean $T - T_v$: mean wet-bulb depression for surface-850 mb layer (measure of the relative dryness of air); RH: mean relative humidity for surface-850 mb layer; W: water content (cm) in the air column from surface-850 mb.

boundary locations in Michigan. Cloud masses were also considerably taller (i.e., lower CTT) over cropland in the mid-afternoon than over forest and boundary types. This pattern contrasts with that for Missouri where, on the same days, cloud development was more vigorous over forest areas. Convective cloud development was also enhanced over land cover transition (i.e., boundary) areas on weak flow days, characterized by weaker subsidence in the free atmosphere, in contrast to best weak flow days, and moderate ($<30\ \mathrm{m\ s^{-1}}$) mid-tropospheric winds. This finding suggests that under specific synoptic flow conditions, the Midwest land cover boundary zones become likely regions of differential vertical circulations that may comprise non-classical mesoscale circulations (NCMCs) between the more homogenous cropland and forest surface covers. Finally, under strong flow conditions, advection dominates near the surface and in the mid-troposphere and a convective signal differentiated by land cover type was not evident.

These findings, which are discussed in greater detail in Carleton et al. (2001), have several implications, including reaffirming the importance of incorporating detailed landscape information in weather forecast models if they are to be capable of predicting convective cloud patterns, which is as crucial to understanding the energy balance of the earth surface as it is for realistically modeling the land surface–atmosphere interactions at local to regional spatial scales. In the next section, we focus on recent modeling studies based on the incorporation of more detailed spatial heterogeneity in the land surface sub-model of RAMS, including high resolution land cover, variable soil moisture, soil type and satellite-derived phenology (e.g., LAI from satellite vegetation greenness indices). We also review recent attempts at simulating seasonally and interannually varying vegetation cover, growth rates, and the feedbacks that underpin crop–climate relations in the central U.S. using crop and ecological models coupled to regional climate models.

## 3. Modeling studies

Initial efforts at modeling the impacts of surface parameters on climate due to large scale anthropogenic land use change focused on one-dimensional modeling of the energy and moisture fluxes in the PBL. These early studies played a key role in providing a better understanding of the influence of the land surface climate and also spurred more complex two- and three-dimensional modeling work. One-dimensional studies focus on the vertical distribution of atmospheric parameters within a column of the atmosphere at a single point in time and space. Two-dimensional models compute the same fluxes over an area, where domain size varies according to model resolution. Three-dimensional models include time or an additional axis as the third dimension and, thus, are able to simulate weather events with significant advection and large-scale baroclinic effects.

Among relatively recent studies are those of Betts and Ball (1994), which showed that the afternoon value of a parcel's equivalent potential temperature (i.e., the potential temperature of the air if all its moisture were condensed and the resulting latent heat used to warm the parcel) increases with increasing soil moisture. Segal et al. (1995) demonstrated an increase in the potential for deep convection with reduced Bowen ratio (i.e., the ratio of the sensible, $Q_H$, and latent, $Q_E$, heating at the surface, $Q_H/Q_E$). Also, Clark and Arritt (1995) showed that the vegetation cover and high initial soil moisture promote the development of deep convection. It has been suggested that if the vegetated areas become comparable to synoptic scales in area (approximately $1000\ \mathrm{km} \times 1000\ \mathrm{km}$ or greater), the increased roughness increases frictional inflow in cyclonic disturbances and significantly increases the rainfall associated with these systems (Anthes, 1984; Segal et al., 1988; Chang and Wetzel, 1991; Pielke et al., 1991).

The impact of managed agricultural systems, especially irrigated agriculture, on local climate has been investigated in a number of modeling studies. For example, Segal et al. (1998) found that irrigation resulted in a spatial redistribution of precipitation, but did not produce additional rainfall. Similarly, Chase et al. (1999) showed that irrigation in the Colorado plains impacted climate in the foothills of the Rockies and in the adjacent mountains. Specifically, areas with altered land cover were shown to have cooler, moister boundary layers, and diminished low-level upslope winds over portions of the plains. At higher elevations, temperatures also were lower as was low-level convergence. In a regional modeling study of the impact of irrigation on surface climate in the U.S. High Plains under dry synoptic conditions, Adegoke et al. (2003) reported a cooling in the near-ground temperature, and significant increases in vapor and latent heat fluxes into the atmosphere in response to this human disturbance of the landscape. These changes are shown to be related to the conversion of the natural prairie vegetation in this region to farmlands. Corroborating evidence from analyses of long-term surface climate data indicates a steadily decreasing trend in mean and maximum air temperature at locations within heavily irrigated areas (Mahmood and Hubbard, 2002; Mahmood et al., 2004), thus confirming the irrigation-induced cooling effect suggested by the RAMS simulations. The changes in ambient temperature and surface fluxes observed in Adegoke et al. (2003) clearly indicate that key components of the PBL, particularly the partitioning of the available surface energy, are very sensitive to changes resulting from increased irrigation. These are examined in greater detail in the next section.

### 3.1. Irrigation impact on PBL processes and surface climate

Early observational studies (Marotz et al., 1975; Barnston and Schickendanz, 1984; Alpert and Mandel, 1986; Pielke and Zeng, 1989) showed that irrigation is one of the key anthropogenic factors influencing climate trends in agricultural/rural areas. Barnston and Schickendanz (1984), for example, found that irrigation increased precipitation in the Texas Panhandle when the synoptic condition provided low-level convergence and uplift, such that the additional moisture produced by irrigation was allowed to ascend to cloud base. Alpert and Mandel (1986) also found a decreasing trend in the diurnal surface wind and temperature with enhanced irrigation.

More recently, regional scale atmospheric models have been used in several studies (De Ridder and Galle'e, 1998; Segal et al., 1998) to simulate the effect of irrigation on various PBL properties because the models are particularly suitable for quantifying irrigation-induced in situ and remote changes in climate elements such as precipitation at meso-scales (i.e., horizontal scale 200–2000 km). Segal et al. (1998) used the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) Mesoscale Model (MM5) (Grell et al., 1993) in their study of irrigated areas in North America. Their model results suggest an increase in the continental average rainfall for the present irrigation conditions compared with those of past irrigation. De Ridder and Galle'e (1998) used a European regional numerical model (Mode'le Atmosphe'rique Re'gional—MAR) and reported a reduction in the diurnal amplitude of temperature and wind speed when a semiarid surface is replaced by a partly irrigated one. The potential for moist convection also increased with surface moisture availability in their simulations. The primary thermodynamic impact of irrigation is the repartitioning of the sensible and latent heat fluxes at the affected sites. Thus, an increase in irrigation or surface wetness reduces sensible heat flux while increasing ET (Pielke, 2001). The resulting additional moisture flux could enhance the characteristic moist static energy within the convective boundary layer (CBL) and consequently become thermodynamically more conducive to an increase in rainfall (Betts et al., 1994; Segal et al., 1998).

In Nebraska, as in much of the U.S. High Plains, corn is the dominant crop cultivated during the warm season months. Irrigated corn, which represented about 10% of total corn producing areas during the early 1950s, now comprises nearly 60% of the total corn producing areas in Nebraska. Data from USDA/NASS for York County in east-central Nebraska further underscore these changes. Between 1950 and 1998 the irrigated corn area in York County increased from 3500 to 80,000 ha (a 2300% increase) while the rain-fed corn area declined rapidly during the same period (National Agricultural Statistics Service, 1998). This rapid land use change was achieved largely by converting rain-fed corn areas to irrigation.

In modeling the impact of irrigation-induced land use change on PBL dynamics and surface climate, we take advantage of the two-way interactive grid nesting in RAMS, which allows local fine mesh grids to resolve small-scale atmospheric systems such as thunderstorm systems, while simultaneously modeling the large-scale environment of the systems on a coarser grid (Walko et al., 1995). The version of RAMS we used includes the Land Ecosystem Atmosphere Feedback model, version 2 (LEAF-2) (Walko et al., 2000). This new submodel of RAMS represents the storage and vertical exchange of water and energy in multiple soil layers, including effects of temporary surface water, vegetation, and canopy air. Surface grid cells are divided into subgrid patches, each with different vegetation or land surface type, soil textural class, and/or wetness index to represent subgrid variability in surface characteristics. Each patch contains separate predicted values of energy and moisture in soil, surface water, vegetation, and canopy air. The grid cell exchange with the overlying atmosphere is weighted according to the fractional area of each patch. A hydrology model, based on Darcy's law for lateral downslope transport, exchanges subsurface saturated soil moisture and surface runoff between subgrid patches. LEAF-2 inputs the standard land use datasets in order to define patches and their areas, as well as to obtain biophysical parameters for different vegetation types.

The Nebraska irrigation simulations consisted of four land use scenarios covering the 15-day period, 1–15 July 1997. The first scenario (control run)

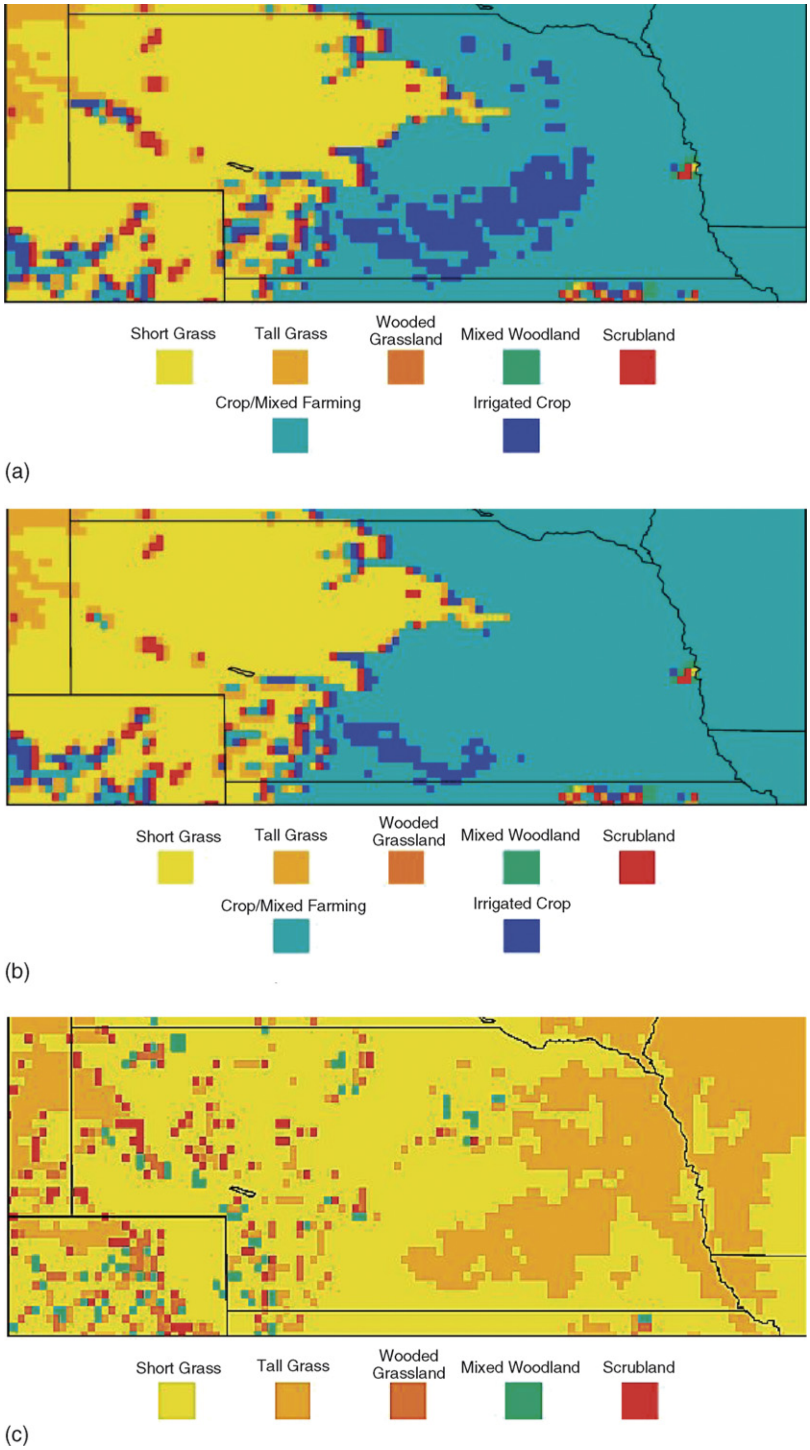


Fig. 3. (a) LANDSAT (1977) derived land cover data for Nebraska. (b) Olson global ecosystem (OGE) land cover data for Nebraska. (c) Kuchler potential vegetation for Nebraska.

represented current farmland acreage under irrigation in Nebraska as estimated from 1997 LANDSAT satellite and ancillary data (Fig. 3a). The second and third scenarios (OGE wet and dry runs) represented the land use conditions from the Olson Global Ecosystem (OGE) vegetation dataset (Fig. 3b), and the fourth scenario (natural vegetation run) represented the potential (i.e., pre-European settlement) land cover from the Kuchler vegetation dataset (Fig. 3c). In the control and OGE wet run simulations, the topsoil of the areas under irrigation, up to a depth of 0.2 m, was saturated at 0000 UTC each day for the duration of the experiment (1–15 July 1997). In both the OGE dry and natural runs, the soil was allowed to dry out, except when replenished naturally by rainfall. The ''soil wetting'' procedure for the control and OGE wet runs was constructed to imitate the center-pivot irrigation scheduling under dry synoptic atmospheric conditions, as observed in Nebraska during the first half of July 2000 (i.e., when little or no rainfall was recorded throughout the state). The observed atmospheric conditions from NCEP reanalysis data (Kalnay et al., 1996) were used to create identical lateral boundary conditions in the four cases.

The inner-domain area-averaged model parameters between the control run and OGE wet run showed very moderate differences (see Table 1 for summary of scenario comparisons). This reflects the rather small change (less than 10%) in the irrigated portion of the OGE vegetation data (Fig. 3b) compared to the more recent LANDSAT-satellite-based land cover estimates (Fig. 3a). In both simulations, the soil-wetting procedure was implemented for the irrigated areas. Larger changes were observed when the control run was compared to the OGE dry run: midsummer 2-m temperature over Nebraska might be cooler by as much as 3.4 °C under current conditions. The cooling effect and the surface energy budget differences identified above intensified in magnitude when the control run results were compared to the potential natural vegetation scenario. For example, the near-ground average temperature was 3.3 °C cooler, the surface latent heat flux was 42% higher, and the water vapor flux (at 500 m) was 38% greater in the control run compared to the natural landscape run. Results of the simulations from all scenarios are summarized in Table 2.

Important physical changes between the natural shortgrass prairie of this region and the current land use patterns include alterations in the surface albedo, roughness length, and soil moisture in the irrigated areas. These changes are capable of generating complex changes in the lower atmosphere (PBL) energy budget. For example, the simulated increase in the portion of the total available energy being partitioned into latent heat rather than sensible heat resulted directly from the enhanced transpiration and soil evaporation in the control run. Although not examined in detail in this study, elevated dewpoint temperature and moisture fluxes within the PBL can increase the convective available potential energy, promote atmospheric instability, and enhance daytime cloud cover (Stohlgren et al., 1998). Localized extreme dewpoints, which do not appear to result from moisture advected from the Gulf of Mexico, are increasingly being observed in the central United States, especially during hot summer periods. These are most likely related to changing agricultural practices, including increased evaporation from irrigation (Sparks et al., 2002). An increase in evaporative fraction over irrigated areas could induce changes in the equivalent potential temperature and ultimately convention. However, the associated changes in the convective available potential energy (CAPE) necessary for convection may not always be realized, especially under very dry conditions similar to the situation in Nebraska for most of the duration of the modeling experiment described here.

### 3.2. Interactive crop–climate simulations

Crop growth models are generally considered resource allocation models and they are increasingly being used to study feedbacks between managed agricultural areas and the regional weather (Pan et al., 1999). Tsvetsinskaya et al. (2001a,b) used such a model for a seasonal simulation over the central United States. In that study the growth functions of CERES-maize crop model were incorporated into the biosphere-atmosphere transfer scheme (BATS), which is the surface scheme for the regional climate model, RegCM2. The coupled surface package was applied to the domain of the U.S. Great Plains to determine the effect of the growing vegetation on surface energy fluxes and local climate. The model was run using European Centre for Medium Range Forecasting (ECMWF) boundary conditions for 1991, a normal

Table 2
Simulated area-averaged model parameters for 7–15 July 1997 for various scenarios (adapted from Adegoke et al., 2003)

| Model Parameters | Control | OGE (wet) | OGE (dry) | Natural vegetation |
|---|---|---|---|---|
| Temperature (°C) | 24.1 | 24.9 (0.8) | 25.5 (1.4) | 27.6 (3.5) |
| Surface sensible heat (W $m^{-2}$) | 76.2 | 79.8 (4.7%) | 86.9 (15%) | 98.4 (29%) |
| Latent heat (W $m^{-2}$) | 102.4 | 98.2 (4%) | 74.5 (35%) | 71.98 (42%) |
| Vapor flux at 500 m (g $kg^{-1}$ m $s^{-1}$) | 11.1 | 10.4 (22%) | 9.1 (22%) | 8.2 (34%) |

year, and 1988, a drought year. Results indicate that for 1988 large differences occur between the non-interactive run and the interactive run. With the interactive growth and development module, the simulated climate is warmer and drier than in the default run, and closer to the observed climate. These results indicate that including growth and development of vegetation in a climate model can have important effects on the simulated climate.

Another group of models that can be applied to studying the coupling between the vegetation dynamics/land-use and the regional atmosphere are the so-called ecological models. These models tend to apply mechanistic relations based on leaf- and canopy-scale responses to environmental changes for transpiration, photosynthesis, and energy and water balance. Although applying these models can produce a more realistic outcome from the coupled studies, scaling the leaf- and canopy-scale relations to a region remains one of the ongoing challenges for these models. Lu et al. (2001) and Eastman et al. (2001a,b) applied different ecological models coupled to RAMS in two-way interactive simulations and found that vegetation dynamics significantly feedback to influence the seasonal weather patterns.

In the Lu et al. (2001) study, the CENTURY ecosystem modeling system (Parton, 1996) was coupled to the climate version of RAMS-ClimRAMS (Liston and Pielke, 2001) and used to simulate biosphere-atmosphere feedbacks in the central United States. In the coupled RAMS-CENTURY modeling system, ClimRAMS provides the atmospheric forcings required by daily time step CENTURY (DayCENT) to describe the plant environment, while DayCENT provides vegetation characteristics of direct importance to the atmosphere that develop in response to plant life cycles and evolution. The results show that variation in seasonal vegetation phenology strongly influences regional climate patterns through its control over land surface water and energy exchange processes. The coupled model captures the key aspects of weekly, seasonal and annual feedbacks between the atmosphere and the underlying surface.

The Eastman et al. (2001a,b) studies are similar except that here, the ecological model General Energy and Mass Transfer Model (GEMTM; Chen and Coughenour, 1994; Coughenour and Chen, 1997) was coupled to ClimRAMS. The coupled system (named GEMRAMS) was used to study seasonal and regional climate response to grazing (Eastman et al., 2001a) and to investigate the impact of conversion of natural to current landscape, including the effect of increased levels of carbon dioxide ($CO_2$) on growing season climate in central plains of the United States (Eastman et al., 2001b). For the grazing study, a novel grazing algorithm was employed to represent pre-European settlement grazing habit of the vast herds of Bison native to this part of the U.S. The algorithm was switched on and off for different simulations to represent with and without grazing conditions and to capture the likely effects on regional atmospheric and biological processes of the Great Plains. The results indicated a cooling response in daily maximum temperatures to removal of grazing. The opposite trends were found for the minimum daily temperature. It was also found that grazing produced significant perturbations in the hydrological cycle.

## 4. Conclusion

We have provided evidence from the literature and from our own work on the influence of surface parameters, particularly land cover differentiation, on the initiation and subsequent evolution of summertime cloud patterns in the U.S. Midwest; and on the impact of agricultural practices and agriculture-related land use change on the surface climate of the U.S. High Plains. Satellite-based observational results of work summarized in this paper indicate that the timing and intensity of cloud development appears to be influenced by both synoptic flow regimes and agricultural land use type. For example, under conditions characterized by high pressure with surface winds generally less than $5\ m\ s^{-1}$, peak cloud development occurred almost two hours earlier over cropland than over the forest or boundary locations in Michigan. Cloud masses were also considerably taller over cropland in the mid-afternoon than over forest and land cover transition zones. Additionally, modeling results for a model domain centered over Nebraska indicate significant differences in the surface energy fluxes between the irrigated (control) and non-irrigated (dry) simulations. Surface latent heat flux was higher by 36% and dewpoint temperature higher by 2.3 °C in the control simulation. Also, surface sensible heat flux of the control simulation was 15% less and the near-ground (2 m) temperature was 1.2 °C lower compared to the dry run, indicating irrigation-induced surface cooling effect. The studies all underscore the importance of incorporating detailed landscape information in weather forecast models if they are to be capable of predicting key boundary layer processes, including the development of convective cloud patterns at mesoscales. The findings also have significance in gaining understanding of the feedback of human modifications to the landscape and climate.

Furthermore, very useful insights on crop–climate interactions have emerged from recent studies based on coupling crop models to regional climate models. Incorporating the important perturbations such as prolonged droughts and the resulting changes in soil and plant nutrient conditions remains one of the biggest challenges in developing these couplings. The interactive feedbacks that have been studied over mid-latitude regions will be significantly different in other ecoregions, particularly in the more arid parts of the world. Moreover, most of the ecological models generally fail to reproduce the extreme environment (e.g., very dry or very wet soil and atmospheric humidity) satisfactorily, and therefore, model simulations are prone to higher levels of uncertainty when assessing the sensitivity of the different agriculture-related environmental forcings on regional climate (see Pielke et al., 2003 for a detailed discussion of these challenges and uncertainties). Further, the ability to provide more realistic vegetation changes as boundary conditions significantly improves the model performance. Thus, it may not be as much a choice of model, but the representation of the correct regional drivers that could be the critical factor. Finally, because crop models tend to operate at the field/plot spatial scale while regional climate models are typically applied to spatial domains with horizontal lengths of a few kilometre to 100–200 km, the task of developing adequate procedures to address this spatial scale disparity is not trivial. It is important to realize that no single model can completely simulate the local, regional, and continental vegetation dynamics, and efforts are needed to compare the different modeling approaches with the observed vegetation dynamics over the various agro-climatic regimes.

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