Implementation of a Two-Way Interactive Atmospheric and Ecological Model and Its Application to the Central United States

LIXIN LU

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado, and Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona

ROGER A. PIELKE SR. AND GLEN E. LISTON

Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado

WILLIAM J. PARTON, DENNIS OJIMA, AND MELANNIE HARTMAN

Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado

(Manuscript received 23 July 1999, in final form 9 February 2000)

ABSTRACT

A coupled Regional Atmospheric Modeling System (RAMS) and ecosystem (CENTURY) modeling system has been developed to study regional-scale two-way interactions between the atmosphere and biosphere. Both atmospheric forcings and ecological parameters are prognostic variables in the linked system. The atmospheric and ecosystem models exchange information on a weekly time step. CENTURY receives as input air temperature, precipitation, radiation, wind speed, and relative humidity simulated by RAMS. From CENTURY-produced outputs, leaf area index, and vegetation transimissivity are computed and returned to RAMS. In this way, vegetation responses to weekly and seasonal atmospheric changes are simulated and fed back to the atmospheric–land surface hydrology model.

The coupled model was used to simulate the two-way biosphere and atmosphere feedbacks from 1 January to 31 December 1989, focusing on the central United States. Validation was performed for the atmospheric portion of the model by comparing with U.S. summary-of-the-day meteorological station observational datasets, and for the ecological component by comparing with advanced very high-resolution radiometer remote-sensing Normalized Difference Vegetation Index datasets. The results show that seasonal vegetation phenological variation strongly influences regional climate patterns through its control over land surface water and energy exchange. The coupled model captures the key aspects of weekly, seasonal, and annual feedbacks between the atmospheric and ecological systems. In addition, it has demonstrated its usefulness as a research tool for studying complex interactions between the atmosphere, biosphere, and hydrosphere.

1. Introduction

Land, covering about one-third of the earth's surface, is a major component of the climate system. Although the concept that climatic features determine land surface characteristics has long been accepted, only until relatively recent years have scientists begun to vigorously explore how land surface processes interact with atmospheric circulations and feed back to the climate system. Since the 1980s, many land surface models have been developed and incorporated into various mesoscale and global-scale atmospheric models to study the potential effects of land surface processes on weather and climate. These land surface models, which are referred to as Simple Vegetation–Atmosphere Transfer Scheme (SVATS) include the Biosphere–Atmosphere Transfer Scheme (BATS) of Dickinson et al. (1986, 1993), the Simple Biosphere Scheme of Sellers et al. (1986), the Simple SiB (Xue et al. 1991), the Bare Essentials of Surface Transfer scheme (Pitman 1991), the Interaction Soil–Biosphere–Atmosphere (Noilhan and Planton 1989), the Land Ecosystem–Atmosphere Feedback model (Lee 1992; Walko et al. 2000), Land–Air Parameterization Scheme (Mihailovic 1996), and the Land Surface Model of Bonan (1996). The Project for Intercomparison of Land-Surface Parameterization Schemes, designed to improve the hydrological, energy, momentum, and carbon exchanges between the surface and atmosphere, can be found in Henderson-Sellers et al. (1993, 1995). Reviews of SVATS and their evaluations are reported in Avissar (1995), Dickinson (1995), and

Corresponding author address: Dr. Lixin Lu, Department of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.
E-mail: lixin@acer.atmos.colostate.edu

Chen et al. (2000). An extensive review of modeling and observational studies of the importance of landscape processes on weather and climate can be found in Pielke et al. (1998), where they concluded that land surface processes play a significant role in defining local, regional, and global climate.

Evaluating the two-way interactions between atmospheric and land surface processes is crucial to our understanding of regional and global climate, vegetation dynamics, and watershed hydrology. Terrestrial biospheric processes respond strongly to atmospheric temperature, humidity, precipitation, and radiative transfer, as well as to surface hydrologic processes including runoff, percolation, and snowpack accumulation and melt. Atmospheric processes, including mesoscale circulations and the formation of clouds and precipitating systems, can be highly dependent on surface heat and moisture fluxes that are largely determined by live and dead vegetation and soil moisture storage. Vegetation plays a major role in determining surface energy partitioning and the removal of moisture from the soil by transpiration. Therefore, a realistic representation of the vegetation response (i.e., the change in live biomass) to atmospheric and hydrologic influences should be accounted for within the land surface parameterizations.

The current generation of land surface models generally have the vegetation component in them. Until recently however, these models assume that vegetation phenology is predefined according to existing climatologies and time of year. This limits the vegetation-related functions from responding to deviations from mean climatology, such as drier or wetter than average seasons or years, or to changes in climate. The underlying hypothesis for this approach is that variations in atmospheric characteristics have no influence on vegetation growth, and that biogeochemical effects are not important to atmospheric processes. Similarly, biogeochemistry models prescribe the atmospheric forcing, thus inherently assume that vegetation dynamics have no influence on weather and climate. In contrast to these assumptions, in the real world, vegetation responds strongly to atmospheric radiation, temperature, precipitation, and soil moisture. Both atmospheric and soil hydrologic processes, including precipitation and runoff, therefore, must be adequately accounted for in order to accurately simulate vegetation growth. In turn, the type and quantity of vegetation strongly influences runoff, evaporation, transpiration, surface heat flux, and consequently the air temperature and development of precipitating systems. The intrinsic two-way interactive feature of the climate–vegetation system requires the coupling of all atmospheric, vegetation, and hydrological processes together into a unified modeling system.

Incorporating interactive vegetation into a land surface model is a fairly new endeavor, but research in this area has already provided important insights. Claussen (1995), for instance, used an interactively coupled global atmosphere–biome model to assess the dynamics of deserts and drought in the Sahel. The model gave two stable equilibrium solutions under present-day conditions of solar radiation and sea surface temperatures. He found that the comparison of atmospheric states associated with these equilibria corroborates Charney's theory (Charney 1975) that deserts may, in part, be self inducing through albedo enhancement. Ji (1995) developed a climate–vegetation interaction model to simulate the seasonal variations of biomass, carbon dioxide, energy, and water fluxes for temperate forest ecosystems in northeastern China. Betts et al. (1997) used a general circulation model iteratively coupled to an equilibrium vegetation model to quantify the effects of both physiological and structural vegetation feedbacks on a doubled-CO_2 climate. They found that long-term vegetation structural changes partially offset physiological vegetation–atmosphere feedbacks on a global scale, and that vegetation feedbacks provide significant regional-scale effects. They concluded that a short-term enhancement of regional climate warming by vegetation physiology may eventually be mitigated by a longer-term modification of surface characteristics due to vegetation morphology. Foley et al. (1998) directly coupled the GENESIS (version 2) GCM and IBIS (version 1) Dynamic Global Vegetation Model through a common treatment of land surface and ecophysiological processes. They found that the atmospheric portion of the model correctly simulates the basic zonal distribution of temperature and precipitation with several important regional biases, and the biogeographic vegetation model was able to roughly capture the general placement of forests and grasslands. An interactive canopy model (Dickinson et al. 1998) was derived and added to the BATS (Dickinson et al. 1986, 1993) to describe the seasonal growth of leaf area as needed in an atmospheric model, and to provide carbon fluxes and net primary productivity; this scheme differs from other studies by focusing on short-timescale leaf dynamics. Tsvetsinskaya (1999) introduced daily plant growth and development functions into BATS and coupled it to the National Center for Atmospheric Research's Regional Climate Model to simulate the effect of seasonal plant development and growth on the atmosphere–land surface heat, moisture, and momentum exchange. She found that the coupled model is in better agreement with observations compared to the noninteractive mode. Eastman (1999) analyzed the effects of CO_2 and landscape change using a coupled plant and meteorological model [GEMTM and the Regional Atmospheric Modeling System (RAMS)]. All of these attempts, including the one conducted in this paper (Lu 1999), demonstrate that both atmospheric and ecologic research communities are beginning to realize the importance of including two-way feedbacks between the atmosphere and biosphere in their models.

Our primary research goal, as reported in this paper, is to develop and validate a comprehensive hydrologic–biospheric–atmospheric model that integrates known important land and atmospheric processes into a unified interactive system. Two state-of-the-art models developed at Colorado State University, the atmospheric model RAMS and the ecological model CENTURY, are chosen for this study. In its current form, RAMS land surface hydrological processes (e.g., evaporation and transpiration), energy exchanges (e.g., latent heat and sensible heat fluxes), momentum exchanges (e.g., roughness length), and biophysical parameters (e.g., vegetation albedo, transmissivity, and stomatal conductance) are heavily parameterized based on the value of leaf area index (LAI). The inadequate and unrealistic description of vegetation evolution in its current land surface models is considered a major deficiency. In this paper, a coupled RAMS and CENTURY modeling system is developed and implemented, in which both atmospheric variables (air temperatures, precipitation, and relative humidity, etc.) and ecosystem variables (LAI, vegetation transmissivity, etc.) become prognostic variables in the linked system. Vegetation responses to weekly, seasonal, and annual variations of atmospheric forcings are simulated and fed back to the atmospheric model. The two-way interactive model forms a sophisticated representation of the coupled atmosphere–land system including relevant aspects of the hydrological cycle. Our study differs from others by focusing on regional atmosphere and terrestrial ecosystem interactions occurring on weekly, seasonal, and annual timescales. Vegetation species composition and community structure changes caused by long-term (i.e., interannual and longer) climate changes are beyond the scope of this study.

The structure of the paper follows the course of our research work. In section 2, the atmospheric and ecological models used in this study are introduced. Since it is essential to the coupling success that the two models are sensitive to the outputs of the other, the offline sensitivity experiments conducted with both RAMS and CENTURY models are presented in section 3. In section 4, we explain the coupling strategies and procedures, and the coupled model control run design. In the results section, we first present the validation of a climate version of RAMS (ClimRAMS) and daily time step CENTURY (DayCENT) in their offline modes for our simulation domain. Then we focus on analyzing the coupled model simulation results in terms of its simulated biomass, weather, and the feedbacks between the atmosphere and vegetation. In section 6, we summarize our findings, further discuss the deficiencies of our coupling approach, and point out possible future research directions.

2. Model description

a. Climate version of RAMS (ClimRAMS)

RAMS is a three-dimensional, nonhydrostatic, general purpose atmospheric simulation modeling system consisting of equations of motion, heat, moisture, and mass continuity in a terrain-following coordinate system (Pielke et al. 1992). RAMS was developed at Colorado State University primarily to facilitate research into mesoscale and regional, cloud and land surface–atmospheric phenomena and interactions (Pielke 1974; Tripoli and Cotton 1982; Tremback et al. 1985; Pielke et al. 1992; Nicholls et al. 1995; Walko et al. 1995a). The model is three-dimensional, nonhydrostatic (Tripoli and Cotton 1980); includes telescoping, interactive nested grid capabilities (Clark and Farley 1984; Walko et al. 1995b); supports various turbulence closures (Deardorf 1980; McNider and Pielke 1981; Tripoli and Cotton 1986); shortwave and longwave radiation (Mahrer and Pielke 1977; Chen and Cotton 1983, 1987; Harrington 1997); initialization (Tremback 1990); and boundary condition schemes (Pielke et al. 1992); includes a land surface energy balance submodel that accounts for vegetation, open water, and snow-related surface fluxes (Mahrer and Pielke 1977; McCumber and Pielke 1981; Tremback and Kessler 1985; Avissar et al. 1985; Avissar and Mahrer 1988; Lee 1992; Liston et al. 1999); and includes explicit cloud microphysical submodels describing liquid and ice processes related to clouds and precipitation (Meyers et al. 1992; Meyers 1995; Walko et al. 1995a). A modified Kuo (1974) scheme is used for convection-produced precipitation. The RAMS horizontal grid uses an oblique (or rotated) polar-stereographic projection, where the projection pole is near the center of the simulation domain. The vertical grid uses a σ_z terrain-following coordinate system (Gal-Chen and Somerville 1975; Clark 1977; Tripoli and Cotton 1982), where the top of the model is flat and the bottom follows the terrain. An Arakawa-C-grid configuration is used in the model, where the velocity components u, v, and w are defined at locations staggered one-half a grid length in the x, y, and z directions, respectively, from the thermodynamic, moisture, and pressure variables (Arakawa and Lamb 1977).

The soil submodel used in this version of RAMS provides prognostic temperature and moisture for both soil and vegetation. For bare soil, RAMS uses a multilayer soil model described by Tremback and Kessler (1985). The moisture diffusivity, hydrologic conductivity, and moisture potential are given by Clapp and Hornberger (1978). The thermal properties of the soil are a function of the soil moisture. The boundary condition for moisture at the deepest soil level is held constant in time and equal to the initial value. The temperature of the bottom soil layer varies following the deep soil temperature model of Deardorff (1978). For the vegetated surface, RAMS uses the ''big leaf'' approach where there is a layer of vegetation overlying a shaded soil (Avissar et al. 1985; Avissar and Mahrer 1988; Lee 1992). The moisture taken from soil by transpiration is accomplished by defining a vertical root profile (Dickinson et al. 1986) and extracting the water masses from the soil depending on the fraction of roots in each soil layer. The surface layer fluxes of heat, momentum, and water vapor are computed using the method of Louis (1979) and Louis et al. (1982).

The climate version of RAMS (ClimRAMS; Liston and Pielke 2000) used in this study was developed based on RAMS version 3b. It contains all of the above features with the addition of several modifications designed to allow single to multiyear integrations. To meet the requirements of a regional model running at both short and long timescales, several modifications to the base modeling system were made. These included 1) prescribing daily sea surface temperatures and vegetation parameters throughout each year; 2) the addition of a collection of routines that simulates grid-scale snow accumulation, snow melt, and their effects on surface hydrology and surface energy exchanges; 3) the implementation of the ''dump-bucket'' parameterization scheme (Rhea 1978; Cotton et al. 1995) to account for large-scale precipitation; and 4) the Mahrer and Pielke (1977) shortwave and longwave radiation model is used in conjunction with the scheme presented by Thompson (1993) to account for the presence of clouds.

b. Daily time step CENTURY (DayCENT)

CENTURY is a biogeochemistry model that was originally designed to simulate long-term dynamics of carbon (C), nitrogen (N), phosphorous (P), and sulfur (S) for different plant–soil systems. Since the mid-1980s, the CENTURY model has been developed, modified, and applied to simulate various ecosystem dynamics over a wide range of spatial and temporal scales (Parton et al. 1987, 1988, 1993, 1994a,b, 1995, 1996; Ojima et al. 1993, 1994; Parton and Rasmussen 1994; Parton 1996). The grassland, agriculture crop, forest, and savanna ecosystems have different plant production submodels that are linked to a common soil organic matter submodel (SOM). The SOM simulates the flow of C, N, P, and S through plant litter and the different inorganic and organic pools in the soil. The model includes three soil organic matter pools (active, slow, and passive) with different potential decomposition rates, above- and below-ground litter pools, and a surface microbial pool that is associated with decomposing surface litter. The plant production models assume that plant production is controlled by moisture and temperature, and that plant production rates are decreased if nutrient supplies are insufficient. The fraction of the mineralized pools that are available for plant growth is a function of the root biomass increases.

The versions of CENTURY model used in this paper are CENTURY version 4 (Parton 1996) and daily time step CENTURY (DayCENT). CENTURY version 4 uses a monthly time step and the major input variables for the model include 1) monthly average maximum and minimum temperature; 2) monthly precipitation; 3) lignin content of plant material; 4) plant N, P, and S content; 5) soil texture; 6) atmospheric and soil N inputs; and 7) initial soil C, N, P, and S levels. The input variables are available for most natural and agricultural ecosystems and can generally be estimated from existing literature (Parton et al. 1987). The databases are required to specify the land-use types, major input variables, and human management practices.

For the coupled RAMS–CENTURY modeling system, DayCENT (Parton et al. 1998; Kelly et al. 2000) was used to predict biomass growth. Based on CENTURY version 4 (Parton 1996), DayCENT is designed to simulate more temporally resolved ecological processes. The primary difference between CENTURY version 4 and DayCENT lies in the water model and the computation of other processes on a finer timescale. DayCENT uses a daily time step for the water and nutrient cycles, and the above- and below-ground biomass are updated weekly.

In DayCENT, a daily water flow submodel and a daily soil temperature submodel are incorporated to compute depth-dependent soil water content and temperature; these submodels replace the monthly water budget and soil surface temperature submodels in CENTURY. In DayCENT, decomposition occurs daily instead of weekly, and organic and inorganic leaching occurs daily instead of monthly. Potential production estimates and growth of trees, crops, and grasses are updated weekly instead of monthly. New equations for the impact of water and temperature on decomposition have been implemented. When daily solar radiation, relative humidity, and wind speed atmospheric forcings are available, DayCENT uses a Penman potential evapotranspiration calculation (Penman 1948); otherwise it uses the air temperature–based Linacre calculation (Linacre 1977; Parton et al. 1993) from the CENTURY model. Event scheduling is adjusted to accommodate multiple time steps in a given month. When an event or management practice was scheduled for a given month, it either occurs weekly (irrigation), in the first week of the month (organic matter addition, fertilization, and cultivation), or in the last week of the month (grazing, fire, tree removal, harvest).

3. Offline sensitivity experiments

Prior to coupling the two models together, it was important to demonstrate that the two models were sensitive to the outputs of the other. For example, for a two-way interaction to be captured by the coupled model, the atmospheric model must be sensitive to variables such as LAI, and the ecosystem model must be sensitive to variables such as temperature and precipitation.

a. RAMS sensitivities to changes in LAI

A series of ClimRAMS simulations were conducted to examine the sensitivities of atmospheric variables, such as maximum temperature, minimum temperature, and precipitation, to changes in LAI. A control run was first integrated from 1 June 1989 to 1 November 1989

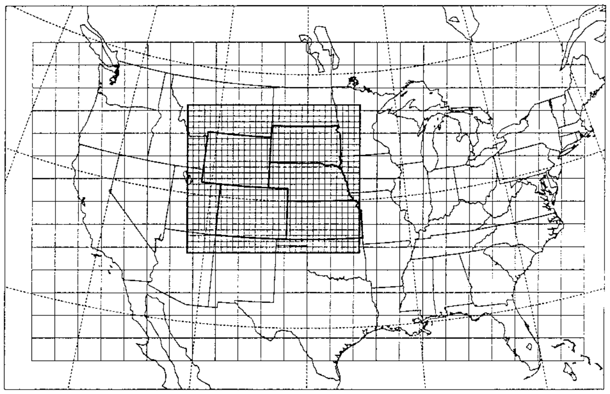

FIG. 1. ClimRAMS simulation domain and grid configuration. The coarse- and fine-grid intervals are 200 km and 50 km, respectively. The coupled RAMS–CENTURY model utilize the same domain and grid configuration.

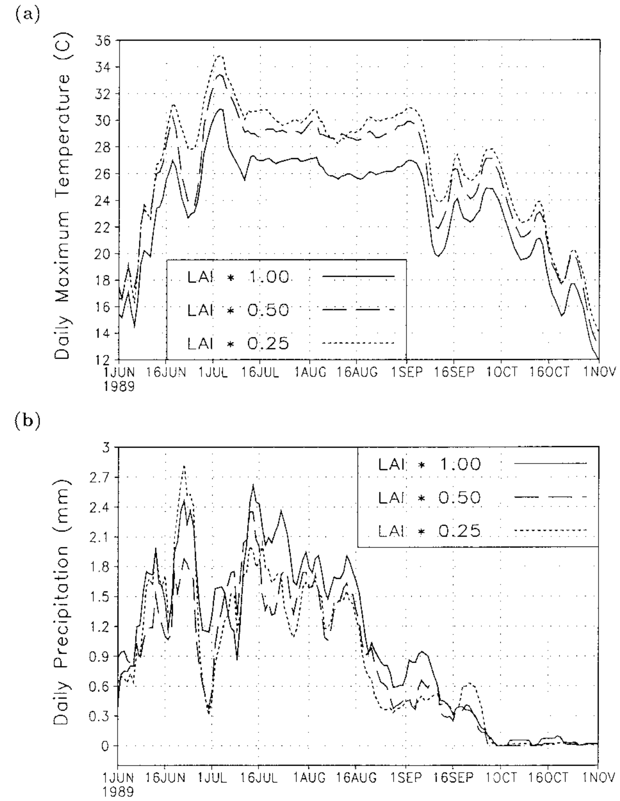

FIG. 2. In ClimRAMS, for the grid cell corresponding to Denver, CO. (a) The effect of changing LAI on daily maximum temperature (°C). (b) The effect of changing LAI on daily precipitation (mm).

using the ClimRAMS-prescribed LAI curve. The model was run on two nested grids over the central United States with 50-km grid spacing for the fine grid and 200-km grid spacing for the coarse grid (Fig. 1). Two perturbation experiments were performed with the LAI value reduced by 50% and 25% of its original value. The grid cell corresponding to Denver, Colorado, was chosen for analyses. Figure 2a shows that screen-height maximum air temperature increases in a nearly uniform manner while LAI decreases. Decreased LAI led to the increased surface temperature due to the reduction of the vegetation's cooling effect. Shown in Fig. 2b are the sensitivities of daily precipitation to LAI changes. In summer there are several mm day^{-1} differences in rainfall between the runs that have the higher and lower LAIs. Vegetation directly influences transpiration of water to the atmosphere. At the same time, its existence alters the surface energy budget through modifying the surface albedo and Bowen ratio, which affects the generation of rain in the model. As a result, the feedback between precipitation and LAI is complex and nonlinear.

b. CENTURY sensitivities to changes in atmospheric forcings

CENTURY version 4 was used to investigate the ecosystem model's sensitivities to changes in atmospheric forcings. The model was configured to run over the Long-Term Ecological Research site at Konza, Kansas. Driven by observed monthly averaged atmospheric forcings of maximum surface temperature (Tmax), minimum surface temperature (Tmin), and precipitation, CENTURY outputs the biomass growth. A simple algorithm was then applied to convert above-ground live carbon to LAI (see the appendix). Besides the control simulation, six sensitivity runs were conducted with Tmax and Tmin increased and decreased 2°C, and precipitation increased or decreased 25%, from their original values. All the integrations start in January 1973 and continue through December 1988, and use a monthly time step.

The CENTURY-simulated LAI from 1973 through 1988 over Konza is shown in Fig. 3a. Large LAI interannual variation clearly occurs over the simulation time span. This suggests that the prescribed LAI curves used in climate models that do not vary between different years are unrealistic and misleading. Therefore, the surface fluxes parameterized based on interannually invariant LAI must also be incorrect. Errors induced by unrealistic LAI specification in atmospheric models are inevitable. Figure 3b shows very significant, up to 50%, LAI changes resulting from a 25% precipitation change. The solid curves indicate the LAI change when precipitation was increased by 25% and the dashed curves indicate the LAI change when precipitation was decreased by 25%. LAI is also sensitive to the Tmax and Tmin changes, but by a smaller magnitude (Figs. 3c and 3d). The above-ground live carbon (aglivc) production increases with temperature to a certain threshold that is vegetation-type dependant. If temperature continues to increase above the threshold, aglivc begins to decrease. Thus, the temperature increase does not always lead to an increased above-ground biomass.

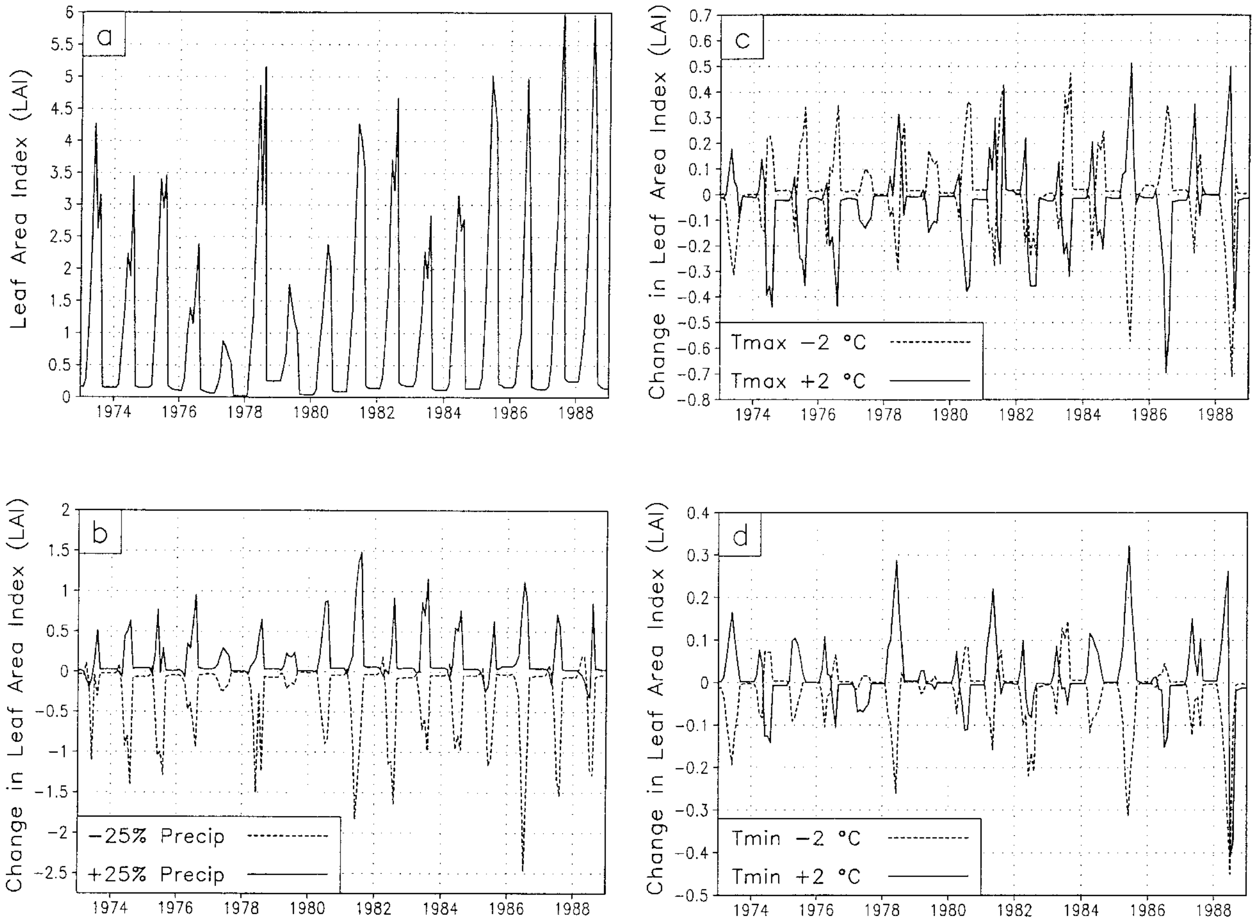

FIG. 3. (a) CENTURY-simulated LAI over Konza, KS, from 1973 to 1988. (b) The changes of LAI from the control run when precipitation was increased and decreased by 25%. (c) Changes in LAI from the control run when maximum screen-height air temperature was increased and decreased 2°C. (d) Changes in LAI from the control run when minimum screen-height air temperature was increased and decreased 2°C.

Figure 4a shows the large interannual variations of root biomass production from 1973 to 1988. An interesting feature stands out if you compare the belowground live carbon (bglivc) in Fig. 4a against aglivc in Fig. 3a. Dry year 1977 had the lowest leaf and root production of the whole simulation period. The leaf production recovered immediately in the following year and reached a new LAI maximum comparable to the previous years, while root biomass started to recover but the production never exceeded the previous years. The comparison between leaf and root maxima during the simulation time span demonstrates that roots react to climate variations at a slower pace and with a smaller magnitude, indicating the ''buffering effect'' roots may play within the climate system. Another implication is that atmosphere–vegetation interactions exist on various timescales, with shorter-term feedbacks represented by the leaves and longer-term feedbacks represented by the roots. Figures 4b, 4c, and 4d show that, under the climatic conditions represented at this site, root biomass is most sensitive to precipitation, less to Tmax, and least to Tmin; increased precipitation always grows more roots, while increased temperature reduces root production.

Offline sensitivity experiments were performed with both atmospheric (ClimRAMS) and ecological (CENTURY) models. The results demonstrate that modifications to the prescribed LAI significantly affects the atmospheric model simulation of temperature and precipitation. Correspondingly, variations in the prescribed atmospheric forcings, such as temperature and precipitation, dramatically influences the biogeochemistry model simulation of above- and below-ground biomass. The fact that the two models are sensitive to the output of the other supports the premise that significant feedbacks exist between the atmosphere and terrestrial ecosystem. The conclusion, therefore, is that vegetation dynamics interacts with weather and climate in a coupled and nonlinear manner. To account for the two-way feedbacks and to better represent the integrated atmo-

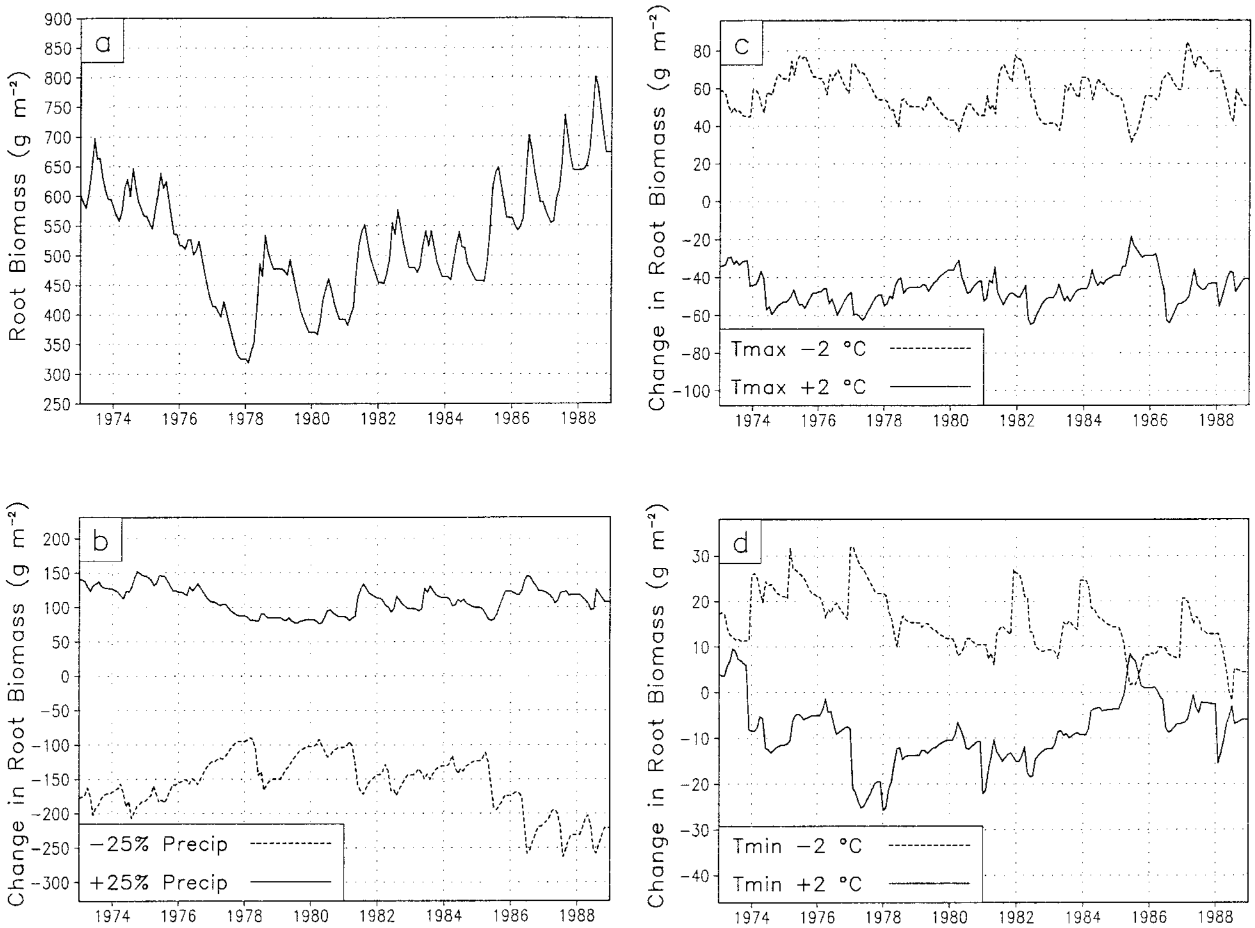

FIG. 4. (a) CENTURY-simulated below-ground live carbon (roots), g m^{-2}, over Konza, KS, from 1973 to 1988. (b) Changes in below-ground live carbon from the control run when precipitation was increased and decreased by 25%. (c) Changes in below-ground live carbon (roots), g m^{-2}, from the control run when maximum screen-height air temperature was increased and decreased 2°C. (d) Changes in below-ground live carbon (roots), g m^{-2}, from the control run when minimum screen-height air temperature was increased and decreased 2°C.

spheric–ecologic system, dynamically coupling the two systems in numerical models is required.

4. Implementation of the coupled RAMS–CENTURY modeling system

a. Coupling strategies and procedures

The model versions used in the coupled modeling system are the climate version of RAMS (ClimRAMS) and daily time step CENTURY (DayCENT). ClimRAMS and DayCENT are very different models since they represent different physical and biological processes associated with land–atmosphere interactions. ClimRAMS is a three-dimensional model running on approximately minute timescales, while DayCENT is a one-dimensional model running on a daily time step. In terms of plant growth, vegetation needs more time to evolve and react to the atmospheric forcings. From an engineering point of view, it is the slowest process that determines the pace of the feedbacks within an integrated system. Therefore, the coupled model was designed to exchange information on a weekly time step. Weekly information exchange between the two models will not only allow vegetation to evolve in response to one week of daily atmospheric forcings, but also reduces the computational time needed to exchange information.

Table 1 summarizes the variables exchanged between the two models. At the end of every week, ClimRAMS collects a week’s worth of daily air temperature, precipitation, radiation, wind speed, and relative humidity data and passes them to DayCENT. Then driven by the daily atmospheric forcings, DayCENT computes the leaf area index and vegetation transmissivity and returns the end-of-the-week values to ClimRAMS. In this way, vegetation responds to daily and seasonal atmospheric changes, and the atmosphere is able to respond to the associated vegetation changes.

Because of the differences in temporal and spatial

TABLE 1. Information exchanged between ClimRAMS and DayCENT. The variables marked with stars have not been coupled in the simulations discussed herein.

ClimRAMS	DayCENT
Precipitation	LAI
Maximum temperature	Vegetation transmissivity
Minimum temperature	*Vegetation fraction
Incoming solar radiation	*Vegetation albedo
Relative humidity	*Vegetation roughness length
Wind speed	*Vegetation displacement height
*Cloud coverage	*Root distribution

resolutions of the two models, computational obstacles need to be overcome. The coupling between ClimRAMS and DayCENT has been performed at the land surface. Each grid cell runs its own DayCENT model according to the land-use type and the atmospheric conditions passed from ClimRAMS. The online coupling between ClimRAMS and DayCENT is achieved through the Internet stream socket and client/server mechanism (Stevens 1998). ClimRAMS works as a server to control the timing of the model runs, and DayCENT is a client to be initiated by calls from Internal Process Control programs. This innovative approach allows the linked models to communicate dynamically and efficiently with each other without changing their original platforms. Currently, the two models are run on a two-processor SUN Ultra-2 workstation, and it takes seven CPU days to perform a coupled model annual integration using the grid increments applied in this study.

Figure 5 is the flow diagram describing the coupling procedures and the information exchanged between the two models. The coupling procedures can be summarized into the following steps: 1) ClimRAMS starts, uses the initial LAI value generated by DayCENT's spinup, and integrates for one week; 2) ClimRAMS stops integration; 3) ClimRAMS calls DayCENT, passes one week's weather to DayCENT; 4) DayCENT starts, the ecosystem evolves for a week according to the weather passed from ClimRAMS, DayCENT generates new LAIs and passes them to ClimRAMS; 5) DayCENT stops; 6) ClimRAMS receives new LAIs, starts again, integrates for a week. Steps 2–6 are repeated until the simulation finishes.

b. The coupled control run design

The coupled model domain and grid configuration are given in Fig. 1, which shows a coarse grid covering the entire conterminous United States at 200-km grid spacing, and a finer nested grid covering Kansas, Nebraska, South Dakota, Wyoming, and Colorado at 50-km grid spacing. This region was chosen for several reasons. First, it includes rather complex topographic features, covering parts of the Great Plains and the Rocky Mountains. The topographic distribution for the fine grid in Fig. 1 is given in Fig. 6. Second, it has rather diversified land-use types including C3 and C4 grassland, various agricultural croplands, evergreen needleleaf trees, shrubland, and tundra; a total of thirty land-use types as defined by the Vegetation–Ecosystem Modeling and Analysis Project (VEMAP) database. The vegetation distribution for the fine grid in Fig. 1 is given in Fig. 7. The land-use types from DayCENT are derived from the VEMAP (Kittel et al. 1996) dataset, and then they are converted to the RAMS 18 vegetation classes through a lookup table (Table 2). These RAMS classes are the same as those used in BATS.

A significant deficiency with the standard RAMS classification is its lack of spatial heterogeity within a

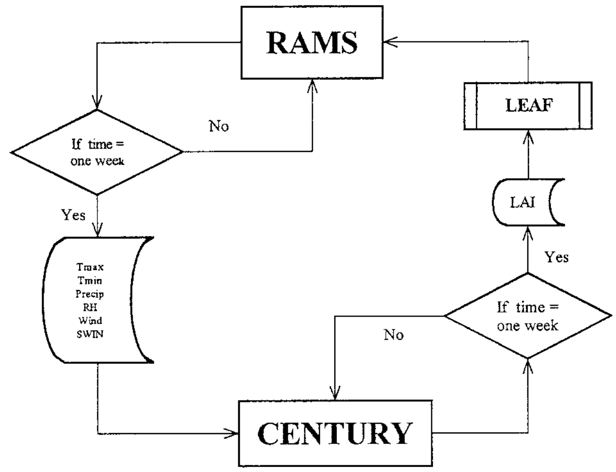

FIG. 5. Flow diagram of the coupled RAMS and CENTURY modeling system.

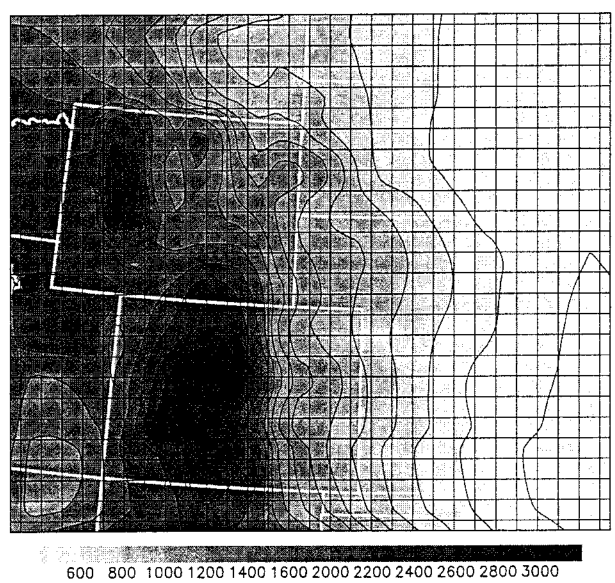

FIG. 6. The topographic distribution (m) for the fine grid in Fig. 1.

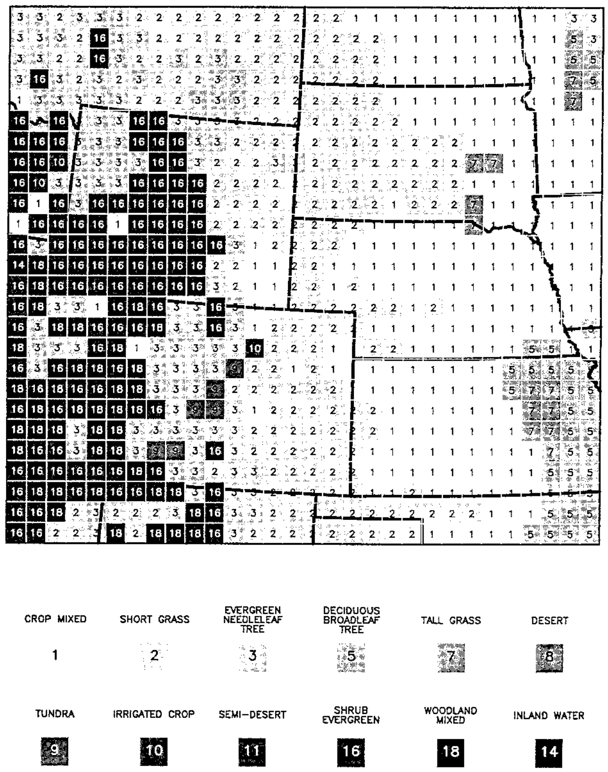

FIG. 7. The vegetation distribution for the fine grid in Fig. 1.

given vegetation category. For instance, there is no difference between the grassland growing in northern Wyoming and that in southern Kansas. Thus, in offline ClimRAMS, the two regions will, unrealistically, have the same LAI specification. When coupled with the DayCENT ecological model, vegetation growth is controlled by land-use type, site-specific geographic information, and the spatially varying atmospheric forcings. Thus, for example, the grassland vegetation type used in Wyoming and Kansas will have different LAI descriptions. The same idea applies to other vegetation types as well.

The finer grid covers an area of 1500 km in the east–west direction and 1300 km in the north–south direction. The pole point for the oblique polar stereographic projection used to define the grid is 40°N latitude and 100°W longitude. There are 20 vertical levels with a thickness of 119 m at the surface, stretching to 2000 m at the 23-km domain top. The model is driven by 6-hourly lateral boundary conditions derived from the National Centers for Environmental Prediction's (NCEP) atmospheric reanalysis products (Kalnay et al. 1996). Lateral boundary condition nudging is performed on the two outer boundary grid cells of the coarse grid. The information provided at the lateral boundary includes horizontal wind speed, relative humidity, air temperature, and geopotential height on pressure levels. The initial atmospheric fields are also provided by the NCEP reanalyses. The time step for the atmospheric model integrations is 2 min.

Heterogeneous soil types were applied to the domain based on the U.S. Department of Agriculture, STATSGO soil database (Miller and White 1998). The soil texture distribution for the finer grid is given in Fig. 8. The model has 10 soil layers at 2.0, 1.65, 1.3, 0.95, 0.65, 0.45, 0.3, 0.2, 0.125, and 0.05 m from the surface. Soil moisture initial distributions are generated by first defining a spatially constant soil moisture content (40% of the total water capacity) over the domain, and running the model for one year. The soil moisture distribution on the last day of that simulation is then used as the initial condition for the next year's simulation.

The coupling between ClimRAMS and DayCENT was performed for the finer grid in Fig. 1. DayCENT was configured and initialized for each grid cell on that grid according to the land-use type (VEMAP members 1995). DayCENT was first spun up for 2000 yr according to a 30-yr mean climatology (averaged over 1961–90), which allows the state variables in the model to reach equilibrium. Then the control run year's climate generated from offline ClimRAMS is used to drive DayCENT cyclically for 3 yr before DayCENT enters the coupled mode. Using 3 yr to spin up DayCENT to the ClimRAMS climate was determined by the numerical experiment shown in Fig. 9. In that experiment, DayCENT was driven by the offline ClimRAMS-produced 1989 climate cyclically for 10 yr after its initial equilibrium state had been reached from the 2000-yr spinup. The figure shows that after 3 years, the aboveground live carbon (aglivc), below-ground live carbon (bglivc), and standing dead material from grass and crops (stdedc) have reached equilibrium, while carbon in forest (rleavc) and total soil carbon (somtc) are still in the process of adjusting to the ClimRAMS climate. Since fast dynamics, such as leaf and root carbon, are more relevant to the feedback loops on seasonal to annual timescales (which is the focus of our current study) than the long-term dynamics such as soil organic matter, and since the computational resources were not available for a longer spinup, 3 years was chosen to adjust DayCENT to be consistent with the ClimRAMS climate prior to starting the coupled simulations.

In order to select an average year for the model simulations, we analyzed the National Climatic Data Center's Summary-of-the-Day (SOD) meteorological station observational datasets from 1982 to 1996. There are approximately 3800 U.S. SOD stations that provide daily precipitation, Tmax, and Tmin data. The SOD station data were gridded to the 50-km ClimRAMS grid using an objective analysis scheme (Cressman 1959), and were used to validate ClimRAMS and drive the offline DayCENT simulations. Figure 10 shows the screen-height daily maximum and minimum air temperature, and precipitation from 1982 to 1996 averaged over the fine-grid domain. The year 1989 is a near-average year and was chosen for the control simulation.

TABLE 2. RAMS and CENTURY vegetation class conversion table (xx implies no equivalent classification).

RAMS classification	CENTURY classification
1 - Crop; mixed farming	101 - Spring wheat and northern small grains
	102 - Small grains
	103 - Winter wheat
	104 - Corn belt
	105 - Southern corn and mixed crops
	118 - Grassland and small grain wheat
2 - Short grass	17 - C3 grassland (include short and tall)
	18 - C4 grassland (include short and tall)
3 - Evergreen needleleaf tree	4 - Temperate continental coniferous forest
	2 - Boreal coniferous forest
4 - Deciduous needleleaf tree	xx
5 - Deciduous broadleaf tree	7 - Temperate deciduous forest
	13 - Temperate deciduous savanna
	114 - Temperate deciduous forest and corn belt
	115 - Temperate deciduous forest and southern corn and mixed crops
	116 - Warm temperate/subtropical mixed forest and southern corn and mixed crops
6 - Evergreen broadleaf tree	xx
7 - Tall grass	18 - C4 grassland (include short and tall)
	17 - C3 grassland (include short and tall)
8 - Desert	xx
9 - Tundra	1 - Tundra
10 - Irrigated crops	106 - Irrigated crops
11 - Semidesert	xx
12 - Ice cap/glacier	xx
13 - Bog or marsh	xx
14 - Inland water	91 - Inland water
15 - Ocean	xx
16 - Evergreen shrub	20 - Temperate arid shrubland
17 - Deciduous shrub	20 - Temperate arid shrubland
18 - Mixed woodland	10 - Temperate mixed xeromorphic woodland
	11 - Temperate conifer xeromorphic woodland

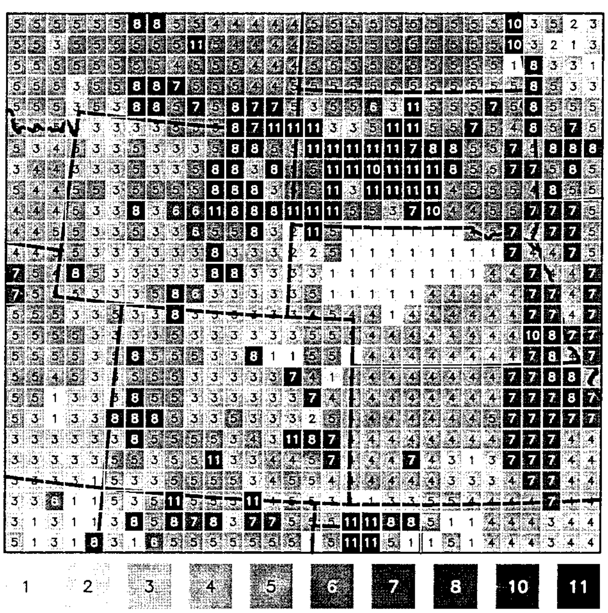

FIG. 8. The soil-texture-class spatial distribution for the fine grid in Fig. 1, defined according to the U.S. Department of Agriculture, STATSGO soils database (Miller and White 1998). The numbers correspond to the following ClimRAMS soil classes: 1, sand; 2, loamy sand; 3, sandy loam; 4, silt loam; 5, loam; 6, sandy clay loam; 7, silty clay loam; 8, clay loam; 10, silty clay; 11, clay. Soil class 9 (sandy peat) and 12 (peat) are not included in this domain at this resolution.

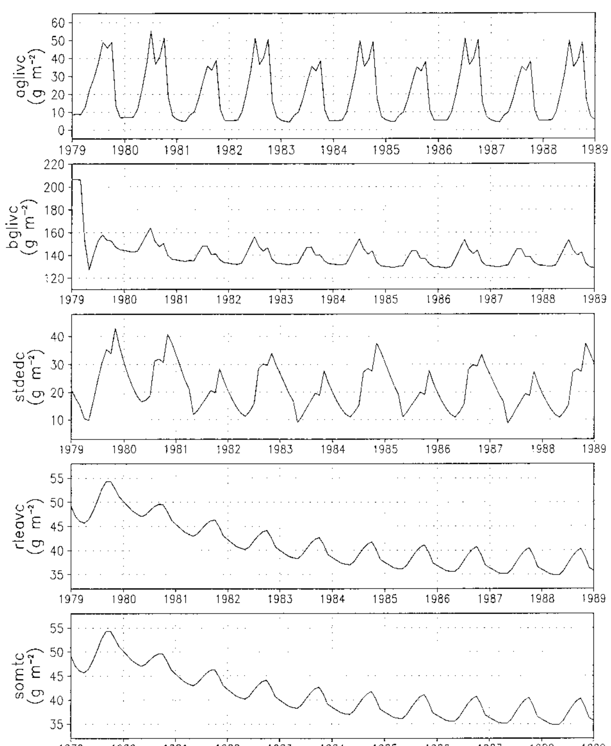

FIG. 9. DayCENT outputs when driven with the ClimRAMS 1989 climate for 10 yr.

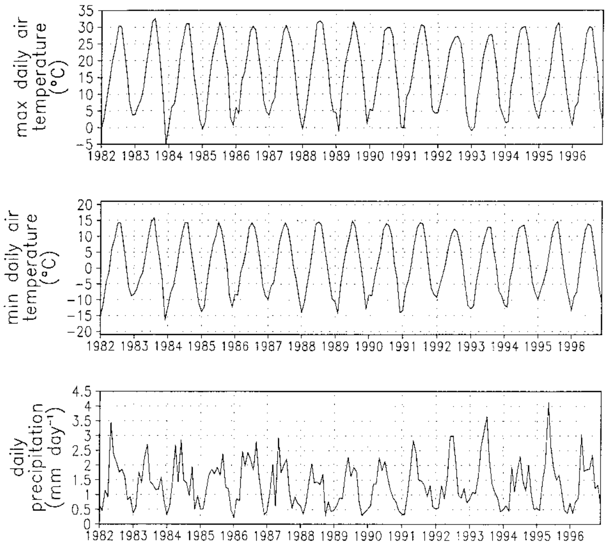

FIG. 10. Observed domain-averaged monthly mean screen-height maximum and minimum air temperature and precipitation for the period 1982–96 (based on U.S. SOD station data).

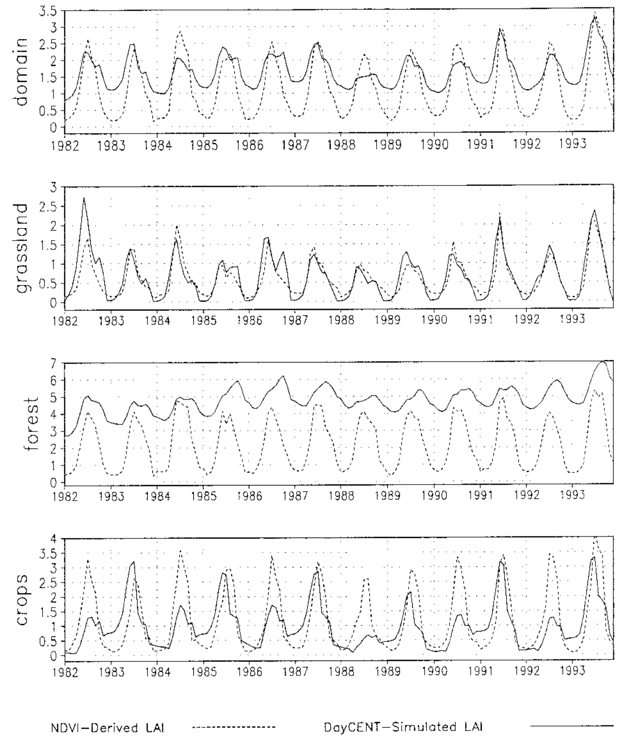

FIG. 11. Monthly NDVI-derived LAI and DayCENT-simulated LAI over the fine grid for the period 1982–93, averaged over the domain, grasslands, trees, and crops.

5. Results

a. Offline model validations

1) DAYCENT

A detailed DayCENT description and validation have been reported in Lu (1999). DayCENT was driven by observed daily atmospheric forcings derived from the U.S. SOD dataset for each grid cell of the fine-grid domain from 1 January 1982 to 31 December 1993. The above-ground live carbon (aglivc) produced by DayCENT was then converted to LAI following the algorithm presented in the appendix.

Figure 11 shows monthly normalized difference vegetation index (NDVI)-derived LAI and DayCENT-simulated LAI. The LAI for the fine grid was then averaged over the domain that includes, grasslands, trees, and crops. The agreement between the two grassland time series is good, with both the seasonal cycle and interannual variation well captured by the model. The simulated LAI maxima for trees, however, are generally 25% higher than observed. The simulated minima are around 4 LAI units, while the observed minima are around 0.5 LAI units. A possible explanation for the large difference in the minima is that the NDVI data may have been contaminated by snow cover during the winter months so that the evergreen forest cannot be detected by the satellite sensors. The large seasonal variation in the forest NDVI-derived LAI data may not be realistic for this reason. Thus, we expect that the seasonal cycle of DayCENT-produced forest LAI is actually more realistic than those derived from the NDVI data. The model-simulated crop LAI clearly shows a 2-yr alternating ‘‘low–high’’ pattern, introduced by DayCENT's crop management practices; field fallow has been scheduled every other year for the winter wheat, which makes up 50% of the croplands. Comparison of the modeled and observed LAI shows DayCENT is capable of representing seasonal and interannual biomass variabilities.

2) CLIMRAMS

A comprehensive model description and evaluation of ClimRAMS can be found in Liston and Pielke (2000). The major difference between the control run performed by a standard ClimRAMS simulation and the one conducted in this section lies in the vegetation-type description, where the former distribution is derived from an International Geosphere–Biosphere Programme dataset and the later is from the VEMAP database (Kittel et al. 1996). Compared to a standard ClimRAMS simulation, differences in results exist due to the difference in vegetation-cover specification.

The model's ability to reproduce the domain-averaged daily maximum (Tmax) and minimum (Tmin) screen-height air temperature and daily precipitation are shown in Fig. 12, where these variables have been averaged over the 50-km grid given in Fig. 1. The differences between the model simulation and the observation are also plotted, including a 30-day running mean of the

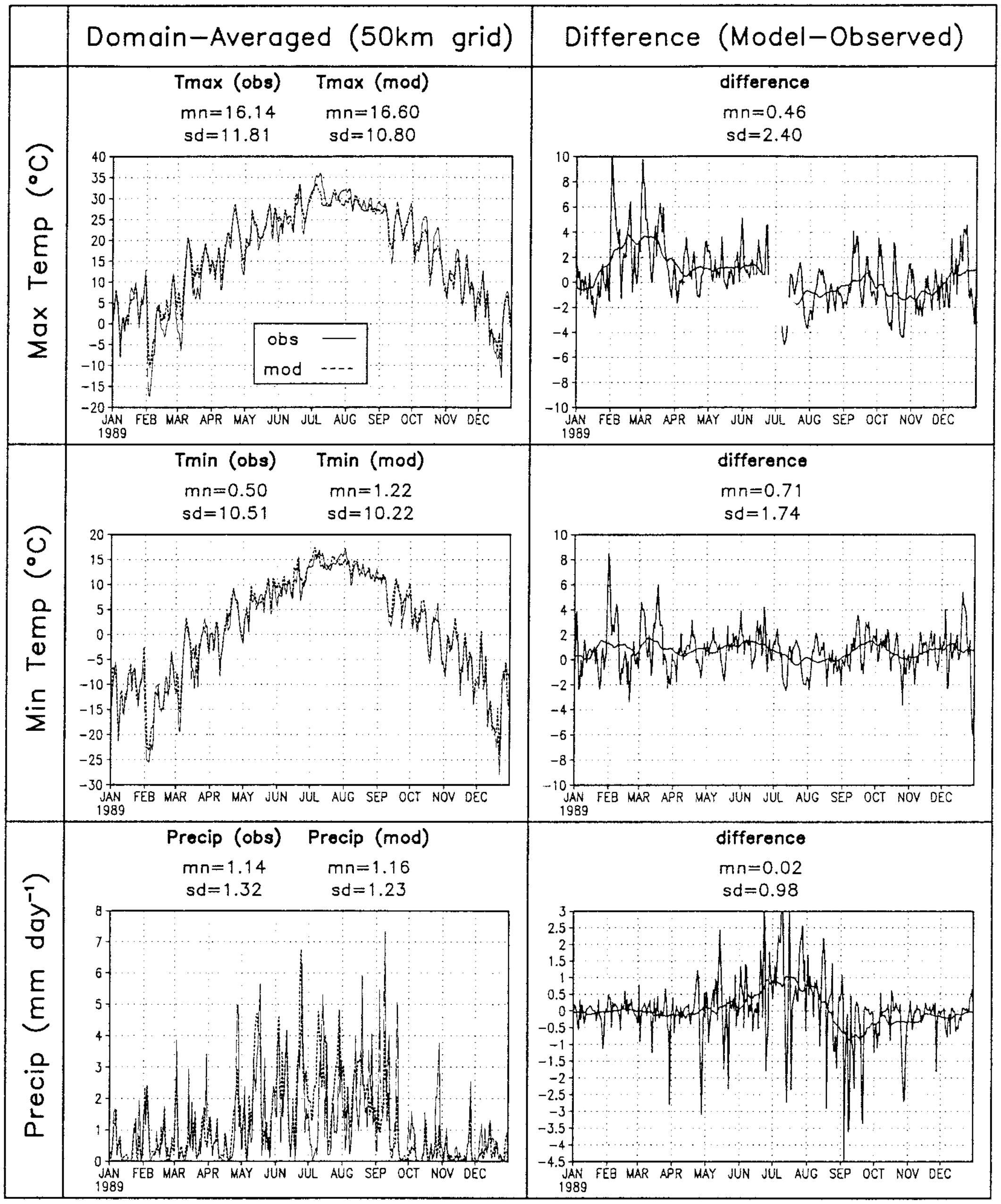

FIG. 12. Modeled and observed, domain-averaged daily maximum and minimum screen-height air temperature and daily precipitation for 1989, where these variables have been averaged over the 50-km grid given in Fig. 1. Also shown is the difference between the model and observations, and the 30-day running mean of the difference values. Included are the mean (mn) and standard deviation (sd) for each panel and variable.

daily values. The model is found to capture the synoptic signals as well as the seasonal temperature evolutions. The total annual precipitation simulated by the model is quite close to the observations despite the use of the simple dump-bucket scheme used as a trade-off between computational time and long-term integration. However, the model tends to rain more frequently and misses the observed precipitation peaks. The spatial patterns of Tmax, Tmin, and precipitation for the winter months and summer months are found to generally capture the observed spatial patterns (Lu 1999). A comparison of the annual cycle of Tmax, Tmin, and daily precipitation at the model grid-cell level, corresponding to three cities (Salina, Kansas; Sioux Falls, South Dakota; and Casper, Wyoming) within the fine-grid domain has shown that the model is able to capture the regional variabilities in both temperatures and precipitation fields of these sites (Lu 1999). Although the model generally does not capture the peak magnitudes of precipitation events, the timings of the individual synoptic events and seasonal cycles are well simulated.

A legitimate question to ask at this point is, why not run ClimRAMS with the observed LAI? First, prior to the work presented in this paper, the vegetation specification in ClimRAMS traditionally follows the BATS scheme with a modification that allows LAI to vary according to the time of the year. Second, ClimRAMS has been adjusted to closely match the observations, by making changes to such things as the soil moisture initialization and the precipitation coefficients. Thus, using a different vegetation specification can lower the model's skill in reproducing the observed climate, even though the new representation is more physically realistic. Third, the observed LAI was derived from the NDVI dataset. Uncertainties and errors exist with regard to the NDVI data retrieval processes and the NDVI-to-LAI conversion algorithm as discussed in section 5a(1). Therefore, it is premature to run the ClimRAMS with the observed LAI since currently only limited insight can be gained by doing so. In addition and most importantly, the two-way atmosphere and vegetation interaction is the focus of this paper. How to use the observed LAI to improve the atmospheric model's simulation skill is reserved for a separate study.

b. Results from the coupled RAMS–CENTURY modeling system

Three types of numerical experiments were performed. They are 1) offline ClimRAMS, where the LAI is prescribed following the curves defined by ClimRAMS; 2) offline DayCENT, where the DayCENT is driven by ClimRAMS-produced atmospheric forcings; 3) coupled RAMS–CENTURY, where ClimRAMS and DayCENT are two-way interactive at a weekly time step.

1) SIMULATED LAI

The coupled model was integrated from 1 January to 31 December 1989. The three curves shown in Fig. 13 are the domain-averaged LAI prescribed in offline ClimRAMS, simulated by the coupled model, and simulated by the offline DayCENT driven by ClimRAMS climate. These curves are 7-day running means. At the first glance, the three curves are very different in both patterns and magnitudes. Recalling the LAI curve derived from the NDVI dataset (Fig. 11), the DayCENT-simulated LAI is closer to the observations both in value and seasonal evolution. The LAI prescribed in ClimRAMS is too high both in winter and summer, producing an unrealistic vegetation evolution pattern for our domain. The coupled model-simulated LAI is generally higher than that simulated by the offline DayCENT. This can be explained later by the fact that the coupled model produces more summer precipitation than the offline ClimRAMS simulation (to be discussed in the next section).

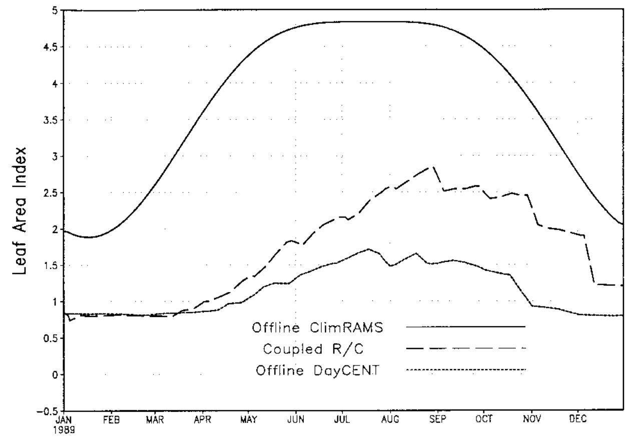

FIG. 13. Domain-averaged, 7-day running mean LAI prescribed in offline ClimRAMS (Offline ClimRAMS), simulated by the coupled model (Coupled R/C), and simulated by offline DayCENT (Offline DayCENT) for the fine grid.

2) SIMULATED CLIMATE

The primary purpose of conducting the coupled model simulation is to provide a dynamic vegetation descriptions for atmospheric model and to study the two-way interactions between the atmosphere and the vegetation. The intent is not to tune the coupled model to match the observations. Therefore, we will focus on analyzing the differences between the coupled and the offline ClimRAMS simulation and what causes them. Shown in Fig. 14 are the daily maximum screen-height air temperature (Tmax) averaged over the fine-grid domain from the offline ClimRAMS, the coupled model, and the observations. The differences between the coupled model and the offline ClimRAMS simulation are also plotted, including a 30-day running mean of the difference values. The coupled and offline model are very close in simulating Tmax for November, December, January, and February. The coupled model is in better agreement with the observations from March to the end of June compared to the offline ClimRAMS run. A much more realistic spring and early summer vegetation green-up description from DayCENT may contribute to the improved simulation during that period. Increased rainfall in the coupled model during the summer months leads to decreased temperatures during that period. While we recognize that the coupled model represents the natural system in a more realistic manner, the coupled model July and August Tmax values in Fig. 14 are further from the observations than the offline ClimRAMS simulation. This is because, at least in part, ClimRAMS must currently include other components

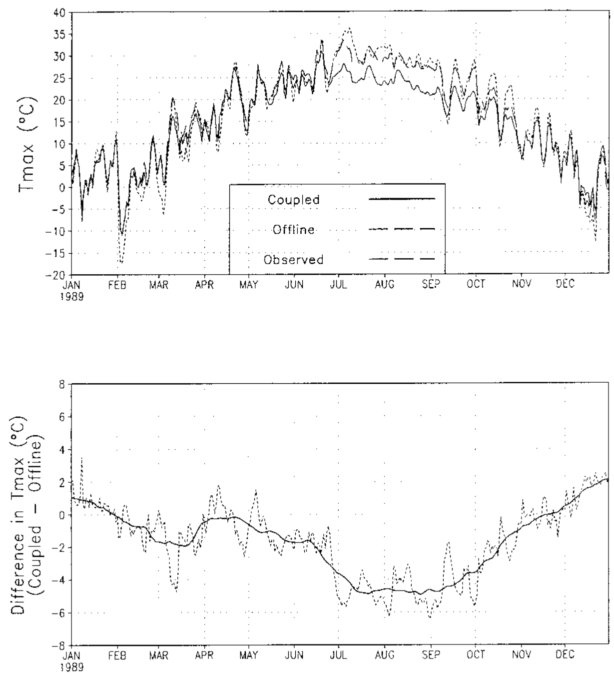

FIG. 14. The daily maximum screen-height air temperature averaged over the fine grid from offline ClimRAMS (Offline), the coupled model (Coupled), and the observations (Observed), for the time period 1 Jan–31 Dec 1989. Also shown is the difference between the coupled model and the offline ClimRAMS, and the 30-day running mean of the difference values.

that compensate for its unrealistic LAI representation. For example, the soil moisture submodel may well misrepresent important components of the soil hydrologic cycle.

Figure 15 displays the same information as Fig. 14 except that it is for the daily minimum screen-height air temperature (Tmin). The coupled run is warmer than the offline run for the winter months, but colder for the summer months, where Tmin can be as much as 3°C colder. This is also closely related to the excessive precipitation produced by the coupled model during the summer period. Figure 16 presented the same information as Fig. 14 except that it is for the daily precipitation. The coupled model produces more rain than the offline simulation throughout the year, especially in the summer, which means that the vegetation phenology from DayCENT enhances the coupled model's ability to capture the precipitation event peaks. However, the coupled model tends to rain more frequently and overestimate the total rainfall amount compared to the observations.

In general, the coupled model's temperature and precipitation simulation captures the synoptic signals as well as the seasonal evolution. The coupled model produced more precipitation in summer, which led to a colder summer compared to the offline ClimRAMS simulations.

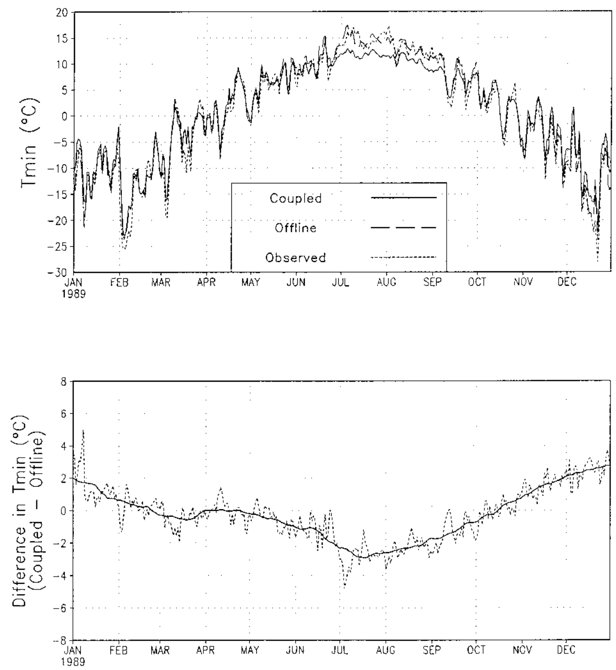

FIG. 15. The same as Fig. 14, but for daily minimum screen-height air temperature.

The reason that the coupled run differs from the offline simulation is explained as follows. First, instead of using prescribed LAI, the coupled simulation uses the LAI generated by DayCENT model, which is only

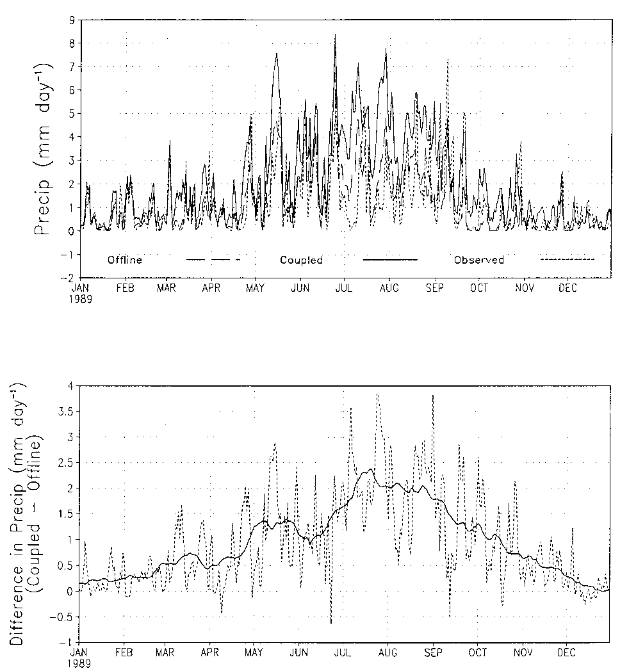

FIG. 16. The same as Fig. 14, but for daily precipitation.

about half the value of LAI traditionally used in ClimRAMS (Fig. 13). At the same time, the representation of vegetation phenologies between the two models are quite different. In addition, the vegetation transmissivity was dynamically coupled to ClimRAMS for the coupled control run. Since in the coupled model LAI is smaller than the prescribed ClimRAMS LAI, the vegetation transmissivity of the coupled model is larger and it allows more solar radiation to reach the land surface. Initially, extra surface heating increases the atmosphere instability, which in turn triggers more convective precipitation. Soon the wetter surface condition becomes important as the evaporation and transpiration from the bare soil and vegetated surface increases. This is accompanied by decreased Bowen ratios and increased latent heat fluxes. Although the lateral atmospheric boundary conditions used in the coupled and the offline ClimRAMS simulations are identical, there is more local moisture available in the coupled simulation. This process leads to the increase of moist static energy that favors the generation of more precipitation. Thus, a positive feedback mechanism exists between the LAI and precipitation when no other environmental conditions are dominating the process, which may contribute to the increase of local moisture and leads to more precipitation. This point will be further discussed in the next section at the individual grid-cell level.

Furthermore, the vegetation classes and LAI specification from the coupled model is simulated by DayCENT (Table 2), while in the offline ClimRAMS simulation it is defined by the RAMS classification and varies only based on the Julian day according to a sine function. Thus, DayCENT provides the domain with much more heterogeneities in terms of both vegetation classes and their LAI evolution patterns. These land surface inhomogeneities can induce atmospheric solenoidal circulations that not only influence the surface layer above the vegetation, but can also act as triggers for moist convection and precipitation in preferred areas, with obvious strong feedbacks to vegetation.

3) Simulated atmosphere and vegetation feedbacks

The coupled model allows us to look into the atmosphere and vegetation feedback dynamics in a much more detailed manner. Figure 17 shows the daily LAI prescribed by ClimRAMS, generated by DayCENT, and simulated by the coupled model, for a single grid cell having a winter wheat land-use type. Also shown is the precipitation difference between the coupled and offline simulation, and the 30-day running mean. The grid cell (26,7) corresponds to Salina, Kansas, located at 38.85°N latitude and 97.40°W longitude. At the beginning of August, the winter wheat harvest occurred that brought the LAI value down to near zero. Corresponding to the harvest event, the coupled model has a dramatic precipitation decrease from August to mid-September due to the sudden shutdown of vegetation transpiration that greatly reduced the local moisture availability. Accordingly, the coupled model starts another year's winter wheat growth with less precipitation and drier soil, resulting in less biomass growth compared to the offline DayCENT that is driven by the offline ClimRAMS climate.

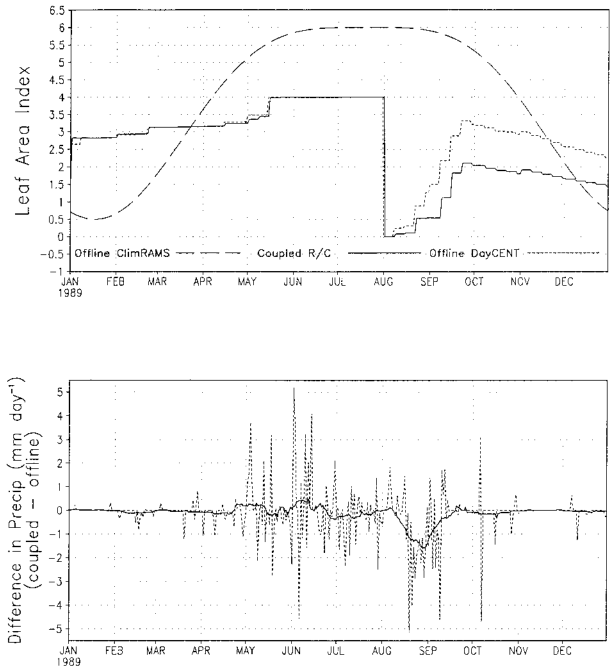

FIG. 17. Daily LAI prescribed by ClimRAMS (Offline ClimRAMS), simulated by DayCENT (Offline DayCENT), and simulated by the coupled model (Coupled R/C), for a single grid cell near Salina, KS. Also shown is the precipitation difference between the coupled and offline simulation, and the 30-day running mean. The land-use type for this grid cell is winter wheat.

Figure 18 shows the daily LAI prescribed by the offline ClimRAMS, generated by offline DayCENT, and simulated by the coupled model, over a C3 grassland near Casper, Wyoming. The location of this grid cell (11, 16) is 42.75°N latitude and 106.43°W longitude. There are dramatic differences between the LAI curves generated by DayCENT and the one originally used in the offline ClimRAMS simulations. The seasonal evolution of LAI is realistically represented in the coupled model. The growing season starts rapidly in late April, peaks in late summer, and senesces in the fall. The coupled model produces less LAI at the beginning of the growing season due to the lower minimum temperature and less precipitation compared to the offline DayCENT run. The extra surface heating brought about by the higher Tmax can, in turn, trigger precipitation if enough lower-level moisture convergence is available. Correspondingly, though with a time lag, the vegetation be-

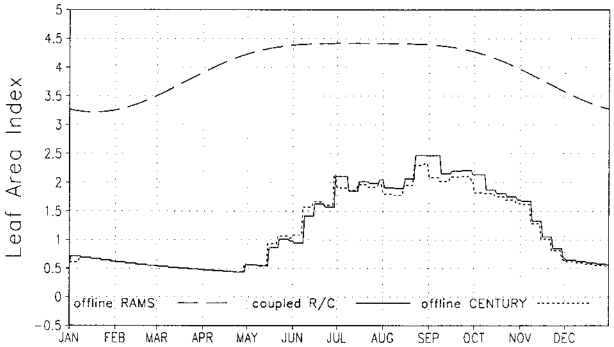

FIG. 18. Daily LAI prescribed by the offline ClimRAMS (offline RAMS), generated by offline DayCENT (Offline CENTURY), and simulated by the coupled model (Coupled R/C), respectively, over a C3 grassland near Casper, WY.

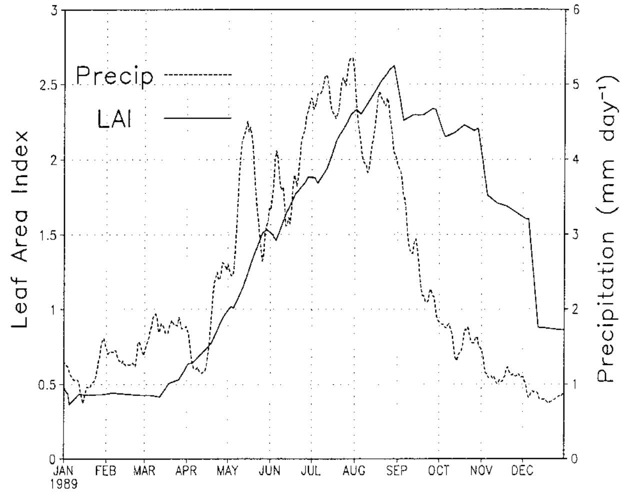

FIG. 19. The 7-day running means of precipitation and LAI, averaged over the fine grid. Notice 1–2-week lag between precipitation maxima and LAI maxima.

gins to grow more biomass in the early summer. This extra biomass increases the latent heat flux and leads to more rain by transpiring water vapor into the air. A short-term, positive but nonlinear, feedback between LAI and precipitation exists when no other limiting factors, such as temperature, nutrients, etc., are causing stress. Another interesting feature is that the LAI evolution simulated by the coupled model clearly shows an accumulating effect on plant growth. Though sometimes the coupled run receives less rain than the offline run, once the vegetation develops, it tends to remain until the end of the year as shown in Fig. 18. From the biosphere point of view, the positive feedback between LAI and precipitation seems to be one of the vegetation's mechanisms to modify the environment and to adjust to the atmospheric conditions in order to maximize their prospects of growth and survival.

To further explore the feedback dynamics between the vegetation and precipitation, the 7-day running means of domain-averaged precipitation and LAI are plotted in Fig. 19. Following each rainfall maximum, an LAI maximum occurred one or two weeks later. This phenomenon lasts until September, when the vegetation senescent processes take over. Figure 19 comprehensively demonstrates that the coupled model is able to represent the two-way feedbacks between the atmosphere and vegetation. Potential longer-term feedbacks from the soil nutrient cycle and roots need to be explored using multiyear simulations.

In the coupled RAMS–CENTURY modeling system, ClimRAMS provides the atmospheric forcings required by 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 simulation results described above provide evidence that introducing dynamic vegetation descriptions in regional climate modeling can cause significant changes in atmospheric conditions that, in turn, influence vegetation growth and evolution.

6. Summary and discussion

The coupled RAMS–CENTURY modeling system has been developed to study the two-way interactions between the atmosphere and land surface. Both atmospheric forcings (air temperature, precipitation, radiation, wind speed, and relative humidity) and ecological parameters (LAI and vegetation transmissivity) are prognoses in the linked system. The coupled model was integrated from 1 January to 31 December 1989, focusing on the central United States. Validation is performed for the atmospheric portion of the model by comparing with meteorological station observations, and for the ecological component by comparing to the Pathfinder advanced very high resolution radiometer remote-sensing NDVI datasets. The results show that seasonal vegetation phenological variability strongly influences regional atmospheric characteristics through its control over land surface water and energy exchange. The coupled model captures the key aspects of weekly, seasonal, and annual feedbacks between the atmospheric and ecologic systems. In addition, the coupled model has demonstrated its usefulness as a research tool for studying the complex interactions between the atmosphere, biosphere, and hydrosphere.

Although the coupled RAMS–CENTURY modeling system provides an approach to represent the two-way feedbacks between the atmosphere and the biosphere, due to limitations in our ability to numerically model the complete dynamics of the two systems, and the nonlinear features of the feedbacks, our efforts may not directly or immediately improve the model's simulation skill. In spite of this, the coupled model provides a valuable tool to study the physical and biological processes and interactions within the climate system. The coupled model and the simulations presented herein also provide guidance on the limits imposed on climate prediction as a result of the nonlinear feedbacks (Pielke 1998; Pielke et al. 1998).

New computer science technologies, such as the Internet stream socket and client/server mechanisms (Stevens 1998), provide the scientific community with an innovative and feasible method to accomplish large-scale model integration and data assimilation. It is particularly efficient and convenient when the linkage involves diversified models running at different temporal and spatial resolutions. Each model involved can be run independent of the other models. Sending and receiving required information between the models at scheduled times can be easily achieved through this mechanism. The implementation of the coupled RAMS–CENTURY modeling system is the first successful attempt utilizing this technology in earth science, and should be viewed as a pilot project that explores a new dimension in model integrations.

In the current configuration of the coupled modeling system, RAMS and CENTURY use their own soil submodels. The use of different soil models may cause inconsistencies in the coupled model's hydrological cycle. For instance, the soil temperature and moisture simulated by CENTURY may be different from that of RAMS even though both soil models receive the same atmospheric forcings such as precipitation and screen-height air temperature. This may constitute a major deficiency of our coupling approach. Developing a common soil model for the coupled modeling system would solve this problem. However, this is a difficult task, not only because the temporal and spatial resolution utilized by the two soil models are different, but also because other components of both RAMS and CENTURY are highly interwoven with their soil water budget submodels. To correct these inconsistencies, a consistent unified soil model is required. Any change made to the soil model must meet the requirement that other processes simulated by both models will not be adversely affected. An alternative approach would be to combine RAMS land surface biophysics component and CENTURY vegetation dynamics to develop a new comprehensive land surface model for regional climate modeling. However, much more work is still needed to explore this research direction.

Moreover, in the current form of the coupled model, the physics of coupling is only partially addressed. For instance, only above-ground live carbon passed from CENTURY has been utilized in RAMS after converted to LAI. Although CENTURY can provide information such as below-ground live carbon (Bglivc) to RAMS, the conversion algorithm to allocate Bglivc to each vertical soil level has yet to be developed. It would be difficult, at least at present, to design an interactive model that includes all the feedback mechanisms between the biosphere and other elements of the climate system. This is because our knowledge of the biosphere processes is insufficient, and the observational datasets for model validation are lacking.

The analysis presented in this paper demonstrates a perspective on regional climate prediction that has not been widely recognized in the modeling community. Much of the previous regional climate modeling has emphasized the atmospheric portion of the climate system. However, as shown in this paper simulation of the regional climate, even for time periods of one month, require that the land surface and the atmosphere be dynamically coupled. Vegetation growth (as represented, for example, by above- and below-ground biomass) and temperature are both dependent variables within the climate system. The land surface therefore is not a boundary but an interface (Pielke 1998). The seasonal regional climate simulations conducted in this study support the conclusion that climate must be considered as an integrated earth system process.

Finally, only static vegetation species and community structures have been used in the coupled RAMS–CENTURY modeling system. To simulate longer-term climate or to study climate change scenarios under specified disturbance, species composition, and community structure changes and evolutions should also be considered. Therefore, linking the Mapped atmosphere–plant-soil system (MAPSS) (Neilson 1995) biogeographical model to form an integrated RAMS–CENTURY–MAPSS modeling system promises to be an important contribution to studying the dynamically coupled earth–atmosphere system.

Acknowledgments. Funding for this work has been provided by the National Park Service (NPS) and the National Biological Survey (NBS) Grants CEGR-R92-0193 and COLR-R92-0204, Environmental Protection Agency (EPA) Grant R824993-01-0, and NASA Grants NAG8-1511 and NAG5-4646. The authors would like to acknowledge the anonymous reviewers for their excellent suggestions. This paper forms part of the first author's Ph.D. dissertation.

APPENDIX

Above-Ground Live Carbon (aglivc) to LAI Conversion Algorithm

The above-ground live carbon (aglivc) produced by the CENTURY and DayCENT models is converted to LAI following the relationship

$$\mathrm{LAI} = \frac{\mathrm{aglivc}}{1000} R_{\mathrm{leaf}}, \tag{A1}$$

where aglivc, g m^{-2}, is above-ground live carbon; and R_{leaf} (m^2 leaf area) (kg leaf carbon)$^{-1}$, is the specific leaf area that varies according to the vegetation type. The value of R_{leaf} for each land cover class is provided in Table A1.

TABLE A1. Conversion factor (R_{leaf}) between above-ground live carbon and LAI.

Vegetation type #	Vegetation type	Specific leaf area (m^2 leaf area) (kg leaf carbon)$^{-1}$
1	Tundra	9.6
2	Subalpine conifer	9.6
4	Continental temperate conifer	14.4
5	Cool temperate mixed forest	31.2
6	Warm temperate/subtropical mixed forest	24
7	Temperate deciduous forest	24
10	Temperate mixed xeromorphic woodland	21.6
11	Temperate conifer xeromorphic woodland	14.4
13	Temperate/subtropical deciduous savanna	24
14	Warm temperate/subtropical mixed savanna	14.4
15	Temperate conifer savanna	14.4
17	C3 grasslands	26
18	C4 grasslands	26
19	Mediterranean shrubland	14.4
20	Temperate arid shrubland	19.8
21	Subtropical arid shrubland	14.4
101	Spring wheat	26
102	Barley	26
103	Winter wheat	26
104	Dryland corn	8.7
105	Southern corn and mixed crops	26
106	Irrigated corn	8.7
114	Temperate deciduous and corn belt (7 + 104)	24
115	Temperate deciduous and mixed crop (7 + 105)	24
116	Warm temperature/subtropical mixed forest and southern corn (6 + 105)	24
118	Winter wheat	26

REFERENCES

Arakawa, A., and R. V. Lamb, 1977: Computational design of the basic dynamical processes of the UCLA general circulation model. *Methods in Computational Physics,* J. Chang, Ed., Vol. 17, Academic Press, 174–265.

Avissar, R., 1995: Recent advances in the representation of land–atmosphere interactions in general circulation models. *Rev. Geophys.,* **33** (Suppl.), 1005–1010.

——, and Y. Mahrer, 1988: Mapping frost-sensitive areas with a three-dimensional local-scale numerical model. Part I: Physical and numerical aspects. *J. Appl. Meteor.,* **27,** 400–413.

——, P. Avissar, Y. Mahrer, and B. A. Bravdo, 1985: A model to simulate response of plant stomata to environmental conditions. *Agric. For. Meteor.,* **34,** 21–29.

Betts, R. A., P. M. Cox, S. E. Lee, and F. I. Woodward, 1997: Contrasting physiological and structural vegetation feedbacks in climate change simulations. *Nature,* **387,** 796–800.

Bonan, G. B., 1996: A land surface model (LSM Version 1.0) for ecological, hydrological, and atmospheric studies: Technical description and user's guide. NCAR Tech. Note 417, 150 pp.

Charney, J. G., 1975: Dynamics of deserts and drought in the Sahel. *Quart. J. Roy. Meteor. Soc.,* **101,** 193–202.

Chen, C., and W. R. Cotton, 1983: A one-dimensional simulation of the stratocumulus-capped mixed layer. *Bound.-Layer Meteor.,* **25,** 289–321.

——, and ——, 1987: The physics of the marine stratocumulus-capped mixed layer. *J. Atmos. Sci.,* **44,** 2951–2977.

Chen, F., R. A. Pielke Sr., and K. Mitchell, 2000: Development and application of land-surface models for mesoscale atmospheric models: Problems and promises. *Observations and Modeling of the Land Surface Hydrological Processes,* V. Lakashmi, J. Albertson, and J. Schaake, Eds., Amer. Geophys. Union, in press.

Clapp, R., and G. Hornberger, 1978: Empirical equations for some soil hydraulic properties. *Water Resour. Res.,* **14,** 601–604.

Clark, T. L., 1977: A small-scale dynamic model using a terrain-following coordinate transformation. *J. Comput. Phys.,* **24,** 186–215.

——, and R. D. Farley, 1984: Severe downslope windstorm calculations in two and three spatial dimensions using anelastic interactive grid nesting: A possible mechanism or gustiness. *J. Atmos. Sci.,* **41,** 329–350.

Claussen, M., 1995: Modeling bio-geophysical feedback in the Sahel. Max-Planck-Instutut für Meteorologie, No. 163, 26 pp. [Available from Max-Planck-Institut für Meteorologie, Bundestrasse 55, 20146 Hamburg, Germany.]

Cotton, W. R., J. F. Weaver, and B. A. Beitler, 1995: An unusual summertime downslope wind event in Fort Collins, Colorado, on 3 July 1993. *Wea. Forecasting,* **10,** 786–797.

Cressman, G. P., 1959: An operational objective analysis system. *Mon. Wea. Rev.,* **87,** 367–374.

Deardorff, J. W., 1978: Efficient prediction of ground surface temperature and moisture, with inclusion of layer of vegetation. *J. Geophys. Res.,* **83,** 1889–1903.

——, 1980: Stratocumulus-capped mixed layers derived from a three-dimensional model. *Bound.-Layer Meteor.,* **18,** 495–527.

Dickinson, R. E., 1995: Land–atmosphere interaction. *Rev. Geophys.,* **33** (Suppl.), 917–922.

——, A. Henderson-Sellers, P. J. Kennedy, and M. F. Wilson, 1986: Biosphere–Atmosphere Transfer Schemes (BATS) for the NCAR community climate model. NCAR/TN-275 + STR, 69 pp.

——, ——, and ——, 1993: Biosphere–Atmosphere Transfer Scheme (BATS) version 1E as coupled to the NCAR community climate model. Tech. Note NCAR/TN-387 + STR, 72 pp.

——, M. Shaikh, R. Bryant, and L. Graumlich, 1998: Interactive canopies for a climate model. *J. Climate,* **11,** 2823–2836.

Eastman, J., 1999: Analysis of the effects of CO_2 and landscape change using a coupled plant and meteorological model. Ph.D. dissertation, Department of Atmospheric Science, Colorado State University, 100 pp. [Available from Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.]

Foley, J. A., S. Levis, I. C. Prentice, D. Pollard, and S. L. Thompson, 1998: Coupling dynamic models of climate and vegetation. *Global Change Biol.,* **4,** 561–579.

Gal-Chen, T., and R. C. J. Somerville, 1975: On the use of coordinate transformation for the solution of the Navier–Stokes equations. *J. Comput. Phys.,* **17,** 209–228.

Harrington, J. Y., 1997: The effects of radiative and microphysical processes on simulated warm and transition season Arctic stratus. Ph.D. dissertation, Atmospheric Science Paper 637, Department of Atmospheric Science, Colorado State University, 289 pp. [Available from Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.]

Henderson-Sellers, A., Z. L. Yang, and R. E. Dickinson, 1993: The project for intercomparison of land-surface parameterization schemes. *Bull. Amer. Meteor. Soc.,* **74,** 1335–1349.

——, A. J. Pitman, P. K. Love, P. Irannejad, and T. H. Chen, 1995: The Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) Phases 2 and 3. *Bull. Amer. Meteor. Soc.,* **76,** 489–503

Ji, J. J., 1995: A climate–vegetation interaction model: Simulating physical and biological processes at the surface. *J. Biogeochem.,* **22,** 2063–2068.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.,* **77,** 437–471.

Kelly, R. H., W. J. Parton, M. D. Hartman, L. K. Stretch, D. S. Ojima, and D. S. Schimel, 2000: Intra-annual and interannual variability of ecosystem processes in shortgrass steppe. *J. Geophys. Res.,* **105,** 20 093–20 100.

Kittel, T. G. F., and Coauthors, 1996: The VEMAP Phase I database: An integrated input dataset for ecosystem and vegetation modeling for the conterminous United States. [Available online at http://www.cgd.ucar.edu/vemap/.]

Kuo, H. L., 1974: Further studies of the parameterization of the influence of cumulus convection on large-scale flow. *J. Atmos. Sci.,* **31,** 1232–1240.

Lee, T. J., 1992: The impact of vegetation on the atmospheric boundary layer and convective storms. Ph.D. dissertation, Atmospheric Science Paper 509, Department of Atmospheric Science, Colorado State University, 137 pp. [Available from Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.]

Linacre, E. T., 1977: A simple formula for estimating evaporation rates in various climates, using temperature data alone. *Agric. Meteor.,* **18,** 409–424.

Liston, G. E., and R. A. Pielke Sr., 2000: A climate version of the regional atmospheric modeling system. *Theor. Appl. Climatol.,* **66,** 29–47.

——, ——, and E. M. Greene, 1999: Improving first-order snow-related deficiencies in a regional climate model. *J. Geophys. Res.,* **104** (D16), 19 559–19 567.

Louis, J. F., 1979: A parametric model of vertical eddy fluxes in the atmosphere. *Bound.-Layer Meteor.,* **17,** 187–202.

——, M. Tiedtke, and J. F. Geleyn, 1982: A short history of the PBL parameterization at ECMWF. *Proc. 1981 Workshop on PBL Parameterization,* Shinfield Park, Reading, United Kingdom, ECMWF, 59–71.

Lu, L., 1999: Implementation of a two-way interactive atmospheric and ecological model and its application to the central United States. Ph.D. dissertation, Department of Atmospheric Science, Colorado State University, 134 pp. [Available from Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.]

Mahrer, Y., and R. A. Pielke, 1977: A numerical study of the airflow over irregular terrain. *Beitr. Phys. Atmos.,* **50,** 98–113.

——, and R. A. Pielke, 1981: Simulation of the effects of surface fluxes of heat and moisture in a mesoscale numerical model. Part I: Soil layer. *J. Geophys. Res.,* **86,** 9929–9938.

McNider, R. T., and R. A. Pielke, 1981: Diurnal boundary-layer development over sloping terrain. *J. Atmos. Sci.,* **38,** 2198–2212.

Meyers, M. P., 1995: The impact of a two-moment cloud model on the microphysical structure of two precipitation events. Ph.D. dissertation, Atmospheric Science Paper 575, Department of Atmospheric Science, Colorado State University, 165 pp. [Available from Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.]

——, P. J. DeMott, and W. R. Cotton, 1992: New primary ice nucleation parameterizations in an explicit cloud model. *J. Appl. Meteor.,* **31,** 708–721.

Mihailovic, T., 1996: Description of a land-air parameterization scheme (LAPS). *Global Planet. Change,* **13** (1–4), 207–215.

Miller, D. A., and R. A. White, 1998: A conterminous United States multi-layer soil characteristics data set for regional climate and hydrology modeling. *Earth Interactions,* **2.** [Available online at http://EarthInteractions.org].

Neilson, R. P., 1995: A model for predicting continental-scale vegetation distribution and water balance. *Ecol. Appl.,* **5,** 362–385.

Nicholls, M. E., R. A. Pielke, J. L. Eastman, C. A. Finley, W. A. Lyons, C. J. Tremback, R. L. Walko, and W. R. Cotton, 1995: Applications of the RAMS numerical model to dispersion over urban areas. *Wind Climate in Cities,* J. E. Cermak et al., Eds., Kluwer Academic Publishers, 703–732.

Noilhan, J., and S. Planton, 1989: A simple parameterization of land surface processes for meteorological models. *Mon. Wea. Rev.,* **117,** 536–549.

Ojima, D. S., W. J. Paron, D. S. Schimel, J. M. O. Scurlock, and T. G. F. Kittel, 1993: Modeling the effect of climatic and CO_2 changes on grassland storage of soil C. *Water, Air, Soil Pollut.,* **70,** 643–657.

——, D. S. Schimel, W. J. Parton, and C. Owensby, 1994: Short- and long-term effects of fire on N cycling in tallgrass prairie. *Biogeochemistry,* **24,** 67–84.

Parton, W. J., 1996: The CENTURY model. *Evaluation of Soil Organic Matter Models,* D.S. Powlson, P. Smith, and J. U. Smith, Eds., NATO ASI Series, Vol. I3, Springer-Verlag, 283–291.

——, and P. E. Rasmussen, 1994: Long-term effects of crop management in wheat-fallow: II. CENTURY model simulations. *Soil Sci. Soc. Amer. J.,* **58,** 530–536.

——, D. S. Schimel, C. V. Cole, and D. S. Ojima, 1987: Analysis of factors controlling soil organic matter in Great Plains Grassland. *Soil Sci. Soc. Amer. J.,* **51,** 1173–1179.

——, J. W. B. Steward, and C. V. Cole, 1988: Dynamics of C, N, P, and S in grassland soils: A model. *Biogeochemistry,* **5,** 109–131.

——, and Coauthors, 1993: Observations and modeling of biomass and soil organic matter dynamics for the grassland biome worldwide. *Global Biogeochem. Cycles,* **7,** 785–809.

——, D. S. Schimel, D. S. Ojima, and C. V. Cole, 1994a: A general model for soil organic matter dynamics: Sensitivity to litter chemistry, texture and management. *Quantitative Modeling of Soil Forming Processes,* SSSA Special Publication 39, R. B. Bryant and R. W. Arnold, Eds., ASA, CSSA, and SSA, 137–167.

——, J. M. O. Scurlock, D. S. Ojima, and K. Paustian, 1994b: Modelling soil biology and biochemical processes for sustainable africultural research. *Soil Biota: Management in Sustainable Farming Systems,* C.E. Pankhurst et al. Eds., CSIRO, Information Services, 182–193.

——, and Coauthors, 1995: Impact of climate change on grassland production and soil carbon worldwide. *Global Change Biol.,* **1,** 13–22.

——, D. S. Ojima, and D. S. Schimel, 1996: Models to evaluate soil organic matter storage and dynamics. *Structure and Organic Matter Storage in Agricultural Soils.* M. R. Carter, Ed., CRC Press, Inc., 421–448.

——, M. Hartman, D. Ojima, and D. Schimel, 1998: DAYCENT and its land-surface submodel: Description and testing. *Global Planet. Change,* **19,** 35–48.

Penman, H. L., 1948: Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. London,* **193A,** 120–145.

Pielke, R. A., 1974: A three-dimensional numerical model of the sea breezes over south Florida, *Mon. Wea. Rev.,* **102** 115–139.

——, 1998: Climate prediction as an initial value problem. *Bull. Amer. Meteor. Soc.,* **79,** 2743–2746.

——, and Coauthors, 1992: A comprehensive meteorological modeling system-RAMS. *Meteor. Atmos. Phys.,* **49,** 69–91.

——, R. A. Avissar, M. Raupach, H. Dolman, X. Zeng, and S. Denning, 1998: Interactions between the atmospheric and terrestrial ecosystems: Influence on weather and climate. *Global Change Biol.,* **4,** 101–115.

Pitman, A. J., 1991: A simple parameterization of sub-grid scale open water for climate models. *Climate Dyn.,* **6,** 99–112.

Rhea, J. O., 1978: Orographic precipitation model for hydrometeorological use. Ph.D. dissertation, Atmospheric Science Paper 287, Department of Atmospheric Science, Colorado State University, 199 pp. [Available from Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.]

Sellers, P. J., Y. Mints, R. C. Sud, and A. Delcher, 1986: A simple biosphere model (SiB) for use within general circulation models. *J. Atmos. Sci.,* **43,** 505–531.

Stevens, W. R., 1998: *Unix Network Programming.* Vol. 1. Prentice Hall, 1009 pp.

Thompson, G., 1993: Prototype real-time mesoscale predication during 1991–92 winter season and statistical verification of model data. M.S. thesis, Department of Atmospheric Science, Colorado State University, 105 pp. [Available from Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.]

Tremback, C. J., 1990: Numerical simulation of a mesoscale convective complex: Model development and numerical results. Ph.D. dissertation, Atmospheric Science Paper 465, Department of Atmospheric Science, Colorado State University, 247 pp. [Available from Dept. of Atmospheric Science, Colorado State University, Fort Collins, CO 80523.]

——, and R. Kessler, 1985: A surface temperature and moisture parameterization for use in mesoscale numerical models. Preprints, *Seventh Conf. on Numerical Weather Prediction,* Montreal, PQ, Canada, Amer. Meteor. Soc., 355–358.

——, G. J. Tripoli, and W. R. Cotton, 1985: A regional scale atmospheric numerical model including explicit moist physics and a hydrostatic time-split scheme. Preprints, *Seventh Conf. on Numerical Weather Prediction,* Montreal, PQ, Canada, Amer. Meteor. Soc., 433–434.

Tripoli, G. J., and W. R. Cotton, 1980: A numerical investigation of several factors contributing to the observed variable intensity of deep convection over South Florida. *J. Appl. Meteor.,* **19,** 1037–1063.

——, and ——, 1982: The Colorado State University three-dimensional cloud/mesoscale model—1982. Part I: General theoretical framework and sensitivity experiments. *J. Rech. Atmos.,* **16,** 185–220.

——, and ——, 1986: An intense, quasi-steady thunderstorm over mountainous terrain. Part IV: Three-dimensional numerical simulation. *J. Atmos. Sci.,* **43,** 896–914.

Tsvetsinskaya, E., 1999: Investigating the effect of seasonal plant growth and development in 3-dimensional atmospheric simulations. Ph.D. dissertation, University of Nebraska, 147 pp. [Available from University of Nebraska at Lincoln, Lincoln, NE 68588.]

VEMAP Members, 1995: Vegetation/Ecosystem Modeling and Analysis Project: Comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO_2 doubling. *Global Biogeochem. Cycles,* **9,** 407–437.

Walko, R. L., W. R. Cotton, M. P. Meyers, and J. Y. Harrington, 1995a: New RAMS cloud microphysics parameterization. Part I: The single-moment scheme. *Atmos. Res.,* **38,** 29–62.

——, C. J. Tremback, R. A. Pielke, and W. R. Cotton, 1995b: An interactive nesting algorithm for stretched grids and variable nesting ratios. *J. Appl. Meteor.,* **34,** 994–999.

——, and Coauthors, 2000: Coupled atmosphere–biophysics–hydrology models for environmental modeling. *J. Appl. Meteor.,* **39,** 931–944.

Xue, Y., P. J. Sellers, J. L. Kinter, and J. Shukla, 1991: A simplified biosphere model for global climate studies. *J. Climate,* **4,** 345–364.