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Seasonal weather prediction as an initial value problem

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Abstract. Using a climate version of a regional atmospheric model, we show that the seasonal evolution of weather is dependent on the initial soil moisture and landscape specification. Coupling this model to a land-surface model, the soil moisture distribution and landscape are shown to cause a significant nonlinear interaction between vegetation growth and precipitation. These results demonstrate that seasonal weather prediction is an initial value problem. Moreover, on seasonal and longer timescales the surface characteristics such as soil moisture, leaf area index, and landcover type must be treated as dynamically evolving dependent variables, instead of prescribed parameters.

1. Introduction

Traditional definitions of weather and climate often distinguish these terms in the context of prediction: weather is considered an initial value problem, while climate is assumed to be a boundary value problem (see *Bryson* [1997], who discusses this topic). Another more recent perspective holds that climate and weather predictions are both initial value problems [*Palmer*, 1999; *Pielke*, 1998]. If climate prediction were a boundary value problem, then the simulations of future weather on that timescale will "forget" the initial values assumed in a model. This is an important distinction. If the "boundary" is actually a dynamic evolving interface with the atmosphere, the surface parameters become dependent variables which must be predicted along with the atmospheric dependent variables such as wind, temperature, and so forth. This paper explores the issue as to whether seasonal weather prediction is an initial value problem or not.

In the context of seasonal weather prediction the boundaries are the ocean surface and the land surface. If these boundaries are fixed in time, evolve independently of the atmosphere such that their time evolution could be prescribed, or had response times that were much longer than the time period of interest in the seasonal weather prediction, then one could conclude that seasonal forecasting prediction is a boundary problem.

Lorenz [1979] proposed the concept of forced and free variations of weather and climate. He refers to forced variations as those caused by external conditions, such as changes in solar irradiance. Volcanic aerosols also cause forced variations. *Lorenz* [1979, p. 1367] refers to free variations as those which "are generally assumed to take place independently of any changes in external conditions." Day-to-day weather variations are presented as an example of free variations. *Lorenz* [1979, p. 1368] also suggests that "free climatic variations in which the underlying surface plays an essential role may therefore be physically possible." We explore this latter theme in this paper.

If the land surface changes over the same time period as the atmospheric changes in a seasonal weather forecasting model, then the nonlinear feedbacks (i.e., two-way fluxes) between the air and land eliminate an interpretation of the land-atmosphere interface as a boundary. Rather than boundaries, this interface becomes interactive [*Pielke et al.*, 1998, and references therein; *Neilson and Drapek*, 1998]. The two-way fluxes that occur between the atmosphere and the land surface must therefore necessarily be considered as part of the predictive system. On the timescale of what we typically call short-term weather prediction (days), important feedbacks include biophysical (e.g., vegetation controls on the Bowen ratio), snow cover, clouds (e.g., in their effect on the surface energy budget), and precipitation (e.g., which changes the soil moisture) processes. This timescale is already considered an initial value problem [*Sivillo et al.*, 1997]. Seasonal weather prediction, however, includes the biogeochemical (e.g., vegetation growth and senescence) feedbacks as discussed in section 3. In the context of *Lorenz*'s [1979] terminology, each of these feedbacks is a free variation.

Recent work [*Claussen*, 1994, 1998; *Claussen et al.*, 1999; *Foley*, 1994; *Texier et al.*, 1997; *Delworth and Manabe*, 1989] has shown that the initial specification of the land surface exerts a strong control on the subsequent atmospheric circulation in global climate prediction models. *Cubasch et al.* [1994] suggest in a greenhouse gas warming experiment with a coupled ocean-atmosphere model that the time evolution of modeled global mean warming is "strongly dependent on the initial state of the climate system."

An important practical conclusion results if seasonal and longer-term weather prediction is an initial value problem. This means that there are necessarily limits on the time into the future which we can predict if the feedbacks between the atmosphere and land surface are sufficiently nonlinear.

This paper specifically investigates the role of the initial soil moisture and vegetation state in forecasting the weather over the following season. There have been very important studies on this issue already. *Liu and Avissar* [1999a, b] have used a general circulation model (GCM) to determine the time period before which the initial soil moisture condition becomes unimportant. They concluded that this memory lasts of the order of 200–300 days. *Eltahir* [1998] and *Zheng and Eltahir*

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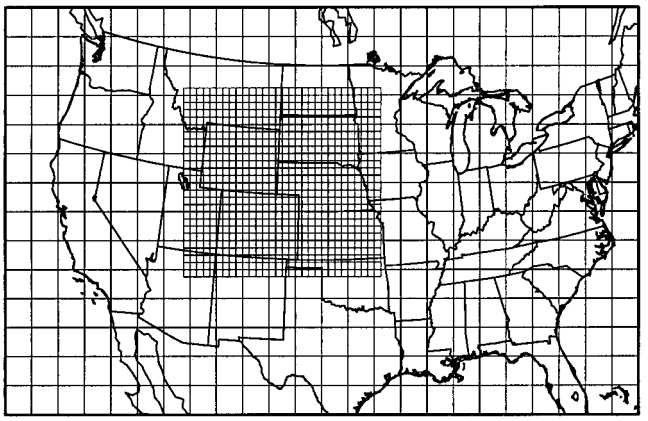

Figure 1. RAMS domain and grid configuration. Coarse and fine grid intervals are 200 km and 50 m, respectively.

[1998] have explored the role of soil moisture in precipitation processes and demonstrated the crucial importance of radiative and dynamical feedbacks in regulating rainfall anomalies that result from soil moisture anomalies. *Zheng and Eltahir* [1997] have also concluded that in certain regions of the world, landscape type plays a crucial role in precipitation processes. They concluded that deforestation along the southern coast of west Africa could result in a complete collapse of the monsoon circulation in this region, with an associated significant decrease in rainfall. *Xue* [1997] has similarly found that a degradation of the land surface in tropical north Africa has a significant impact on the weather in this region. *Xue* [1996] also concluded that desertification of the Inner Mongolian grassland has had the effect of warming and drying the area. In the Indian subcontinent, *Laval et al*. [1996] have shown that if transpiration from vegetation is not included, their GCM model does not accurately simulate the interannual precipitation variation.

These effects are superimposed on other seasonal and longer-term weather prediction influences such as El Niño. *Shabbar et al*. [1997] illustrate the major difference of winter weather patterns in the Great Plains and elsewhere, when the warm anomaly sea surface temperatures (SSTs) of an El Niño are replaced by cold SSTs. *Chase et al*. [1996] found that landscape changes in the tropics, which have a major influence on the patterning and intensity of deep cumulus convection, actually have an equivalent or even greater impact on Great Plains winter weather than the SST anomalies. *Polcher* [1995] explored how different tropical landscape changes can influence deep tropical convection, while *Polcher and Laval* [1994] concluded that tropical deforestation weather effects are largely independent of El Niño influences in this region.

That soil moisture conditions and landscape changes influence weather and climate should not be surprising. *Lewis* [1998] has shown, for instance, that deforestation in western Canadian locations has caused an average ground surface temperature increase of ~1°C, as a result of an ~10% reduction in transpiration from the originally forested area. *Desborough* [1997] demonstrated the significant effect of roots on weather. He found that varying the near-surface (upper 10 cm) root fraction between 10% and 90% produces transpiration differences of up to 80 W m^{-2}. He found that the entire seasonal cycle of transpiration was sensitive to the near-surface root fraction, which will necessarily influence sensible heat surface fluxes as well.

Over the central United States, there have been several studies which have explored the importance of landscape on seasonal weather patterns. *Xue et al*. [1996], for instance, concluded that land-surface effects on atmospheric variables in the summer are pronounced and persistent, although largely limited to the area of "anomalous land-surface forcing." *Copeland et al*. [1996] demonstrated, for a specific July, that temperature and precipitation patterns have been significantly altered as a result of changing much of the vegetative landscape in this region from its natural state to agriculture. *Giorgi et al*. [1996], however, concluded that local effects associated with surface evaporation played only a minor role in model simulations of the 1988 drought and 1993 flood conditions over the central United States.

On a smaller scale, *Pielke et al*. [1997] illustrated how land conversion in the Oklahoma-Texas Panhandle region, from its natural shortgrass prairie condition to cropland, can provide sufficient energy input to cumulus clouds to produce tornadic thunderstorms. In that modeling study, only shallow cumulus clouds are simulated with the natural landscape despite identical meteorological initial and lateral boundary conditions. Using idealized experiments, *Emori* [1998] showed how the interaction between cumulus convection and soil moisture variations work to maintain a heterogeneous soil moisture distribution. *Pielke et al*. [1998] also show how soil moisture variations can feedback to cumulus cloud responses.

In this paper, examples of model simulations over the central Great Plains and Rocky Mountain region are presented to explore the issue of seasonal weather prediction as an initial value problem. This area coincides with much of the Global Energy and Water Cycle Experiment (GEWEX) Continental-Scale International Project (GCIP) Mississippi Basin study area. Section 2 examines the sensitivity of a seasonal simulation in which soil moisture is perturbed from a control simulation at the beginning of the calendar year and at a particular time during the growing season. Section 3 illustrates the feedbacks which occur when vegetation is permitted to grow (or go senescent) in response to the precipitation and temperature variations resulting from perturbations in the initial soil moisture content.

2. Effect of Soil Moisture Perturbations on Seasonal Weather

2.1. Model Description

A climate version of the Regional Atmospheric Modeling System (ClimRAMS (G. E. Liston and R. A. Pielke, A climate version of the Regional Atmospheric Modeling System, submitted to *Journal of Climate*, 1999) was used in this study to examine the effect of soil moisture initialization on monthly and annual regional weather simulations over the model domain shown in Figure 1. RAMS was developed at Colorado State University primarily to facilitate research into mesoscale and regional, cloud and land-surface atmospheric phenomena and interactions [*Nicholls et al*., 1995; Pielke, 1974; *Pielke et al*., 1992; *Tripoli and Cotton*, 1982; *Tremback et al*., 1985; *Walko et al*., 1995a]. The model is fully three-dimensional and nonhydrostatic [*Tripoli and Cotton*, 1980]; includes telescoping, interactive nested grid capabilities [*Clark and Farley*, 1984; *Walko et al*., 1995b]; supports various turbulence closures [*Deardorff*,

1989; *McNider and Pielke*, 1981; *Tripoli and Cotton*, 1986], shortwave and longwave radiation [*Chen and Cotton*, 1983, 1987; *Harrington*, 1997; *Mahrer and Pielke*, 1977], initialization [Tremback, 1990], and boundary condition schemes [see *Pielke et al*., 1992]; includes a land-surface energy balance submodel which accounts for vegetation, open water, and snow-related surface fluxes [*Avissar and Mahrer*, 1988; *Lee*, 1992; *Mahrer and Pielke*, 1977; *McCumber and Pielke*, 1981; *Tremback and Kessler*, 1985; Liston and Pielke submitted manuscript, 1999]; and includes explicit cloud microphysical submodels describing liquid and ice processes related to clouds and precipitation [*Meyers*, 1995; *Meyers et al*., 1992; *Walko et al*., 1995a].

The climate version of RAMS 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 both short and long timescales, several modifications to the base modeling system were made. These included (1) daily updating of sea surface temperatures and vegetation parameters; (2) the addition of a collection of routines which simulates grid-scale snow accumulation, snow melt, and their effects on surface hydrology and surface energy exchanges; (3) the implementation of a moisture-physics scheme [*Cotton et al*., 1995] suitable for long model runs; (4) saving of sufficient variables to perform complete surface energy and moisture balances over a wide range of timescales (hourly to yearly); and (5) saving data on an hourly, 6-hourly, or daily basis, depending on the model-output variable.

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 Hrnberger* [1978]. The soil thermal properties are temporarily evolving and soil moisture dependent. The moisture condition at the deepest soil level is held constant at the initial value. Heterogeneous soil types were applied to the domain based on the soil data sets of *Miller and White* [1998]. The model has 10 soil layers with the bottom of each layer 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, respectively.

For the vegetated surface, a "big leaf" approach is used where there is a layer of vegetation overlying a shaded soil. Soil moisture is removed by transpiration by defining a vertical root profile [*Dickinson et al*., 1986] and extracting the water mass depending on the root fraction in each soil layer.

2.2. Experimental Design and Results

The goal of this investigation is to examine the sensitivities of basic atmospheric variables, such as maximum temperature, minimum temperature, and precipitation to the initial values of soil moisture. We also seek to examine the length of the model's memory with respect to the soil moisture initialization. The model domain and grid configuration given in Figure 1 show 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.

The model is driven by 6-hourly lateral boundary conditions defined using the National Centers for Environmental Prediction (NCEP) atmospheric analyses for the time period January 1, 1989, through December 31, 1989. The time step of the integration is 2 min. The model's ability to simulate domain-averaged maximum and minimum temperature and precipitation are shown in Figure 2. The skill of ClimRAMS is discussed further in section 3.1. An important consequence of using the NCEP data for the lateral boundary conditions for all of the experiments is that our results will provide a minimum effect of dynamic landscape properties on seasonal weather prediction.

Two groups of experiments were conducted in this study. The first group includes comparison of five, month-long integrations starting with soil moisture perturbations imposed on July 1, 1989, and ending on July 31, 1989. As a spin-up for the model's variables to reach reasonable states before the sensitivity tests started, the controlled run was first integrated from January 1 to June 30, 1989.

Using June 30 data as the initial condition, a control and four sensitivity runs were constructed by varying the soil moisture to 25% drier and wetter and 50% drier and wetter relative to the control run. Figure 3 compares the time series of domain-averaged soil moisture at layer one, which is 5 cm in depth. The same information is shown in Figure 4 but for layer five, which is 45 cm from the surface and 15 cm thick. Both Figures 3 and 4 show that the differences in soil moisture persist throughout the length of the integration.

Domain-averaged surface temperature differences also persist through most of the simulation period as seen in Figures 5 and 6 but decrease with time in much the same way as soil moisture. Figure 7 shows rather complex, nonlinear feedbacks between precipitation and soil wetness. The rainfall intensities vary due to the differences in initial soil moisture. The month-long simulation results suggest that initial soil moisture anomalies may persist for >1 month. Such differences can impact monthly and seasonal predictions through alterations in the surface moisture balance.

The second group of experiments are five, year-long simulations. All the integrations started on January 1, 1989, and continued through December 31, 1989. Again, soil moisture was perturbed to 25% drier and wetter and 50% drier and wetter, respectively, at the beginning of the calendar year from a control simulation. Other initial conditions are identical for the five integrations.

The annual evolution of domain-averaged soil moisture for the top soil layer is shown in Figure 8. The differences in soil moisture persist for $\sim$5 months before they began to converge in summer. However, the differences began to diverge again in late August, and this trend lasted through the end of the year. In contrast to the surface layer the differences in soil moisture initialization for the layer five, which is 0.45 m below the surface, persist throughout the year, as seen in Figure 9. This indicates the inherent long-period memory of initial conditions of the model with regard to the deep soil layers as soil moisture differences in the deeper soil layers began to propagate upward when the atmospheric forcings, such as precipitation and evaporation, became weaker at that time of the year.

Figures 10, 11, and 12 display the differences of domain-averaged maximum temperature, minimum temperature, and precipitation between the perturbed runs and the control run. The daily values have been smoothed to a 7-day average in order to filter the high-frequency variability and show the long-term tendency. While the maximum temperature differences vanish by the end of the year, the differences in minimum temperature decrease from January to September and then increase in October due to the long-term memory of the deep soil layers initial soil moisture conditions. The domain-averaged precipitation appears to be affected by initial soil

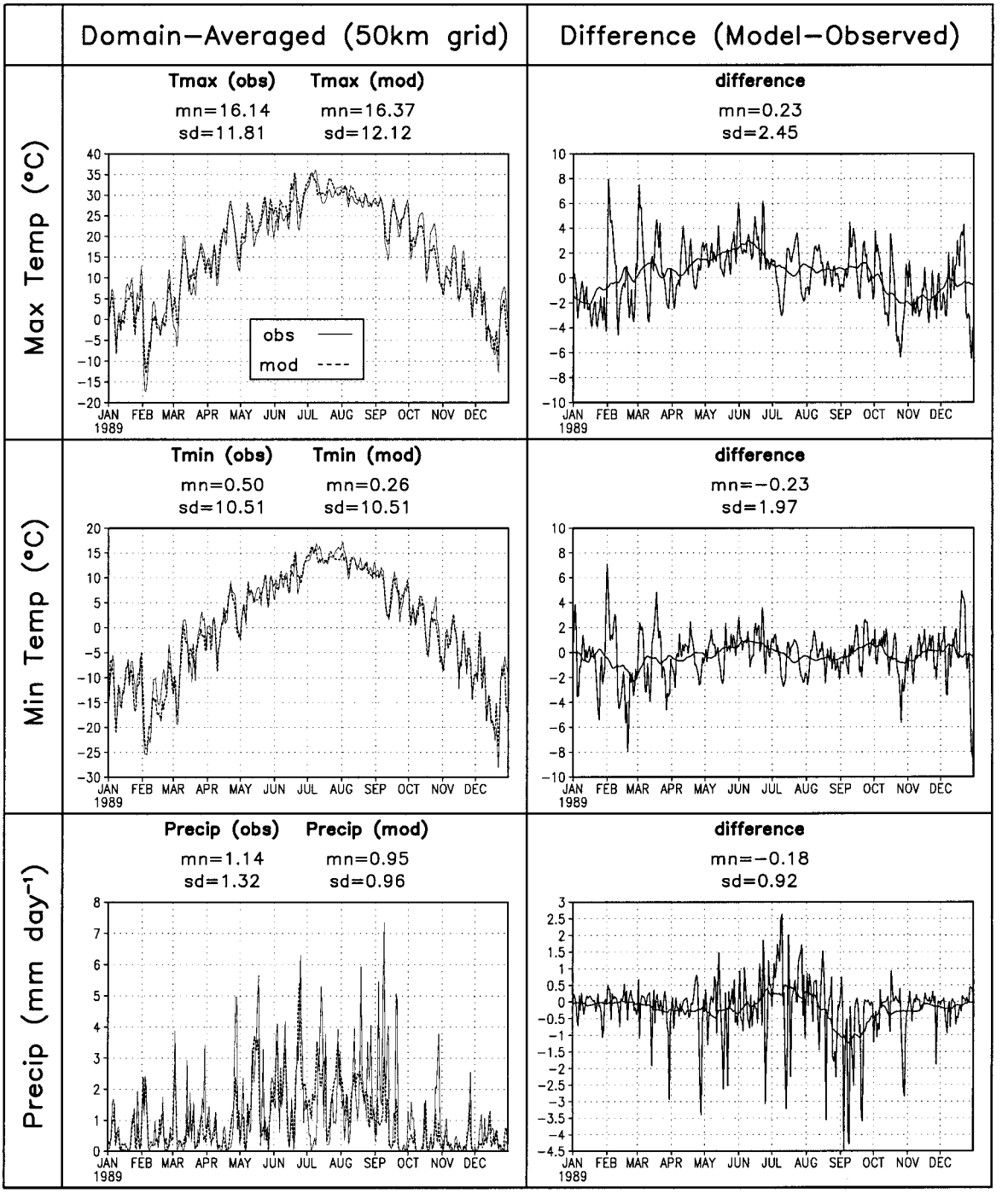

Figure 2. Modeled and observed, domain-averaged daily maximum and minimum screen-height air temperature and daily precipitation, where these variables have been averaged over the 50-km grid in Figure 1. Also shown is the difference between the model and observation and the 30-day running mean of the difference values. Included are the mean (mn) and standard deviation (sd) for each panel and variable.

moisture until the cases converge at the end of integration, indicating >10 months of memory.

The year-long simulation results reveal a strong sensitivity of this regional climate model with respect to initial soil moisture. In other words, the initial specification of the soil moisture exerts a strong control on the subsequent atmospheric circulation in regional climate simulation models, which can last as long as 12 months. Although there is a tendency for the soil moisture perturbations to adjust toward each other, the differences persist for more than one season and even longer for the deep soil layers.

3. Effect of Regional Vegetation Change and Soil Moisture on Seasonal Weather

In this portion of the study a plant-scale photosynthesis model is coupled with ClimRAMS to aid in ascertaining the effects of landscape change on predicted meteorological fields.

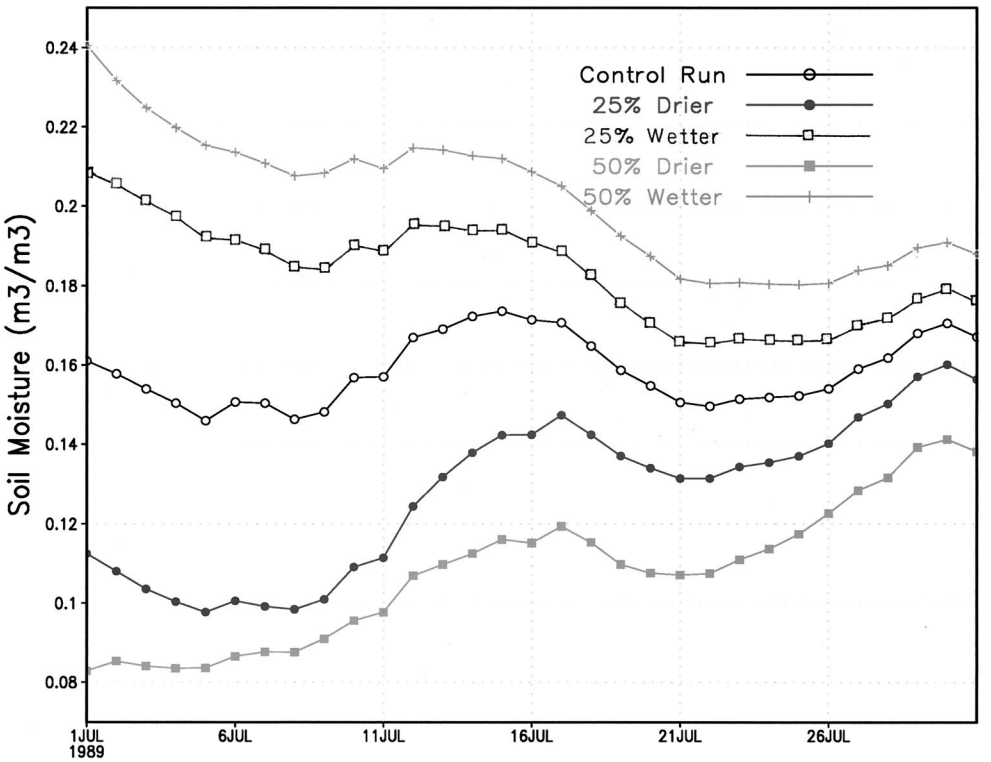

Figure 3. The domain-averaged soil moisture at layer one which is 0.05 m below the surface. The model integration period is from July 1 to 31, 1989.

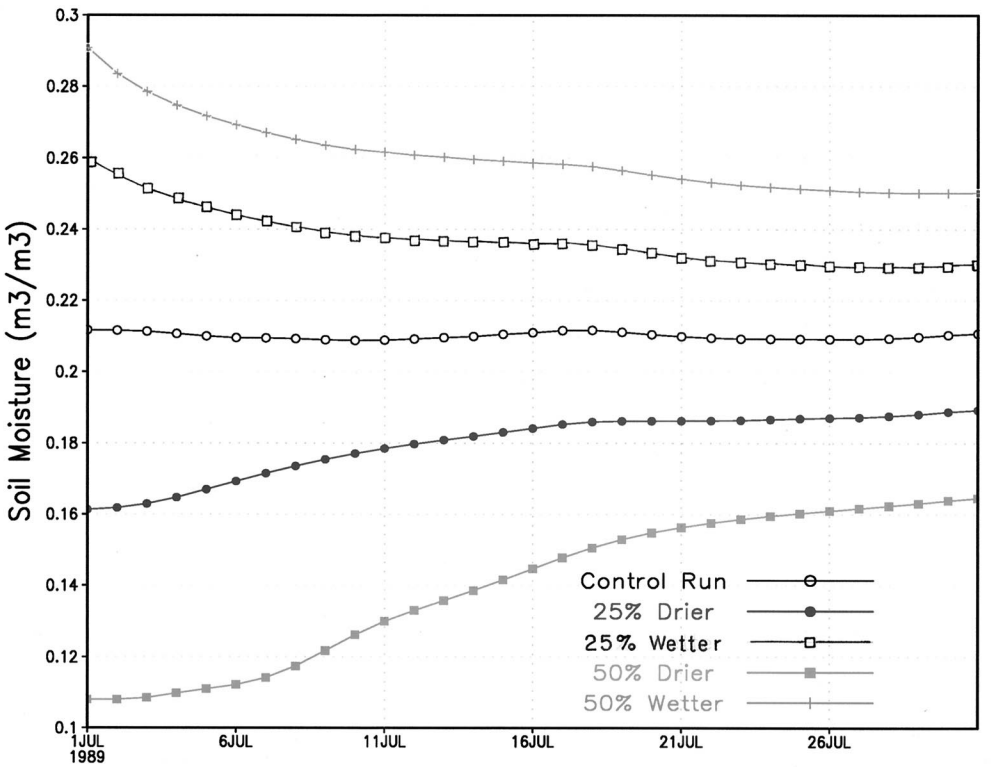

Figure 4. The domain-averaged soil moisture at layer five, which is 0.45 m below the surface. The model integration period is from July 1 to 31, 1989.

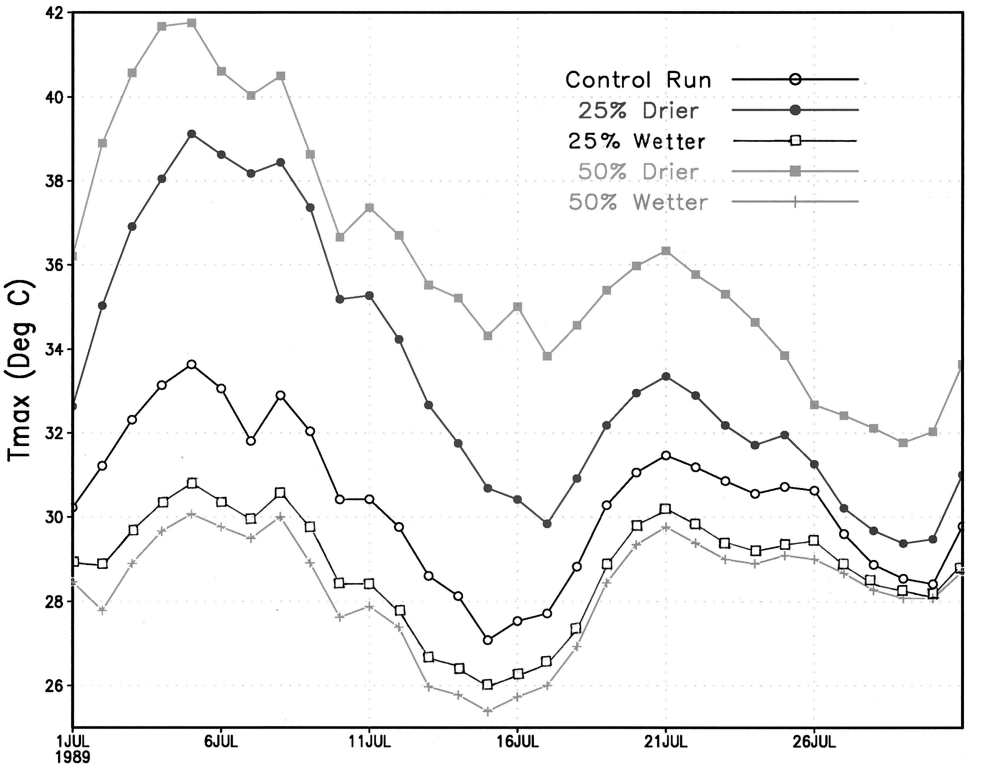

Figure 5. The domain-averaged daily maximum temperature from July 1 to 31, 1989.

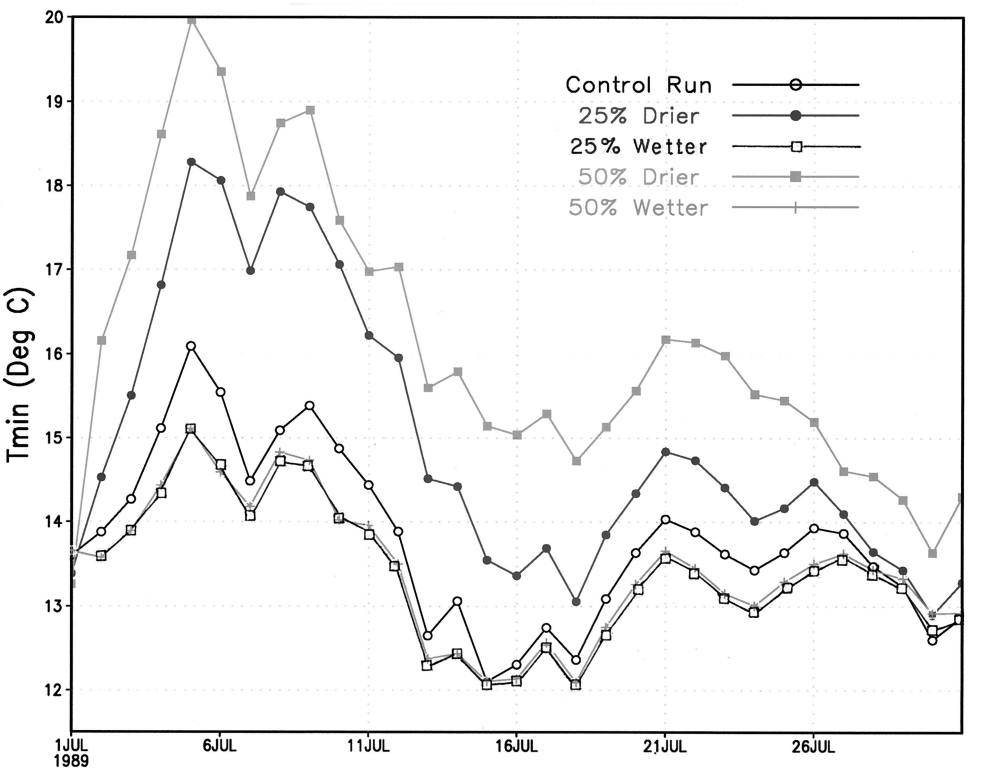

Figure 6. The domain-averaged daily minimum temperature from July 1 to 31, 1989.

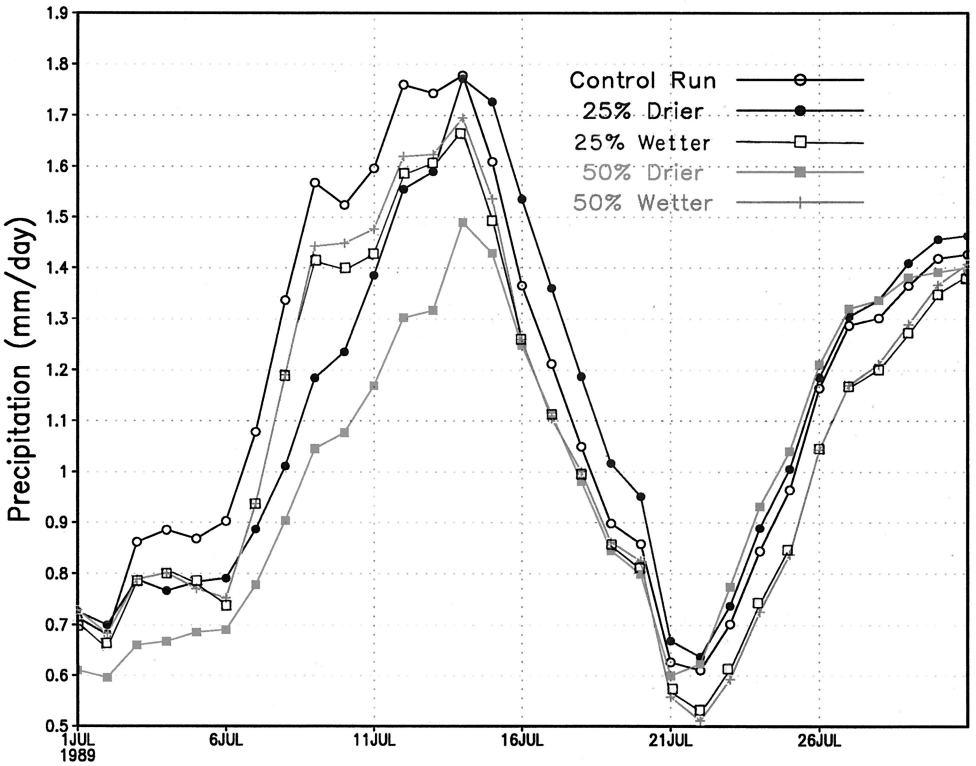

Figure 7. The domain-averaged daily precipitation from July 1 to 31, 1989.

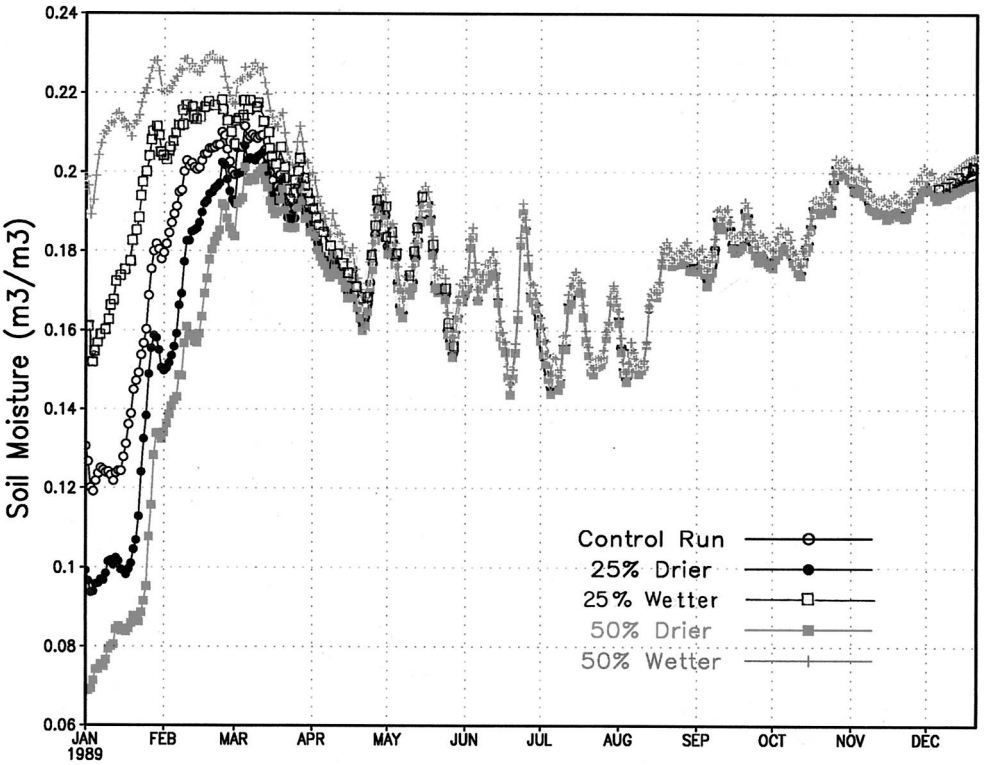

Figure 8. The domain-averaged soil moisture at layer one which is 0.05 m below the surface. The model integration period is from January 1 to December 31, 1989.

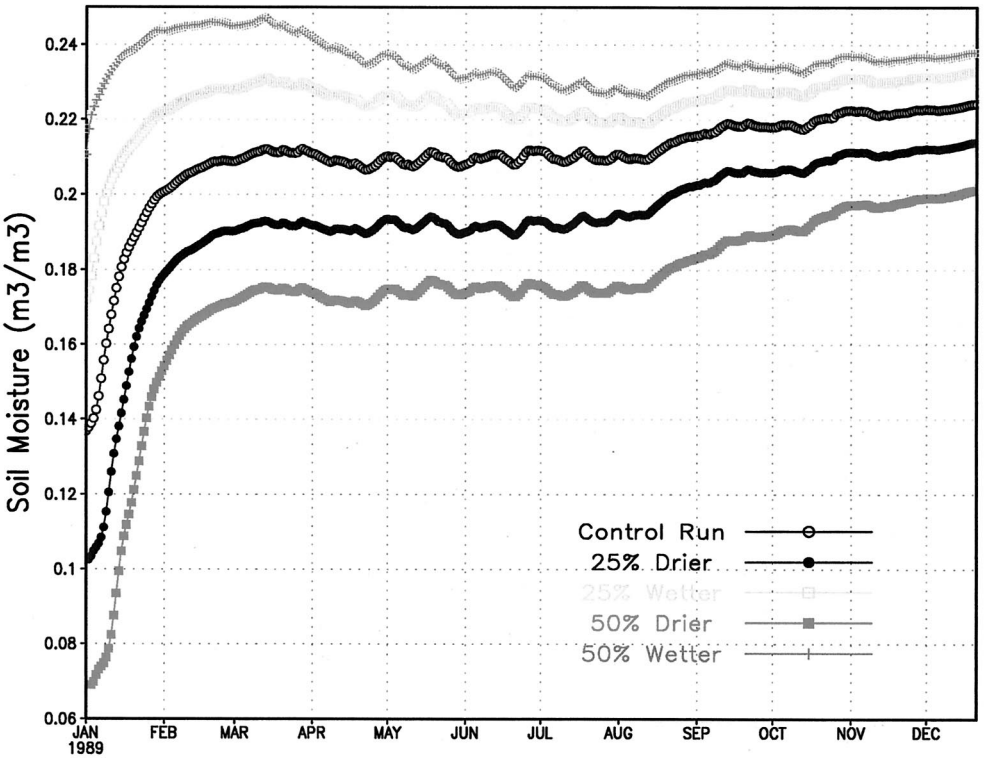

Figure 9. The domain-averaged soil moisture at layer five, which is 0.45 m below the surface. The model integration period is from January 1 to December 31, 1989.

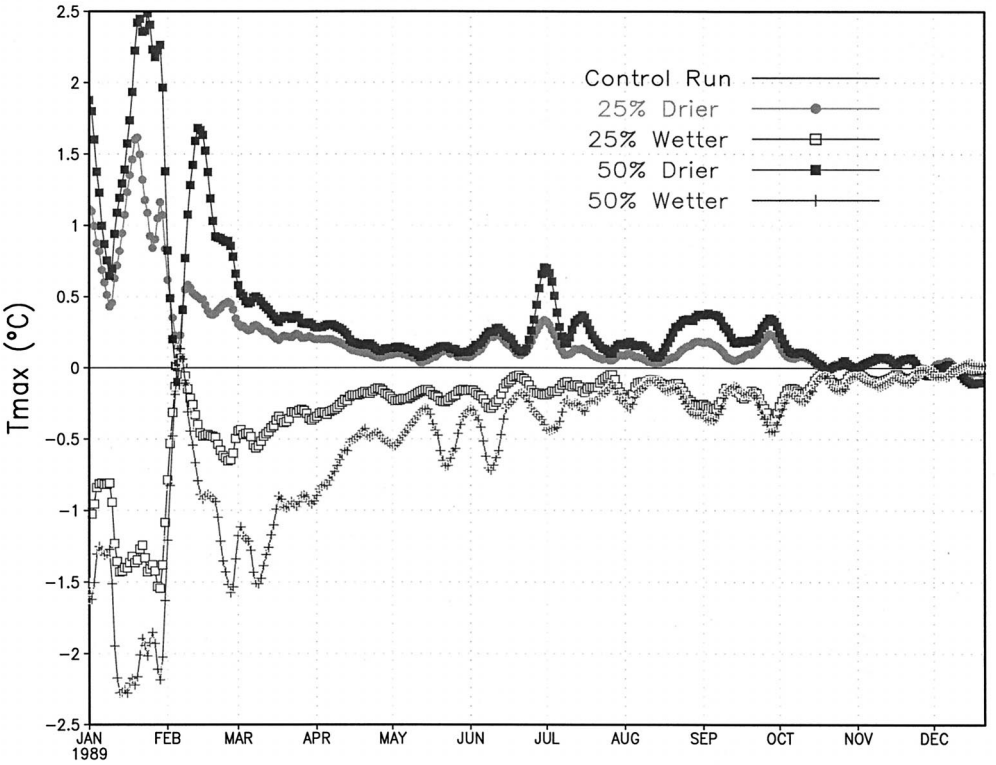

Figure 10. The domain-averaged daily maximum temperature from January 1 to December 31, 1989.

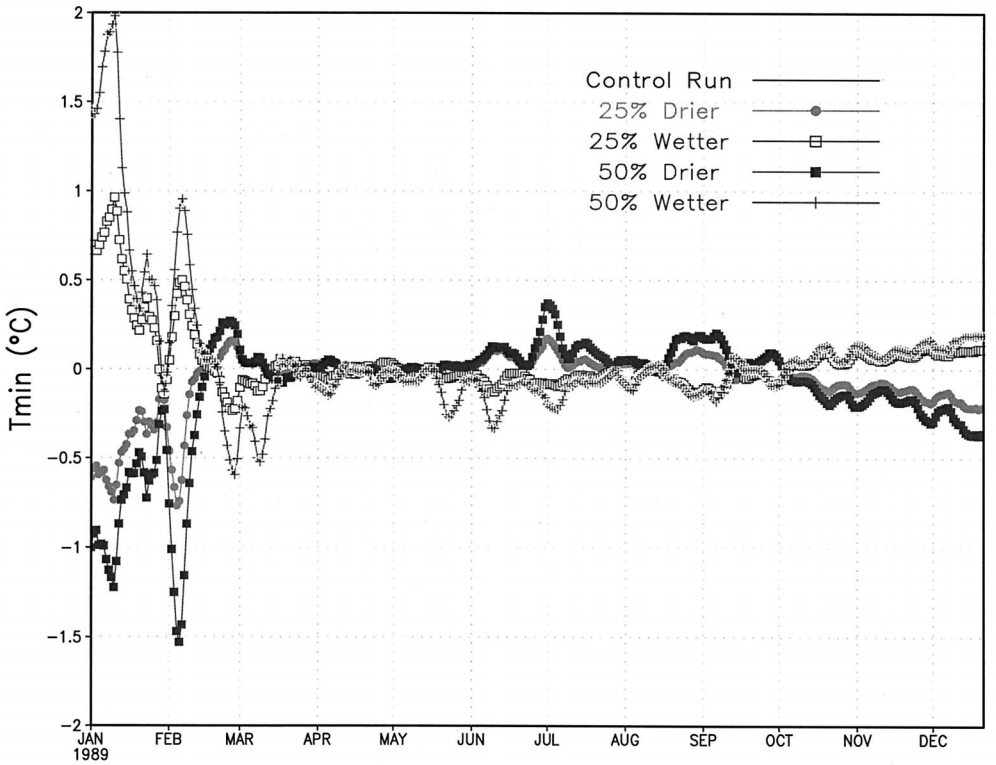

Figure 11. The domain-averaged daily minimum temperature from January 1 to December 31, 1989.

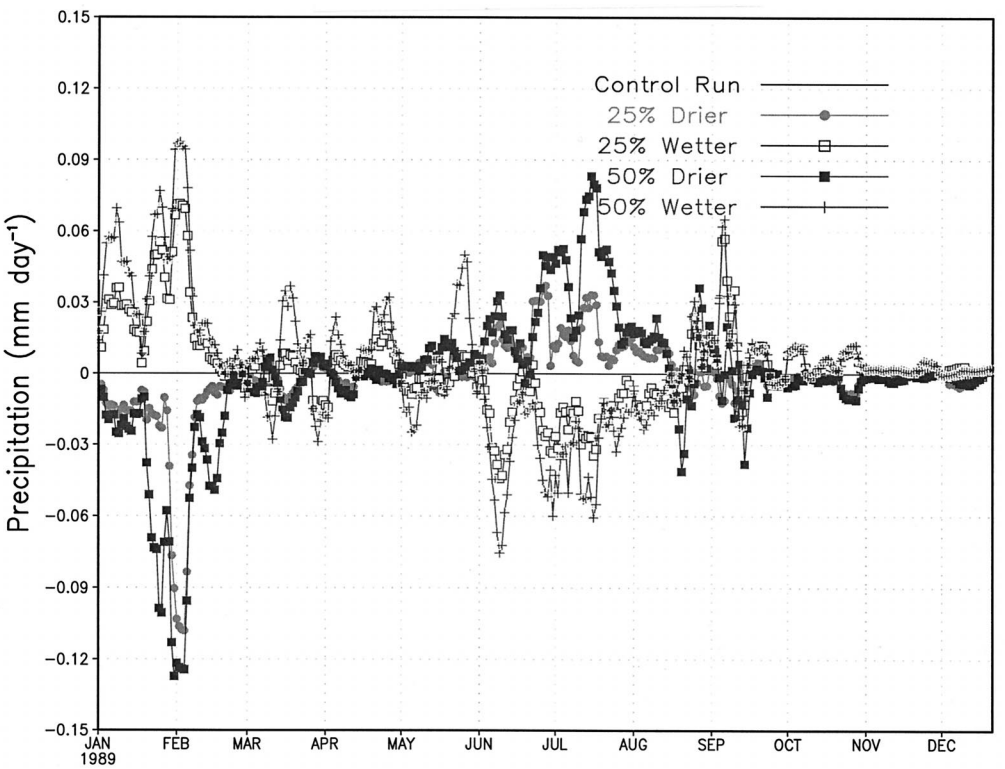

Figure 12. The domain-averaged daily precipitation from January 1 to December 31, 1989.

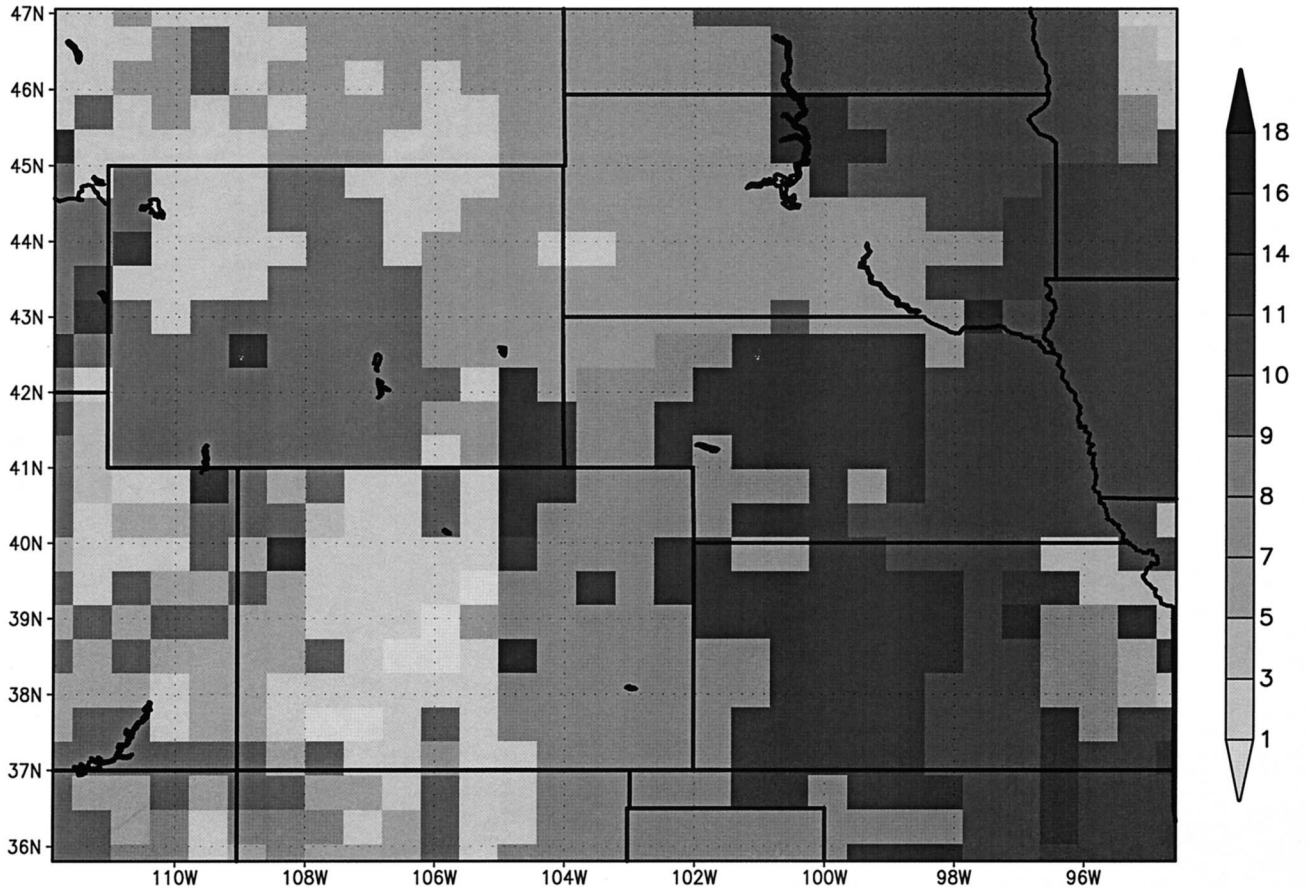

Figure 13a. Distribution of current vegetation over the VEMAP small grid. The numbers correspond to 1, tundra; 2, subalpine; 3, temperate conifer; 4, temperate deciduous; 5, temperate xeromorphic; 6, temperate coniferous xeromorphic; 7, savanna/deciduous; 8, C3 grassland; 9, C4 grassland; 10, temperate arid shrub; 11, spring wheat small grains; 12, small grains; 13, winter wheat; 14, corn belt; 15, irrigated crop; 16, deciduous forest/crop/corn; 17, subtropical mixed forest; 18, grassland/grain/wheat.

The modeling system is integrated for a single growing season using current and potential vegetation as defined by *Kittel et al.* [1995]. The fields are then averaged temporally and spatially in order to quantify the effects of changing the landscape. It will be demonstrated that temperatures increase when the potential vegetation for this region is replaced by the current vegetation. On finer scales some areas exhibit cooling, while most show varying degrees of warming. In addition, spatial and temporal shifts in precipitation are evident. The influence of soil type and thermodynamic state also appears to play a key role in the evolution of the plant morphology and possibly the subsequent feedback to the prognosed meteorology. We will first briefly describe the modeling system, and then we will present the results.

3.1. Model Description

The same meteorological model described in section 2.1 (ClimRAMS) is also employed in this portion of the study, and the model simulations cover the same domain as that discussed in section 2 (Figure 1). In addition, improved plant and root submodels, derived from the General Energy and Momentum Transfer Model [*Chen and Coughenour*, 1994], were added. This was done to provide more realistic forcing at the surface interface, as well as provide a more accurate representation of below ground processes. The model also has dynamic control over the stoma [*Ball et al.*, 1987], which in turn exerts control on transpiration rates, thus affecting the surface water and heat budgets. The basic features of the plant model are as follows: (1) calculation of C3 [*Farquhar et al.*, 1980] and C4 [*Chen et al.*, 1994] photosynthesis, (2) biomass allocation, respiration, death rate, and growth rate algorithms based on temperature and moisture relations, (3) spatially explicit root model with resistances for water effluence and uptake, as well as branching and lengthening algorithms dependent on temperature, and root- and soil-water status [*Chen and Lieth*, 1992, 1993], (4) nine-layer canopy radiation model for prediction of diffuse and direct radiation at each level in the canopy and subsequent impact on layer photosynthesis rates [*Chen*, 1983], (5) variable initialization of biomass characteristics employing advanced very high resolution radiometer/normalized difference vegetation index (AVHRR/NDVI) 8 km data, and (6) unlimited species-specific initialization. A unique aspect of this modeling system is that both atmosphere and vegetation are considered dynamic dependent variables. Leaf area index (LAI), for example, is a predicted value.

3.2. Experimental Design

In this study a total of four integrations were performed. For simulations using the current and potential vegetation distributions, two different initial soil moisture values were as-

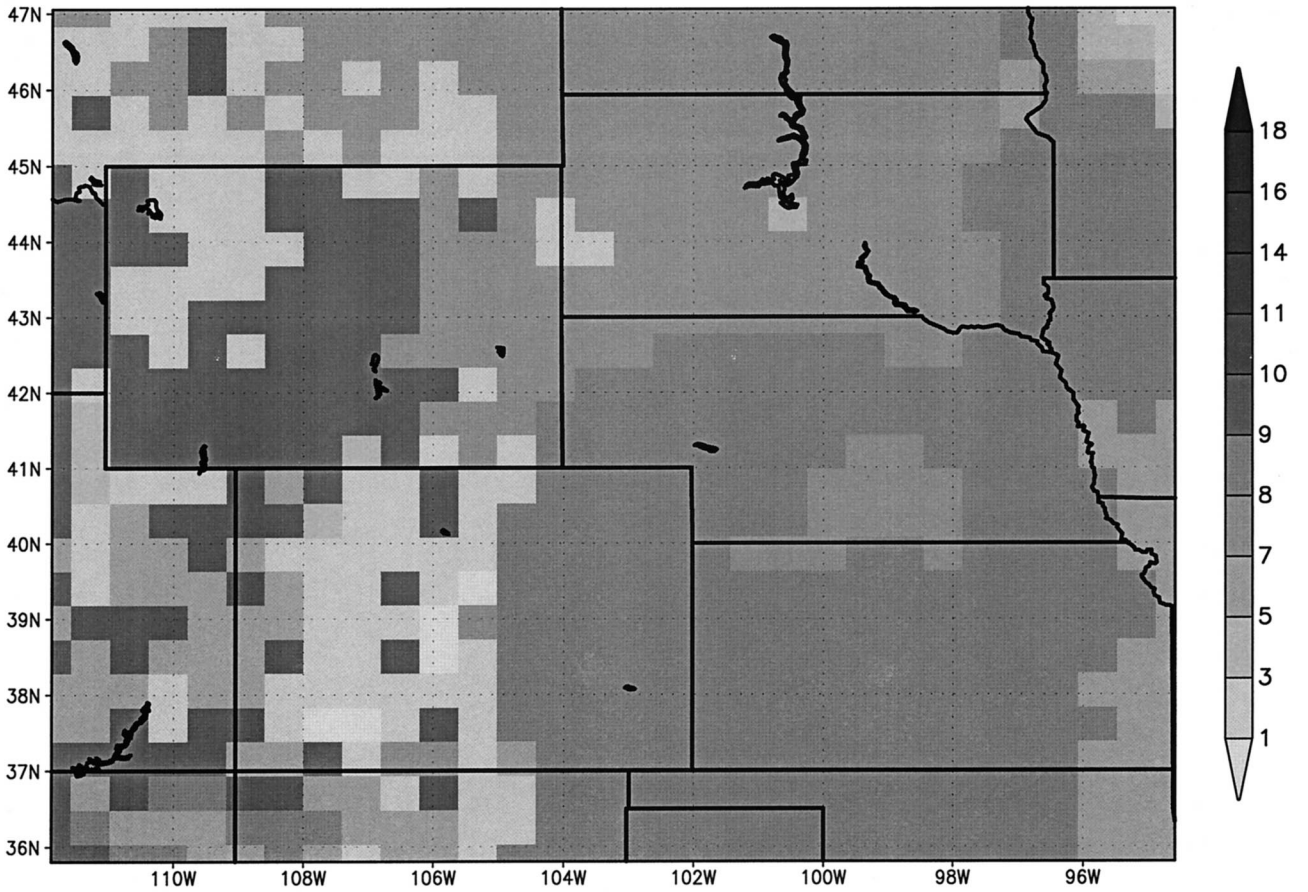

Figure 13b. Same as Figure 13a, except for potential vegetation.

signed. The actual amount of soil water change is dependent on the specific soil textural class but represented about a 25% change for the two soil moisture values used. The simulation using natural vegetation and the wetter soil moisture value represents the control run in this experiment. A total of four simulations were performed in order to separate contributions due to underlying vegetation, initial soil moisture, and the interaction between the two. The separation technique is outlined by *Stein and Alpert* [1993].

3.3. Model Initialization

The meteorological model was initialized with the NCEP global 2.5 × 2.5 global reanalysis data set. These objectively analyzed data were used to variably initialize the entire domain and corresponded to 0000 UT on April 1, 1989. The boundary conditions were then produced at 12-hour intervals using objectively-analyzed NCEP data through 1200 UT on July 31, 1989. The soil textural classes were directly input from the State Soil Geographic Database (STATSGO) soils data set. Since the model was started in early spring, the soil moisture was homogeneously initialized to −0.25 MPa for the wet simulations, a value representative of saturated soil conditions encountered in early spring. For the dry simulations, values of −0.75 MPa were used, which is a modest soil moisture decrease.

The vegetation classes used in this model were mapped from an existing data set for potential vegetation classes [*Küchler*, 1975] and current vegetation [*Kittel et al.*, 1995; T. G. F. Kittel and D. Ojima, personal communcation, 1998]. Figure 13 shows the domain and vegetation classifications (current and potential) used in this investigation. Figure 13 demonstrates the large areal impact of humans on the vegetative patterns. Large tracts of tall and short grasslands have been removed and replaced with agricultural regions. Most of the change occurred in the eastern half of this domain, while the western portion exhibits little alteration in terms of vegetation distribution. The time of year will influence the initial values of the vegetation variables (e.g., LAI). We chose to start the integration at the beginning of the growing season.

3.4. Model Validation

A comparison of the current vegetation run with observational data for this set of experiments was performed. This validation test needs to be performed even though a similar evaluation was presented in section 2.2, since this is a different version of the RAMS–land surface coupled modeling system. This is shown for the maximum daily temperature and total precipitation. The model calculations were checked against an objectively analyzed surface data set. The realism of the model run with the current vegetation provides confidence in the interpretations that we make from the sensitivity experiments which follow in this Section.

Figure 14 represents the modeled and observed domain-averaged maximum daily temperature, with the model in open circles and observations in shaded circles. The model appears to do a good job of representing the observed temporal variability and trend of this temperature. There is no systematic bias in the model simulation.

In Figure 15 the model domain-averaged precipitation is

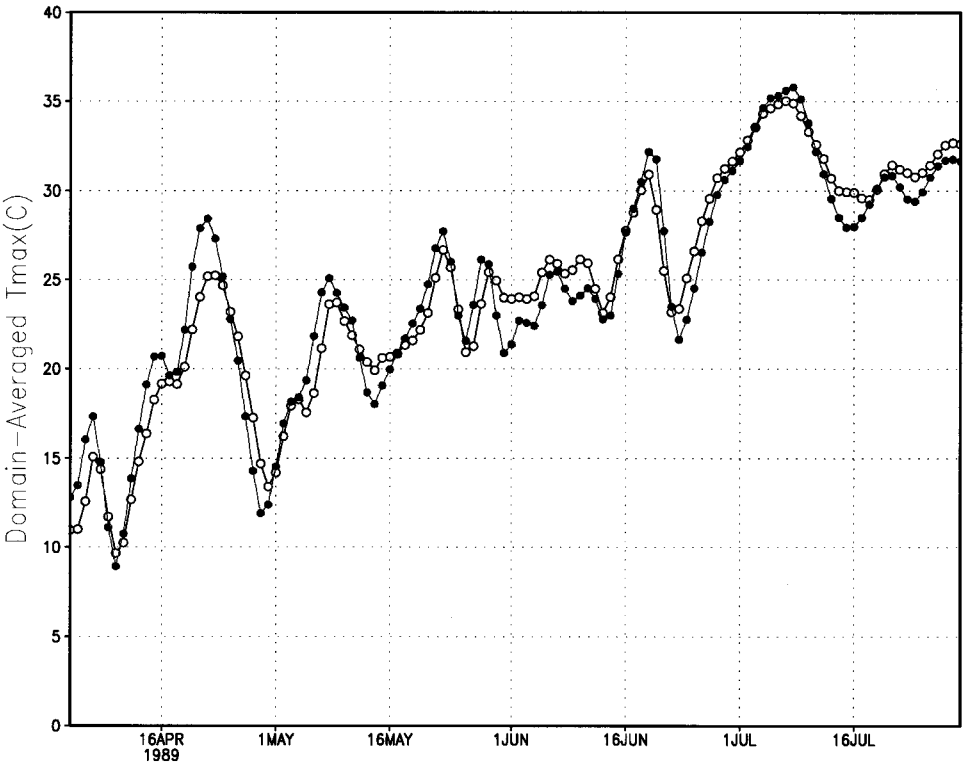

Figure 14. Modeled and observed domain-averaged maximum daily temperature. Model is shown with open circles, and observations are shown with shaded circles.

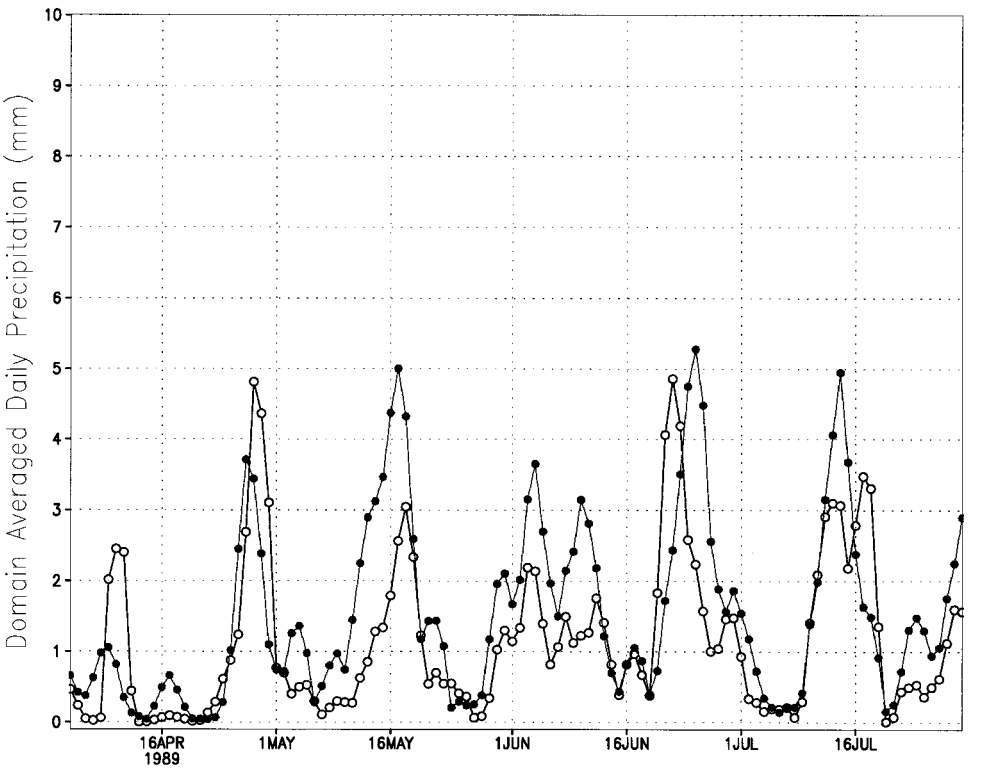

Figure 15. Same as Figure 14 but for precipitation.

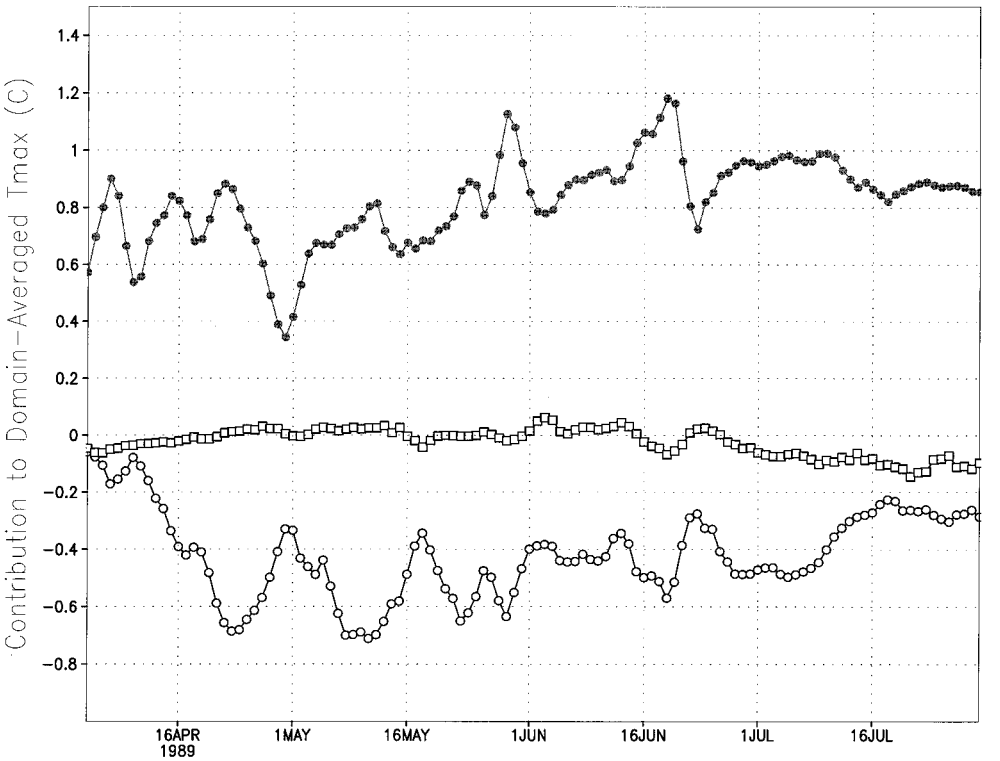

Figure 16. Contribution to the maximum daily temperature averaged over the domain due to natural vegetation (open circles); reduced initial soil moisture (shaded circles); and the interaction of current vegetation and reduced initial soil moisture (squares). A positive value means that the contribution was an increase from the control.

compared. Figure 15 shows that the model is realistically representing most of the precipitation events, although the model generally somewhat underpredicts the amount. This is not surprising given the relatively coarse horizontal resolution of the model which requires that precipitation processes be represented by the relatively simplistic Kuo and dump bucket schemes. The skill of predicting precipitation, however, is about the same as obtained in other research and operational forecast models using this spatial resolution [*Takle et al.*, this issue].

3.5. Simulation Results and Discussion

The model fields were separated using the technique developed by *Stein and Alpert* [1993]. Following their nomenclature, we assign the control run to the current vegetation with wetter initial soil conditions. We can then extract the contribution to a given variable by forming difference fields. The fields from the simulation with natural vegetation and wet initial soil moisture, when the control run is subtracted off give the contribution due to natural vegetation alone. A similar difference between the current vegetation simulation with drier initial soil gives the contribution to a given field due to drier initial soil moisture. The fourth simulation, with natural vegetation and drier initial soil enables the determination of the contribution due to the interaction of the drier initial soil and natural vegetation.

Figure 16 displays the effect on maximum temperature due to natural vegetation and drier soils and their interaction. The effect of decreased soil moisture produces a domain-averaged increase in maximum daily temperature of nearly 0.8°C. The effect due to natural vegetation indicates a domain-averaged decrease in maximum daily temperatures. Spatial maps averaged over the 120-day period (not shown) indicate a general decrease in temperature over the eastern half of the domain with natural vegetation, which is where most of the land cover change has occurred. The effect of decreased soil moisture is seen as a domain-wide increase in maximum daily temperature. The change over the C3 grassland was found in spatial maps averaged over the 120-day period (not shown) to be most pronounced. This is likely due to a greater water use efficiency in C4 grasses that is not realized by the C3 shortgrass. The effect due to the interaction between vegetation change and decreased initial soil moisture is small when averaged over the domain, although local increases and decreases of less than half a degree occurred due to this effect.

The effects on the precipitation due to a change to natural vegetation and drier soils and their interaction are shown in Figure 17. The outer three grid points of the inner model domain are excluded from the analysis. Vegetation change had it largest effect where significant precipitation occurred in the model, as would be expected. The effect of decreased soil moisture produced a decrease in precipitation over the same areas. The drier initial soil moisture resulted in the largest changes, with the first 2 months of the season exhibiting lower precipitation, followed by enhanced precipitation later in the growing season. This could be due to enhanced wind convergence due to higher convective temperatures later in the season, which is also consistent with the higher maximum daily temperature with drier soils. The combined effects due to the interaction of soil moisture and vegetation change were small. The changes in the soil water potential (SWP), in MPa, averaged over the depth of the soil column due to the change to

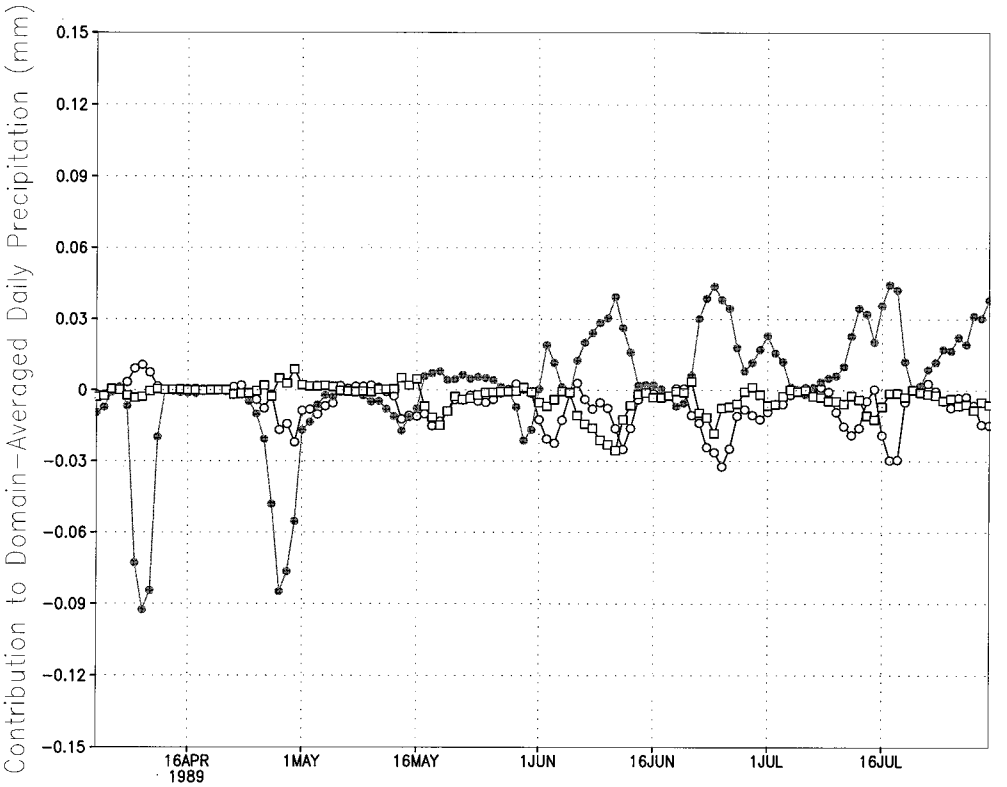

Figure 17. Same as Figure 16 except for daily-averaged precipitation.

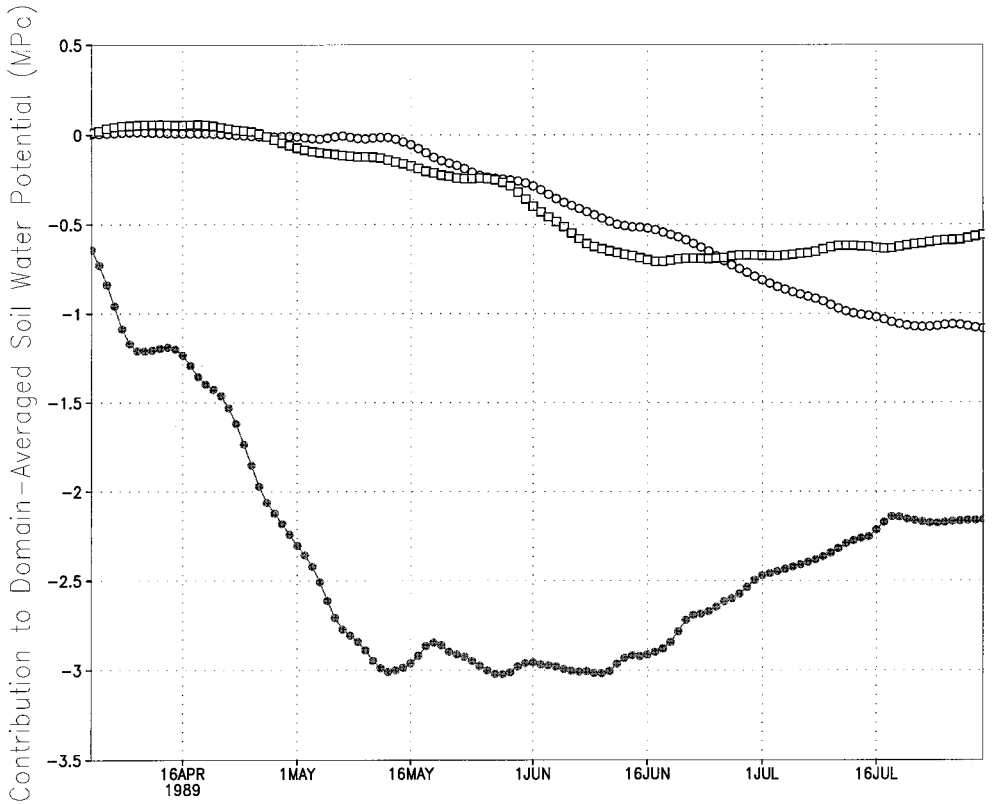

Figure 18. Same as Figure 16 except for soil water potential averaged through the root profile.

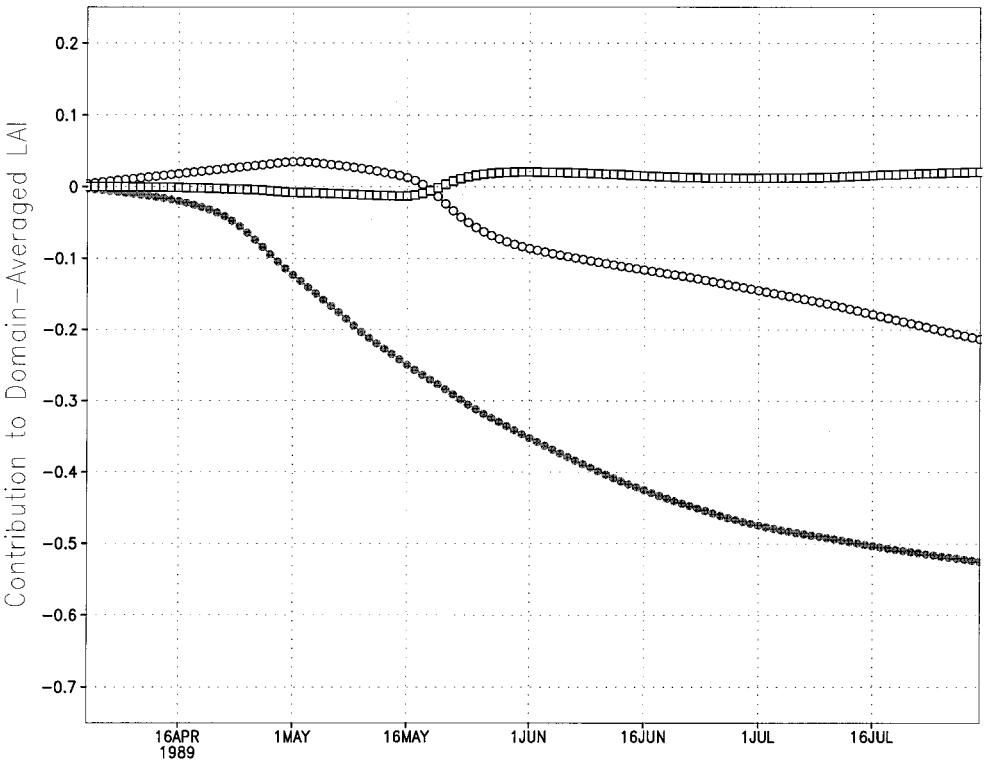

Figure 19. Same as Figure 16 except for leaf area index.

natural vegetation and drier soils, and their interactions are shown in Figure 18. The largest change was due to drier soil moisture.

Finally, we can examine the biomass and its response to the soil moisture and vegetation change factors. This is represented by leaf area index (LAI) in Figure 19. The control simulation had values of LAI from 0.5 to 3 over the Great Plains, with large LAIs in the mountains, indicative of evergreen, needled, woody vegetation. The change of vegetation from a current to natural state reveals a nearly domain-wide decrease in LAI later in the growing season. The decrease in initial soil moisture produced a substantial decrease in LAI. When we examine the interaction between the two factors, the effect, which is spatially varying, is relatively small when averaged over the domain. This is not surprising since different plant species have a variety of nonlinear, nonmonotonic responses to water resource availability.

It is evident from the discussed figures that initial conditions can have large impacts on simulations, even after long integrations. These results also indicate that changing land use patterns can alter large-scale atmospheric fields. In addition, it appears that the hydrological cycle has been changed, but in a nonlinear manner. For example, a complicated spatial pattern in precipitation fields was produced. Finally, the biomass characteristics over this domain indicated a similar complex pattern in response to different amounts of soil moisture and vegetation type. For longer integrations this could prove to be very important, since the memory of the root system can span several growing seasons.

4. Conclusions

Using a climate version of a regional atmospheric model, we show that the seasonal evolution of weather is dependent on the initial soil moisture and landscape specification. Coupling this model to a land-surface model, the soil moisture distribution and landscape are shown to cause a significant nonlinear interaction between vegetation growth and precipitation. These results demonstrate that seasonal weather prediction is an initial value problem. Moreover, on seasonal and longer timescales the surface characteristics such as soil moisture, leaf area index, and land cover type, must be treated as dynamically evolving dependent variables, instead of prescribed parameters.

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