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Abstract
Regional climate simulations driven by three sets of initial and lateral boundary conditions—analyzed observations, GCM control climate, and GCM enhanced greenhouse-gas scenario climate—are used to assess model accuracy in predicting soil moisture and to examine changes in soil moisture in the scenario climate. Simulated soil moisture does not show noticeable drift during the 10-year simulations. Observed and simulated soil moisture for Illinois and Iowa correspond reasonably well for the top 10 cm soil layer but a consistent low bias is present in the top 1 m. Growing season depletion of soil water is simulated well but recharge after growing season is slower than observed, at least in part due to underprediction of precipitation in autumn. This suggests that improvements in simulating soil moisture depend greatly on improvements in simulating precipitation. The climate change scenario produces drier soil in the top 10 cm during winter but wetter top soil in warm seasons because of greater precipitation, while top l m soil is wetter in all seasons.

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Soil moisture in a regional climate model: simulation and projection

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Abstract. Regional climate simulations driven by three sets of initial and lateral boundary conditions - analyzed observations, GCM control climate, and GCM enhanced greenhouse-gas scenario climate - are used to assess model accuracy in predicting soil moisture and to examine changes in soil moisture in the scenario climate. Simulated soil moisture does not show noticeable drift during the 10-year simulations. Observed and simulated soil moisture for Illinois and Iowa correspond reasonably well for the top 10 cm soil layer but a consistent low bias is present in the top 1 m. Growing season depletion of soil water is simulated well but recharge after growing season is slower than observed, at least in part due to underprediction of precipitation in autumn. This suggests that improvements in simulating soil moisture depend greatly on improvements in simulating precipitation. The climate change scenario produces drier soil in the top 10 cm during winter but wetter top soil in warm seasons because of greater precipitation, while top 1 m soil is wetter in all seasons.

Introduction

Soil moisture has a long memory in forcing atmospheric processes over land, and in some sense plays a role similar to that of sea surface temperature over oceans [*Entin et al.*, 1999]. In the short term, soil wetness controls partitioning between sensible and latent heat flux at the earth's surface, affecting planetary boundary-layer characteristics as well as initiation and maintenance of convection. In the long term, soil water content modulates droughts and floods. For example, the 1993 Midwest Great Flood can be attributed in part to wet soil in the winter of 1992 and spring of 1993.

For several reasons soil moisture is one of the least known variables in climate simulation. Soil moisture is not routinely observed on scales larger than catchments; moreover, soil moisture is highly heterogeneous in space because of variability in soil type, landscape and precipitation [*Entin et al.*, 2000]. This variability severely reduces the representativeness of soil moisture measurement and complicates its parameterization in numerical models. A few studies have used limited soil moisture observations in the U.S. to validate GCMs [*Chen and Mitchell*, 1999; *Robock et al.*, 1998; *Srinivasan et al.*, 2000]. Other model validation studies have been carried out for Russia and to a lesser extent China, where more soil moisture measurements are available [*Entin et al.*, 2000; *Robock et al.*, 2000].

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The present study has two objectives: (i) to evaluate regional climate model performance in simulating soil moisture by comparing model results to long-term observations, and (ii) to describe an example of possible changes in soil moisture by comparing regional climate model simulations driven by GCM output for control and future climate scenarios.

Observed data

Observations collected by the Illinois Climate Network are to our knowledge the only soil moisture data for the U.S. that cover a whole state and span most of the period (1979-1988) of our regional model simulations. Biweekly or monthly soil water content was measured throughout the year for 19 grassland stations, using neutron probes. The observations are for 11 layers to a depth of 2 m with the uppermost and lowest layers being 10 cm thick while intermediate layers are 20 cm thick. Further details of this data set are given by *Hollinger and Isard* [1994] and *Robock et al.* [2000]. Some comparisons are also made with an Iowa data set taken near (41.2°N, 95.6°W) for 6 sites constituting essentially a single location in terms of model resolution. The Iowa data were measured at 7.5 cm and at increasing intervals downward to 240 cm, with weekly temporal resolution from 1972 onward, and were only taken in the warm season (April through November). Monthly observed precipitation was evaluated using 0.5° latitude-longitude gridded data compiled by the Vegetation and Ecosystem Modeling and Analysis Project [VEMAP; *Kittel et al.*, 1995].

Simulation and model configuration

This study used the regional climate model RegCM2, which was developed at NCAR based on the Penn State/NCAR MM4 [*Giorgi et al.*, 1993a,b]. RegCM2 incorporates the CCM2 radiation package and the BATS version 1e [*Dickinson et al.*, 1993] surface package. The model domain covers most of the continental U.S. using 101×75 grid points with a horizontal spacing of 52 km, centered at (37.5°N, 100°W). The simulations use 14 layers in the vertical with the lowest layer about 40 m above the surface.

RegCM2 was used to perform three 10-year simulations with differing data sources for initial and lateral boundary conditions. The data sources were (i) analyzed observations for 1979-1988 from the NCEP/NCAR reanalysis [*Kalnay et al.*, 1996]; (ii) a 10-year segment of a control climate simulation from HadCM2, the second-generation Hadley Centre coupled ocean-atmosphere GCM [*Johns et al.*, 1997]; and (iii) a 10-year segment of a HadCM2 transient enhanced greenhouse-gas scenario simulation, nominally for the years 2040-2049. (The HadCM2 output is the same as that used

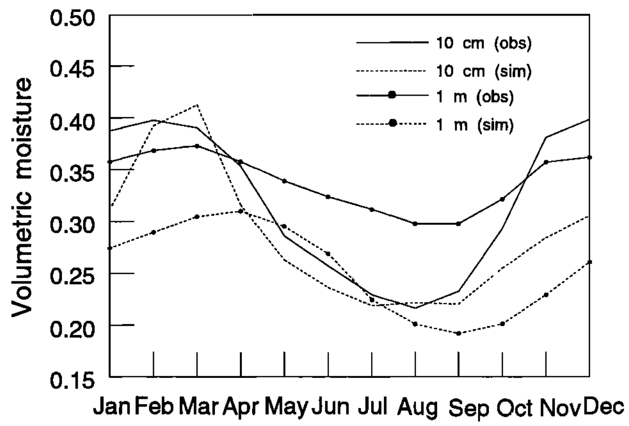

Figure 1. Annual composite of observed and simulated monthly volumetric soil moisture (volume H_2O / volume soil) for 1981-88 averaged over 19 observing sites in Illinois. Solid curves, observations; dotted curves, results of a RegCM2 simulation using initial and boundary conditions from the NCEP/NCAR reanalysis. Heavy dots denote the top 1 m soil layer; otherwise curves are for the top 10 cm soil layer.

in *Arritt et al.* [2000], to which the reader is referred for details.) Simulation (i) overlaps the Illinois observations for 8 years (1981-88). Thus RegCM2 results for 1979-80 are not evaluated here, providing a two-year model "spinup" period so that the influence of initial soil moisture is reduced. Simulation of soil moisture is evaluated through comparison of results from (i) with observations, while inferences of possible changes to soil moisture in the enhanced greenhouse-gas climate are obtained by comparing (iii) with (ii).

Initial and boundary conditions for RegCM2 were interpolated from the NCEP/NCAR reanalysis with a horizontal node spacing of about 1.875° and 28 vertical levels, and from HadCM2 data on the native model grid with spacing of 2.5° latitude by 3.75° longitude and 19 levels. Boundary conditions were updated every 6 hours with temporal interpolation to the model time step. RegCM2 prognostic variables were nudged to the reanalysis or HadCM2 output in a 16 grid point buffer zone near the lateral boundaries.

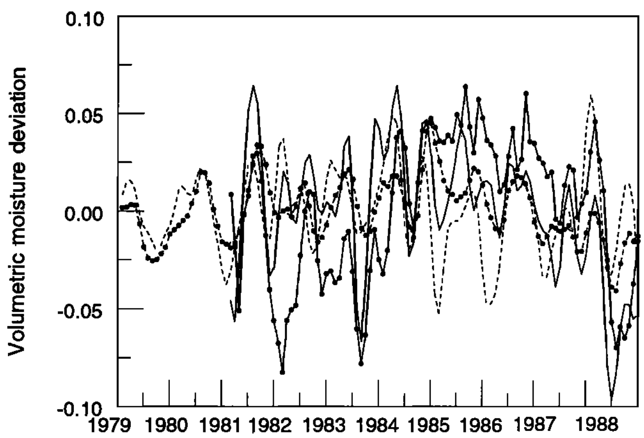

Figure 2. Time series of observed and simulated monthly volumetric soil moisture anomaly, expressed as deviations of monthly values from the respective composite annual cycle. Ticks mark the start of each calendar year. Meaning of the curves is the same as in Figure 1.

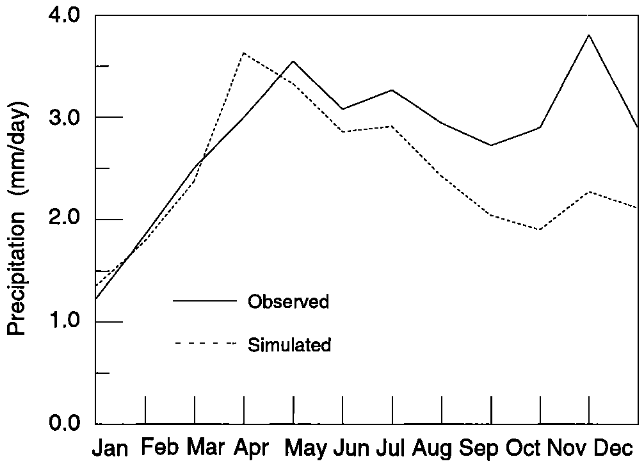

Figure 3. Annual composite of monthly precipitation for Illinois, averaged over 1981-88: solid curve, observed; dotted, simulated.

The land surface scheme in RegCM2 has 18 categories of land use and 12 soil types. The soil model in RegCM2 consists three overlapping soil layers: top layer (10 cm), root layer (top 1-2 m depending on vegetation type), and total layer (top 10 m). Soil moisture is computed using the water budget equation

$$\frac{\partial W}{\partial t} = P + S_m - E - R + \gamma \tag{1}$$

where W is volumetric soil water content, P is precipitation, S_m is snow melt, E is evapotranspiration, R is runoff, and γ is water transfer between soil layers. Because the soil layers overlap, Equation (1) applies to each layer but with different γ for individual layers.

Comparison of simulated soil moisture to observations

Considering the strong spatial heterogeneity of soil moisture [*Entin et al.*, 2000; *Vinnikov et al.*, 1999], only spatial averages of all stations are presented here. Annual composites of monthly observed top 10 cm soil moisture for Illinois during 1981-88 show a well-defined annual cycle with high values in early Spring and low values late in the growing season (Figure 1). Simulated volumetric soil moisture content, W, has a strong peak in spring implying that winter accumulation (which includes snowmelt) is well simulated. Growing season depletion of W also is well simulated. The early part of the recharge period (September—December) is not simulated well. This suggests that input (precipitation) is too small, output (evapotranspiration) is too large, or both. Another possibility is that runoff, including ground water drainage, is overpredicted.

Observed W for the top 1 m varies similarly to the top 10 cm but with a weaker amplitude. Simulated W in the top 1 m soil has a systematic low bias, with largest errors in late summer through early winter. In Iowa, observed W is about 0.30 (near field capacity) in April and decreases to 0.23 in August, increasing to 0.30 again by November (not shown). Modeled W captures the summer depletion although the model has a one-month lag. In terms of spatial variations, modeled W in the top 1 m has its largest dry bias in southern

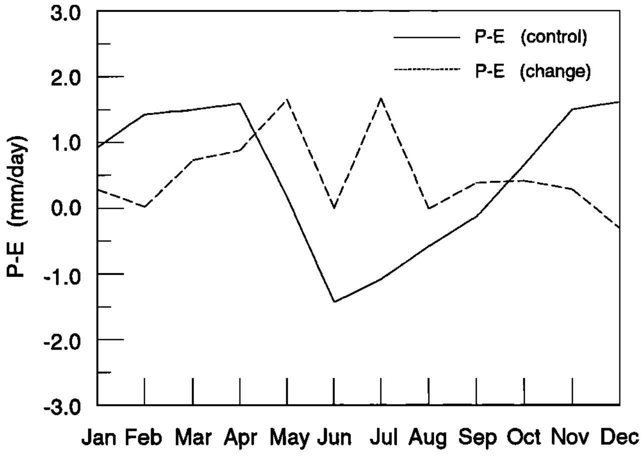

Figure 4. Annual composite of difference between precipitation and evaporation ($P - E$) for Illinois: solid curve, results of a RegCM2 simulation using initial and boundary conditions from NCEP/NCAR reanalysis; dashed, difference between RegCM2 simulations using initial and boundary conditions from HadCM2 enhanced greenhouse-gas scenario climate versus HadCM2 control climate.

Illinois (not shown). This corresponds with a low bias for model precipitation that becomes more severe toward the southern part of the domain.

Simulated W tends to capture dry and wet years but with lower interannual variability than observed (Figure 2). There is no apparent tendency for long-term drift in the simulations. Correlation coefficients between observed and simulated monthly soil moisture anomalies are 0.44 for the top 10 cm and 0.46 for the top 1 m. This contrasts with results for AMIP GCM simulations reported by *Robock et al.* [1998] who found that none of the models could capture interannual variability of soil moisture. Initialization of W could be a source of error, but this does not seem likely as larger model errors occurred beginning in 1985, when observed soil water increased but simulated W did not. Representation of soil water also depends on runoff and snow processes which are treated simplistically in the regional model.

Soil water budget components

Observed precipitation for Illinois shows a sharp peak in November with a broader peak in late spring and early summer (Figure 3). (The November peak is especially large because our record includes 1985, the wettest November of the 20th century for Illinois.) Simulated precipitation captures the annual cycle with a substantial negative bias except for late winter-early spring. Negative precipitation bias is largest in November, coinciding with the most negative soil moisture bias. If we consider the limiting case in which all of the missing precipitation were to enter the top 1 m soil layer and all other soil moisture budget components were unchanged, the precipitation error could account for up to a 0.045 increase in W or about 35% of total error in W for November. Runoff is likely only a minor contributor to soil moisture error as climatological runoff in November is about 0.18 mm/d compared to 1.5 mm/d of precipitation error. The seasonal pattern of error in simulated precipitation for Iowa (not shown) consists of a small positive bias in the cold season and large negative bias in the warm season, consistent with the summer negative bias in W. The only difference is that there is a one-month lag between the W and P bias, possibly reflecting the longer time scale for the top 1 m of soil [*Entin et al.*, 2000].

The soil moisture budget is influenced mainly by the difference between P and E, which typically is small relative to P and E. Thus a small error in P or E could produce a large error in soil moisture. For Illinois $P > E$ in the cold season and $P < E$ in the warm season (Figure 4), implying water input for soil in winter and depletion in summer. The simulated $P - E$ time series for Iowa is similar to Illinois.

Climate projection

Climate changes are evaluated here as differences between the two RegCM2 runs driven by HadCM2 control and scenario climate. This is a common method for evaluating simulated climate change, which is based on the assumption that systematic biases may partially cancel between the two model runs.

Soil moisture in the HadCM2 control driven run was slightly higher than in the reanalysis driven run but with a very similar annual cycle (not shown). In the scenario run top 10 cm W is projected to be drier in winter (December–March) (Figure 5). During the remaining months, the top layer is projected to be wetter. The warm season wetting can partly, at least in terms of sign, be explained by more positive $P - E$ during this season in the scenario climate. For the top 1 m, W increases year round. In Iowa, W increases in the warm season for both layers (not shown).

Summer wetting in RegCM2 for the greenhouse-gas scenario (which disagrees with some previous GCM simulations) is mainly caused by an increase in precipitation relative to evaporation during the spring and summer. Increased spring precipitation for the central U.S. in the greenhouse-gas scenario also is produced by HadCM2 itself [*Arritt et al.*, 2000]. Looking separately at the changes in E and P for June-July-August, we find ΔE=0.27 mm/d and ΔP=0.81 mm/d. Model bias could also affect these results; for example, RegCM2's cold bias may affect ΔE because of the dependence of saturation vapor pressure on temperature.

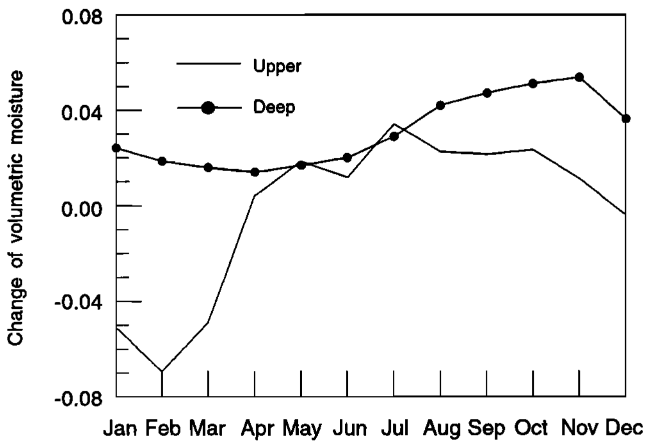

Figure 5. Simulated change of volumetric soil moisture computed as the difference between RegCM2 simulations using initial and boundary conditions from HadCM2 enhanced greenhouse-gas scenario climate versus HadCM2 control climate. Heavy dots denote top 1 m, otherwise for top 10 cm.

Summary and discussion

We have compared soil moisture variations in 10-year regional climate simulations with observed soil moisture data for Illinois and Iowa. Simulated top 10 cm soil moisture compares reasonably well with observations, while soil moisture in the top 1 m has a consistent negative bias. The largest negative model bias in both soil moisture and precipitation is in autumn. Growing season depletion of soil water is simulated well. Interannual variations in soil moisture reflect observed variations but with reduced amplitude. Simulated soil water content does not show long-term drift.

Comparison of soil moisture for a run driven by a GCM 10-year enhanced greenhouse-gas scenario with that from a run driven by the corresponding control climate simulation indicates that soil becomes wetter in summer, probably because warm-season precipitation also increases in this scenario. In winter, the top 10 cm soil becomes drier while the top 1 m soil becomes slightly wetter.

Errors in soil moisture correspond both in space and in time with precipitation errors, suggesting that much of the soil moisture error is attributable to a low bias of precipitation. Our results indicate that improvement of soil moisture simulation will depend mainly on improvement in predicting precipitation, as well as improved representation of biophysical processes that control evapotranspiration.

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