Simulation of Soil Moisture and Its Variability in East Asia

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ABSTRACT

Soil moisture and related hydrological process play an important role in regional and global climates. However, large-scale and long-term observation of soil moisture is sparse. In this study, the latest NCAR Community Land Model is used to simulate regional soil moisture in East Asia for recent 25 years with the atmospheric forcing provided by NCEP/DOE reanalysis. A 50-year simulation has been conducted with the first 25 years as the model spins up for soil moisture to reach steady state. The last 25 years simulation provides a soil moisture dataset with physical consistency and spatio-temporal continuity. Our analysis focuses on spatial and temporal variability of the regional soil moisture based on the last 25-year modeling. Additionally, The trend in the regional soil moisture and its possible link to climate warming is examined. The main conclusions can be summarized as follows:

1. Simulated soil moisture exhibits clear sensitivity to its initial condition. Such sensitivity is a function of soil depth. This study indicates that the equilibrium time of soil moisture increases with the depth of soil layers. It takes about 20 years to reach equilibrium below 1.5m. Therefore either a longer spin-up (20 years or more) or accurate initial soil moisture is necessary for a quality land surface modeling.
2. In comparison with the reanalysis and in-situ measurements, the model reproduces the observed large-scale structure reasonably well. The simulation shows mesoscale spatial variation as well.
3. Linear trend analysis shows that soil has become drier in most areas of East Asia in recent years except southern China and the Tibetan Plateau where soil gets wetter. Further analysis indicates that such dry trend may have a close link to warming surface climate through enhanced evaporation.

Key Words: Land surface model; Soil moisture; trend analysis

1. INTRODUCTION

Soil moisture is a key physical variable in controlling the exchange of water, energy fluxes between the land surface and atmosphere in regional and global scales. It thus affects near-surface climate by changing soil property such as albedo, soil thermal capacity. Soil moisture plays a same important role in the formation and development of meso- and micro-scale weather system. The spatial variation of soil moisture may affect baroclinic structure of the lower tropospheric atmosphere (e.g., formation of convective thunderstorm, Chang and Wetzel 1991). In the hydrological process, the soil moisture is also a comprehensive indicator in hydrological process and ecosystems[1-8].

Although soil moisture plays an important position in weather, climate and ecosystems, wide range and long-term observations of soil moisture are extremely sparse. For this reason, a land surface model is a very useful tool to provide comprehensive soil moisture dataset for weather and climate research and prediction. Such modeling approach is able to generate a dataset that has consistence in physics and continuity in space and time. In this paper, we use NCAR Community Land Model (CLM3) to simulate soil moisture in East Asia. The model and associated experiments is briefly described in section 2. In section 3, the sensitivity of soil moisture to its initial condition is discussed. Spatial and temporal variability of simulated soil moisture and comparison with observations are presented in section 4. Section 5 examines regional trend in soil moisture followed by summary in section 6[9-11].

2. Model and Experiment Description

CLM3 has been developed for international climate community. It combines the best features of three existing land models, which developed by Dickinson et al. (1986), Dai and Zeng(1997),and Bonan(1998), respevtively. CLM has a single

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vegetation canopy layer, 10 unevenly spaced soil layers, and up to 5 snow layers which determined by the snow height. For off-line experiment, CLM can be forced by observational atmospheric data or reanalysis data. In this paper, NCEP/DOE reanalysis are used to drive CLM3[12-22].

We choose East Asia (70º-135ºE, 15º-55ºN) as our model domain with a resolution of 0.5°. Two 25-year (1979 to 2003) offline simulations are conducted. The first 25-year simulation with soil moisture initialized an arbitrary soil moisture, while the second 25-year simulation with soil moisture initialized with the steady state moisture at the end of the first 25-year simulation. We call the first simulation as spin-up experiment, which is used to address the sensitivity of soil moisture to initial conditions, and the second 25-year simulation is called equilibrium experiment, which is used in analyzing spatial and temporal variability. In the analysis and comparison with observations, monthly mean model output is used.

3. Sensitivity of Soil Moisture to Initial Conditions

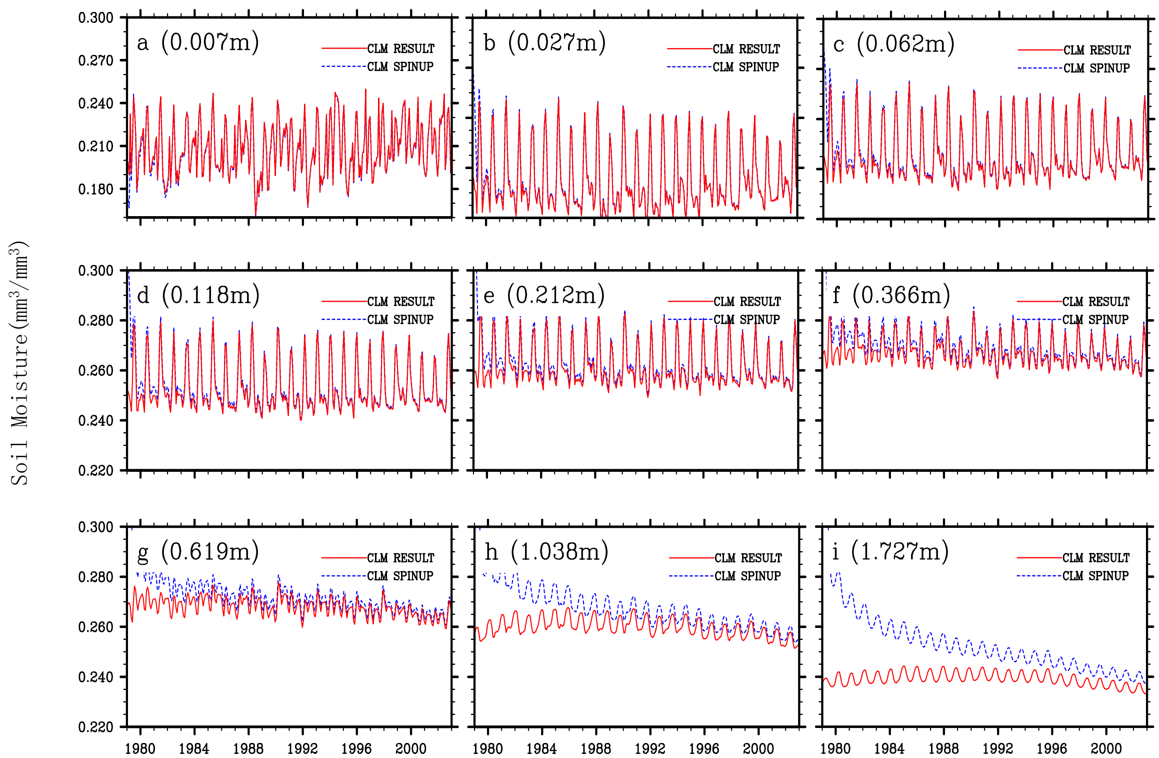

Fig.1 Simulated monthly soil moisture at different levels from 1979 to 2003.The dashed and solid curves indicate the results initialized from arbitrary soil moisture and from the soil moisture at the end of spin-up period, respectively

Soil energy flux follows Force- restoration's law, so the temperature at each layer has same change. On the other hand, soil water flux can be described by Darcy's law, the change at each layer is inconsistent. The soil moisture at upper layers is affected much more than the soil moisture in deeper layers by precipitation, which has phase difference between adjacent layers. Soil water at each layer, especially in deeper layer need longer time to achieve equilibrium state. Therefore, soil moisture is the key physical variable to evaluate spin-up timescale.

Figure 1 shows comparison of area averaged soil moisture at different layers form 1979 to 2003 with two experiments. It is obvious that the spin-up time for soil moisture varies with the depth of soil layers. The deeper a soil level is, the longer the soil moisture reaches its equilibrium state. The adjusting time of soil moisture at shallow layers (0.7cm-6.2cm) is very short (less than 1 year) to reach equilibrium state because temperature and precipitation can quickly affect the soil moisture in these layers. At middle layers (11.8cm-36.6cm) the adjusting time is much longer (about 10 years). The equilibration time is about 20 years layers below 1.5m. Soil moisture in deep layers changes with regular pattern and with small amplitude because of less impact from air temperature and precipitation. In addition, there is a phase difference about 1-3 month between the soil moisture at deep levels and the soil moisture at shallow levels.

The varying equilibrium time indicates that soil moisture is sensitive to its initial condition in the land process model. Therefore a long spin-up process is necessary in climate modeling studies related with land hydrological processes or accurate initial soil moisture is required. As Du et al. (2003) have demonstrated that four-dimensional variational assimilation is a necessary to improve the quality of soil moisture initialization.

4. Comparative Analysis

Selected station measurements within our model domain from Global Soil Moisture Data Bank are used to validate CLM3 simulation in terms of vertical profiles, seasonal and interannual variability (not shown). We find that CLM3 can reasonably reproduce the seasonal cycle and interannual variability of soil moisture in East. Fig. 2 shows 25-years average soil moisture distributions at two layers (0-10cm and 10-100cm) from CLM3 and NCEP/DOE reanalysis. We can see that the simulated soil moisture generally captures most large-scale features in the reanalysis.

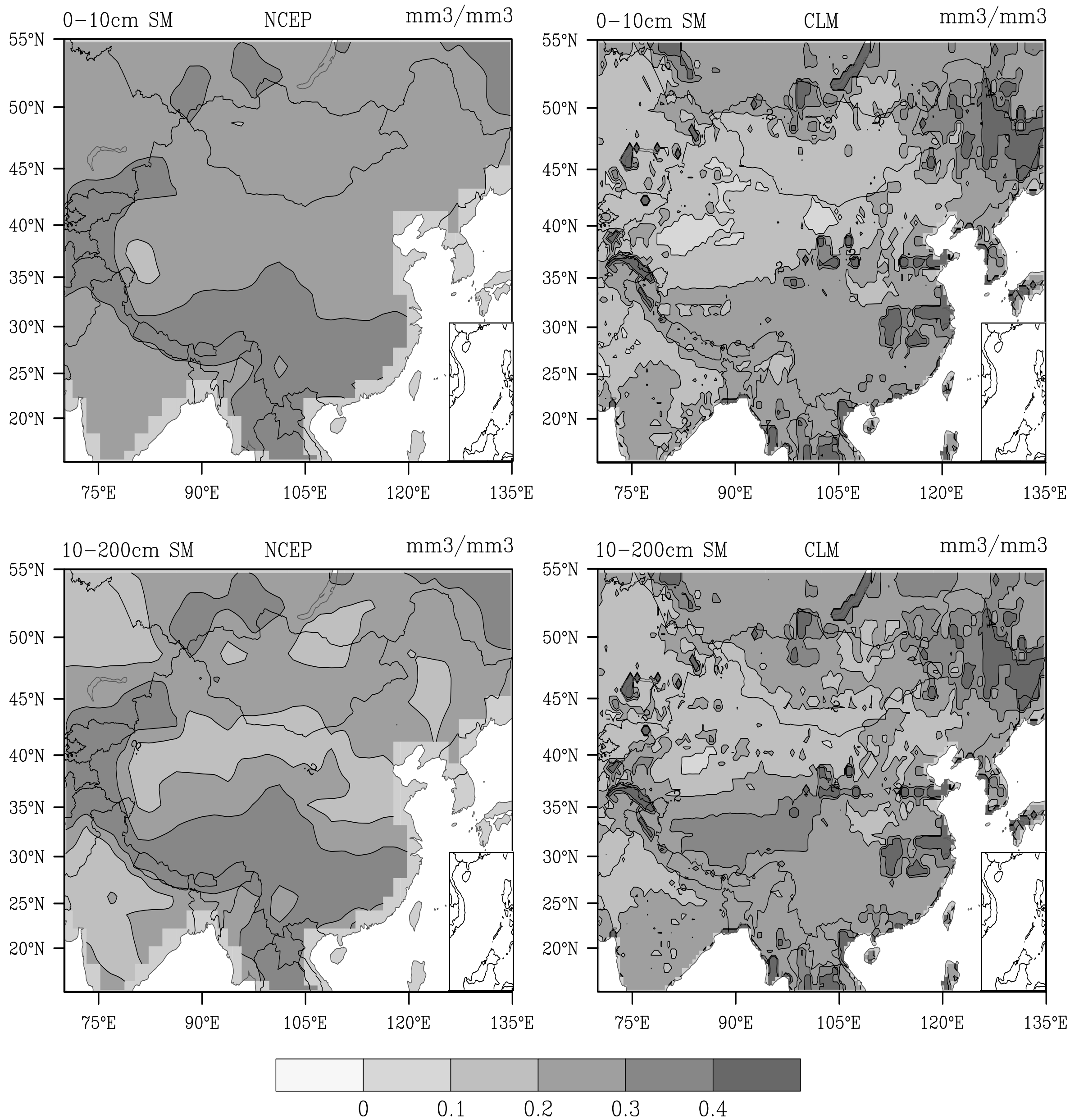

Fig.2 Distributions of 0-10cm (top) and 10-200cm (bottom) 1979-2003 annual-mean soil moisture from the NCEP reanalysis (left panels) and from the CLM simulation (right panels).

Compared to the NCEP 2 reanalysis of soil moisture (Figure 2 top) at 0-10cm level, the simulated soil moisture's value is less than the NCEP R2 about 0.11 mm^3/mm^3 (Boisserie et al. 2006), and because of higher resolution in CLM, the simulated soil moisture can describe more details in East Asia, such as Taklimakan Desert, the wetland in Northeast etc. From the pattern of the distribution of soil moisture between CLM and NCEP, the wet and dry region is basically consistent with a boundary at 35°N.

The structure of 10-200cm soil moisture distribution is much more complex than 0-10cm(Figure 2 bottom). There is not a clear boundary to divide the wet and dry region with a similar layout. CLM simulation of 10-200cm (Figure 2 right panels) has same distribution in Northeast with 0-10cm pattern because that this region belongs to the biggest wet land in China, the soil can reach saturation very easily. We also can find a wet band along with Tibet Plateau which is more humid area than other's, it may been influenced by snow height or soil ice (Qin et al. 2006).

5. Trend Estimation

As greenhouse gases in the atmosphere increase, global mean surface temperature goes up. The increased temperature in turn may enhance surface evaporation. We use simulated regional soil moisture, observed air temperature and precipitation to investigate their relationship. We use following equation to scale the soil moisture to a single value W for the sake of analysis:

$$W = \sum_{i=1}^{10} \theta_i h_i \Big/ \sum_{i=1}^{10} h_i$$

where i represents layer, θ_i is for soil moisture at layer i, h_i is for depth of layer i.

Figure 3 shows the linear trend of soil moisture simulated by CLM, the shadow means decrease of soil moisture, the darker the shadow is, the less the soil moisture is. Fig.3a is for winter(Dec, Jan, Feb), although the decreasing area of soil moisture is more, but its magnitude is less than the summer's, the main decreasing area concentrates at north of China. Fig.3b for summer (June, July, August). The major decreasing area is 30°N and North(Manabe and Wetherald 1986). The center of decreasing is in Northeast China and Mongolia, which is consistence with the study by Manabe and Wetherald (1986).

The physical mechanism responsible for the summer dryness in Northeast Asia may be related to recent climate change. Thus it is necessary to compare trends in soil moisture with precipitation and surface air temperature in this region. Figure 4 shows anomaly time series of global temperature, East Asia temperature, precipitation and soil moisture in north of 30°N from 1980 to 2002. Undoubtedly, the earth is undergoing a warmer period including East Asia. The mean precipitation tendency increase only slightly. In summer, when surface temperature and associated saturation vapor pressure are high, a major fraction of the heating due to temperature increase is used to enhance evaporation, thus local water resource may decrease gradually, and soil water is also decreasing. This indicates East Asia has become drier in the background of global warming

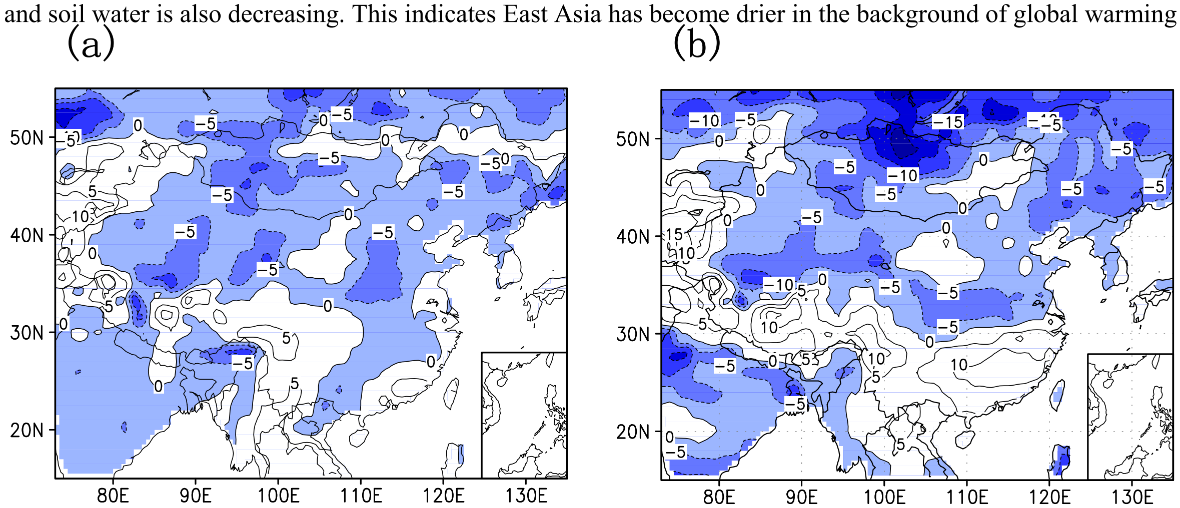

Fig.3 The linear trend of CLM-simulated winter (a) and summer (b) mean soil moisture over East Asia during 1979-2003 ((mm^3/mm^3)/100a).

Hydrological process related to soil moisture plays an important role in determining regional and global climate. However, a wide range and long-term observation of soil moisture is extremely sparse. In this study, using CLM to simulate the soil moisture in East Asia through a long off-line experiment under 0.5°(longitude) × 0.5°(latitude) resolution and real atmospheric forcing of the NCEP/DOE reanalysis during1979-2003.

The spin-up time of soil moisture varies with the depth of soil layers. The deeper a soil level is, the longer the soil moisture reaches its equilibrium state. The equilibration time needs about 20 years long at soil levels below 1.5m. This shows that the soil moisture is sensitive to its initial condition in the land process model that a long spin-up process is necessary in climate modeling studies related with land hydrological processes. By comparing the CLM-simulated soil moisture with the output of NCEP reanalysis in East Asia, we find that the CLM can reasonably reproduce horizontal distribution of soil moisture with much more details.
Based on CLM3 simulated soil moisture, linear trend analysis for recent 25 years shows that soil in most regions of East Asia

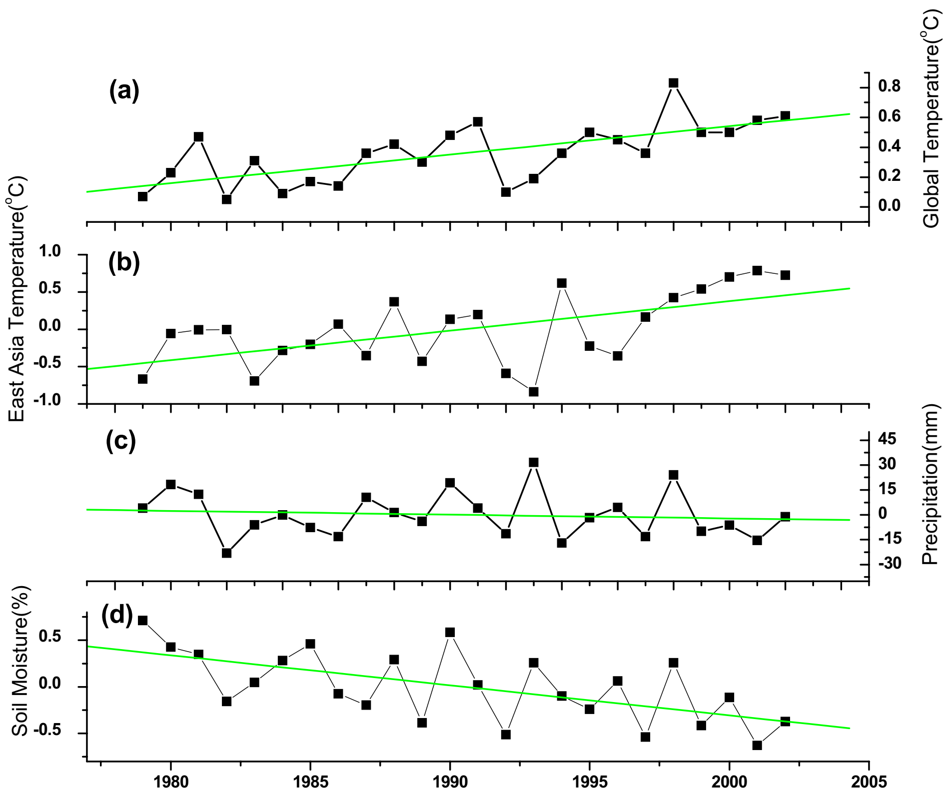

Fig.4 Year-to-year variations and their linear treads of global surface air temperature anomaly (a, ^{o}C), surface air temperature anomaly averaged for East Asia (b, ^{o}C), regionally-averaged precipitation anomaly (c, mm) and regionally-averaged soil moisture anomaly (d, %) for East Asia north of 30^{o}N in summer.

has become drier, particularly, 30°N and North, but wetter in southern China and Tibetan Plateau, especially in summer. The regionally-averaged soil moisture indicates a significant drying tendency in northeast Asia. However, no clear tendency in summer precipitation is observed during the same period. Therefore, we attribute the regional drying to increasing of the land-surface evaporation induced by regional surface temperature warming.

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