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Soil thermal dynamics of terrestrial ecosystems of the conterminous United States from 1948 to 2008: an analysis with a process-based soil physical model and AmeriFlux data

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Abstract The spatiotemporal distribution characteristics of soil temperature are a significant, but seldom described signal of climate warming. This study examines the spatiotemporal trends in soil temperature at depths of 10, 20, and 50 cm in the conterminous US during 1948–2008. We find a warming trend of between 0.2 and 0.4 °C at all depths from 1948 to 2008. The lowest soil temperatures are in Colorado and the area where Wyoming, Idaho, and Montana meet. The coastal areas, such as Texas, Florida, and California, experienced the highest soil temperature. In addition, areas that experienced weak cooling in summer soil temperature include Texas, Oklahoma, and Arkansas. Warming was recorded in Arizona, Nevada, and Oregon. In winter, Mississippi, Alabama, and Georgia show a cooling trend, and Montana, North Dakota, and South Dakota have been warming over the 61-year period. Additionally, mix-forest areas experience slightly cooler soil temperature in comparison with air temperature. Shrubland areas experience slightly warmer soil temperature in comparison with air temperature. This study is among the first to analyze the spatiotemporal distribution characteristics of soil temperature in the conterminous US by using multiple site observational data. Improved understanding of the spatially complex responses of soil temperature shall have significant implications for future studies in climate change over the region.

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1 Introduction

In the ongoing discussion of the causes and effects of global warming, the recent rise in air temperature has dominated the discussion (Jones et al. 1985; Robeson 2002; Jaha and Saha 2011). However, the complex response of soil temperature to changes in air temperature and precipitation has significant implications for climate change (Zhang et al. 2005; Qian et al. 2011). Soil temperature is an important factor to affect soil organic carbon decomposition (Jerry et al. 2011; Zhuang et al. 2003; Euskirchen et al. 2006) and plant growth (Goulden et al. 1998; Wraith and Ferguson 1994; Germán et al. 1996; Jesse and Michael 2013). Thus, the heat stored in soil and temperature variations cannot be ignored when studying air temperature variations and their effects on ecosystems. To date, soil temperature has not received much attention because soil temperature data are not widely available in space and time (Qian et al. 2011; Song et al. 2013).

Long-term changes in soil temperature may differ from that of air temperature due to changes in vegetation, snow, soil moisture, and other climate variables (i.e., precipitation, solar radiation, and humidity) (Zhang et al. 2005). Studies show that changes in snow depth and precipitation are as important as changes in air temperature for influencing changes in soil temperature (Pavlov 1994; Schmidt et al. 2001; Zhang and Roger 2001; Harris et al. 2003; Stieglitz et al. 2003; Zhang et al. 2005; Qian et al. 2011). Model sensitivity analysis studies show that the spatial distribution of mean annual soil temperature is similar to that of air temperature, but the mean annual soil temperature differed from the mean annual air temperature in some places (Riseborough 1985). Soil temperature changes could be due to the combined effects of snow cover, precipitation, soil organic layers, and vegetation. Therefore, we cannot simply use the projected or measured warming trend in the atmosphere to represent the trends in soil temperature (Williams and Smith 1989).

One major difficulty to understanding the spatial distribution of soil temperature is that there are limited data available for analysis. Although the trends in the observed soil temperature at different depths were analyzed along with observed climatic variables at the same locations (Zhang and Roger 2001; Hu and Feng 2003; Qian et al. 2011), the observation sites are still sparse geographically (Jesse and Michael 2013). The spatiotemporal distribution of soil thermal dynamics has not been well characterized. In the conterminous US, soil temperature has been estimated using remote sensing and geographical information system techniques (Hu and Feng 2003; Jesse and Michael 2013). And some researches focus on the effects of soil temperature on CO_2 fluxes, vegetation growth, microbial communities, and agricultural yield (Lindsey and Ivan 1994, 1998; Gregory et al. 1997; Germán et al. 1996). Further, daily soil temperatures of the contiguous US have been analyzed (Zheng et al. 1993; Hu and Feng 2003). However, the spatial distribution of soil temperature for the entire USA is insufficiently represented. Here, we examine the spatiotemporal characteristics of soil thermal dynamics using data at covariance flux tower sites. (FlUXNET: http://cdiac.esd.ornl.gov/programs/ameriflux/data_system/aamer.html).

2 Methods

2.1 Overview

This study examines the dynamics of the soil thermal regime in natural ecosystems of the conterminous US from 1948 to 2008 at a spatial resolution of 0.05 degree (latitude×longitude). The spatiotemporal patterns of soil temperature at different depths are analyzed in conjunction with vegetation type and climatic variables. We first derive climate data from satellite data. Second, we parameterize the model using flux tower data at site levels. Finally, we use a soil thermal model to analyze the spatiotemporal patterns of soil temperature trends.

2.2 Model description

TEM is a global-scale ecosystem model, originally designed to make monthly estimates of carbon and nitrogen fluxes and pool sizes in the terrestrial biosphere, using spatially referenced information on climate, topography, soils, and vegetation (Zhuang et al. 2010). Within TEM, two sub-models, the soil thermal model (STM) and the updated hydrological model (HM), are coupled to provide daily soil temperature and soil water content, respectively.

The STM is an extended version of the Goodrich model (Goodrich 1978) with the capability of operating with either 0.5 h or 0.5 day internal time steps, and being driven by either daily or monthly air temperature (Zhuang et al. 2001). The vertical profile in the STM is divided into six layers, including snow cover, moss, upper organic soil, lower organic soil, upper mineral soil, and lower mineral soil layers. Within each layer, there are several sublayers, whose locations are abstracted as nodes at the middle of each sublayer, sequentially. To run the STM, simulation depth steps, layer specific information of layer thickness, and thermal properties are prescribed (Appendix 1).

2.3 Model parameterization and verification

Before running the STM, we organized the meteorological data including radiation, air temperature, and precipitation from three representative eddy covariance flux sites for each vegetation type to parameterize and verify the model. To test the performance of the STM, we organized the same data from 14 additional sites covering all six vegetation types across the conterminous US. We gathered daily Level 4 soil temperature data at depths of 10, 20, and 50 cm (http://cdiac.esd.ornl.gov/programs/ameriflux/data_system/aamer.html) at these sites (Tables 1 and S2).

Values for some parameters of the STM could be found in publications (e.g., Zhuang et al. 2010; Tang and Zhuang 2011), and others were determined by calibration (Table S1). In this study, we developed parameters for six major vegetation types across the USA (Fig. 1). Specifically, we added elevation as a covariant when interpolating the air temperature. Soil temperatures (Tables 1 and S2) used to calibrate the model and verify the parameters are daily mean values based on field measurements with either thermistor or thermocouple sensors at depths of 10, 20, and 50 cm (Dennis et al. 2005). Daily means were computed from the original 30 min datasets using the mean diurnal course gap-filling method (Falge et al. 2001). The calibration was done by minimizing the distance between the observed and simulated soil temperatures at each site for approximately 5 to 6 years of data (Appendix 2). The definitions and parameter values for each of the six biomes are listed in Table 1. Statistics of R^2 and RMSE were calculated to quantitatively evaluate the model performance (Table 1 and S2). Because our primary goal is to simulate the soil temperature at depths of 10, 20, and 50 cm, we calibrated parameters for only the first three layers while keeping the rest the same as prescribed in Zhuang et al. (2010).

2.4 Regional simulation

To conduct regional simulations, we organized the regional data on vegetation, soils, topography, and climate at a spatial resolution $0.05° \times 0.05°$. Elevation was derived from the Shuttle

Table 1 Geographic, vegetation, and comparison between simulations and observations at study sites

Site Name	Latitude	Longitude	Vegetation type	Years	R^2			RMSE(°C)			References
					10 cm	20 cm	50 cm	10 cm	20 cm	50 cm	
Sky_Oaks_Young	33.37	−116.62	Closed Shrubland	2001–2005	0.90	0.93	0.93	2.28	2.47	2.60	Grant et al. (2012)
Willow_Creek	45.80	−90.07	Deciduous Broadleaf Forest	1999–2006	0.96	0.97	0.97	3.42	3.27	3.65	Sprintsin et al. (2012)
Flagstaff_Unmanaged_Forest	35.08	−111.76	Evergreen Needleleaf Forest	2006–2007	0.93	0.90	0.90	2.74	2.53	2.48	Sorensen et al. (2011)
Audubon	31.59	−110.51	Grassland	2002–2006	0.94	0.93	0.98	3.42	3.38	3.62	Krishnan et al. (2012)
Sylvania Wilderness	46.24	−89.35	Mixed Forest	2001–2006	0.94	0.96	0.82	3.93	3.26	3.00	Tang et al. (2012)
Santa Rita Mesquite Savanna	31.82	−110.86	Woody Savanna	2004–2006	0.91	0.91	0.96	2.57	3.31	3.17	Scott et al. (2009)

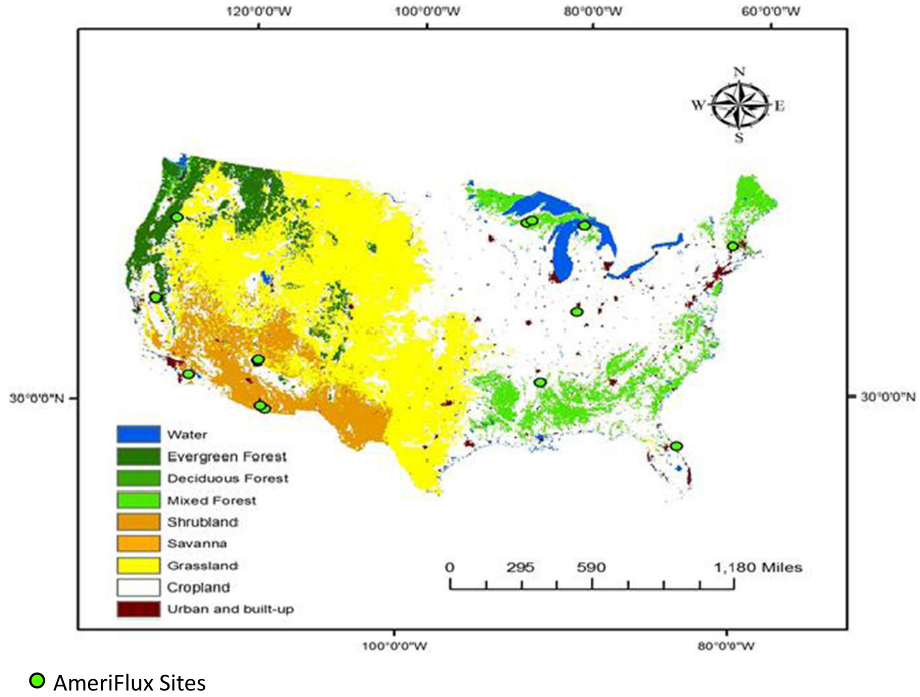

Fig. 1 Land cover map of the conterminous USA (0.05°×0.05°) used in regional simulations. The map was reclassified based on MODIS product Land Cover Types Yearly L3 Global 0.05 Deg CMG (MOD 12 C1). *Green points* indicate the location of the AmeriFlux sites used in this study

Radar Topography Mission (SRTM), and soil texture information gathered from the FAO-UNESCO soil map (1971) was organized in our previous study (Zhuang et al. 2010). We obtained land-cover information from MODIS product Land Cover Types Yearly L3 Global 0.05 Deg CMG (MOD12C1) (Year 2004) found on the NASA Goddard Space Flight Center website (http://modis-land.gsfc.nasa.gov). We used the International Geosphere and Biosphere (IGBP) land-cover classification system to classify the map of the conterminous US into six major vegetation types, which are used in our STM simulations (Table S3).

Mean monthly climate data, including air temperature, cloudiness fractions, vapor pressure, and precipitation were extracted from NCEP global datasets at a 0.5 spatial resolution (Fig. 1). Spatial elevation data and soil texture data are from previous studies by Zhuang et al. (2003). All of the data were interpolated into a 0.05 spatial resolution using the Inverse Distance Weighted method to match MODIS data (Appendix 3).

3 Results and discussion

3.1 Model performance at AmeriFlux sites

The parameterized STM is able to reproduce the monthly dynamics of the observed soil temperature at 10, 20, and 50 cm for all six biomes, with R^2 mostly larger than 0.9, and root mean square errors (RMSE) of 2–4 °C (Table 1). Specifically, at mixed forest sites, soil temperature at 10 cm has a relatively larger RMSE (3.93 °C) than values at other sites. TEM has a crude treatment of snowpack; hence, at deciduous broadleaf forest sites with heavy snowfall in winter, the temperatures at 10, 20, and 50 cm are not well simulated.

Our test at nine additional sites shows model performed well, except for the Vaira Ranch site and the Flagstaff-Managed Forest site (Table S2). At the Vaira Ranch site, the disagreement at 10 cm is likely because that grass dies during the summer (Thompson et al. 2011; Wilson and Meyers 2007), which changes the thickness of top soil layer that has not been considered in our modeling. It has been reported that soil temperature at 10 cm increased significantly as the height and density of grassland was reduced (Song et al. 2013). At the Flagstaff Managed forest site, soil temperature at 50 cm has a larger RMSE (4.66 °C) because the observed data are displaced by measurements at a depth of 45 cm.

3.2 Temporal trend of mean soil temperature

At depth 10 cm, the mean annual soil temperature from 1948 to 2008 was 10.1 °C, with a mean annual minimum temperature 9.2 °C in 1979, and a mean annual maximum temperature 11.22 °C in 2006. During the period 1980–2008, mean annual soil temperature was mostly above the mean and has risen 0.3 °C. Soil temperature decreased 0.1 °C from 1948 to 1968, but increased 1.0 °C from 1969 to 1981 at a rate of 0.1 °C year^{-1}. For the period 1982–1994, soil temperature increased approximately 1.2 °C at a rate of 0.1 °C year^{-1}. For the period 1994–2006, soil temperature increased by 0.6 °C, with a rate of 0.05 °C year^{-1}. The rate from 1982 to 1994 is higher (0.05 °C year^{-1}) than that from 1994 to 2006. The mean soil temperature (10.2 °C) from 1982 to 1994 is 0.4 °C lower than that (10.6 °C) from 1994 to 2006 (Fig. 2).

At depth 20 cm, the mean annual soil temperature from 1948 to 2008 was 9.0 °C, with a mean annual minimum temperature 8.6 °C in 1978, and a mean annual maximum temperature 9.6 °C in 2006. However, for the period 1948–1979, annual soil temperature (8.9 °C) was generally below the mean value. For the period 1980–2008, annual soil temperature (9.2 °C) was mostly above its mean value and has risen approximately 0.1 °C. Soil temperature decreased 0.3 °C from 1948 to 1968; however, it increased 0.6 °C from 1969 to 1981 at a rate of 0.05 °C year^{-1}. For the period 1982–1994, soil temperature increased to approximately 0.7 °C at a rate of 0.1 °C year^{-1}. For the period 1994–2006, it increased by 0.2 °C at a rate of 0.01 °C year^{-1}. The rate from 1982 to 1994 is higher by 0.05 °C year^{-1} than that from 1994 to 2006, but the mean soil temperature (9.0 °C) from 1982 to 1994 is lower by 0.3 °C than that (9.3 °C) from 1994 to 2006 (Fig. 2).

At depth 50 cm, the mean annual soil temperature from 1948 to 2008 was 9.1 °C, with a mean annual minimum of 8.6 °C in 1948 and a mean annual maximum of 9.7 °C in 2008. However, for the period from 1948 to 1979, the mean annual soil temperature (8.9 °C) was generally below its mean value. For the period from 1980 to 2008, mean annual soil temperature (9.2 °C) was mostly above its mean value and had risen approximately 0.2 °C. Soil temperature decreased 0.1 °C from 1948 to 1968; however, it increased 0.5 °C from 1969 to 1981 at a rate of 0.04 °C year^{-1}. For the period from 1982 to 1994, soil temperature increased approximately 0.7 °C at a rate of 0.05 °C year^{-1}. For the period from 1994 to 2006, soil temperature increased by 0.15 °C at a rate of 0.01 °C year^{-1}. The rate from 1982 to 1994 is higher by 0.04 °C year^{-1} than that from 1994 to 2006, but the mean soil temperature from 1982 to 1994 (9.0 °C) is lower by 0.3 °C than that from 1994 to 2006 (9.34 °C) (Fig. 2a).

There was a general increasing trend in soil temperatures with time at all depths during the period 1980–2008, with a rate of change of 0.005 °C year^{-1} at 10 cm, 0.007 °C year^{-1} at 20 cm, and 0.007 °C year^{-1} at 50 cm (Fig. 2b). The mean annual soil temperature increased approximately 0.2 °C at 10 cm, 0.3 °C at 20 cm, and 1.2 °C at 50 cm during a period of 61 years. Soil temperature at 50 cm increased significantly. At 20 cm, the mean annual soil

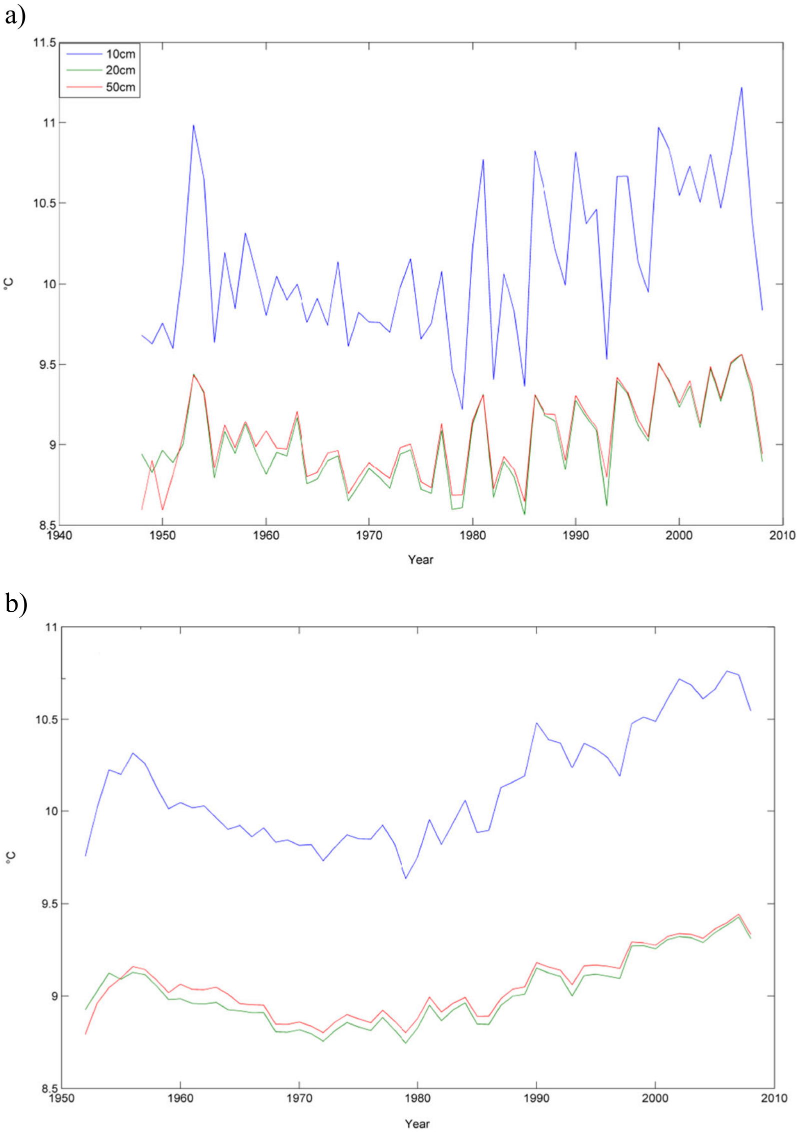

Fig. 2 **a** Mean soil temperature (°C) from 1948 to 2008 at depths of 10, 20, and 50 cm, **b** 5-year averages to show the trends

temperature is the coolest among the recorded temperatures. This result is similar to previous findings (Hu and Feng 2003, 2005).

3.3 Spatial pattern of the simulated mean soil temperature from 1948 to 2008 in the United States

We analyzed annual and seasonal mean soil temperature at three depths (10, 20, and 50 cm) over the period of 1948–2008 and the spatial patterns of soil temperature in the conterminous

US (Fig. 3). We found that the annual mean soil temperature at three depths increased southward as the climate shifts from a temperate continental climate in the northern areas to subtropical humid or dry regime in the southern USA. At depths of 10, 20, and 50 cm, the spatial pattern of the annual mean soil temperature is similar to the patterns for air temperature. The annual mean air temperature ranges from 24 °C in the coastal areas along the Gulf of Mexico to −3 °C in the USA–Canada border. These results are consistent with the findings of Hu and Feng (2003, 2005). In the southeastern coastal area, soil temperature values at depths of 20 and 50 cm are lower than those at a depth 10 cm. However, in the southwest coastal area, soil temperatures at depths of 20 and 50 cm are higher than that at depth of 10 cm.

At depth 10 cm, the lowest soil temperature is in the state of Colorado and the zone of junction between Wyoming, Idaho, and Montana. The coastal areas of Texas, Florida, and

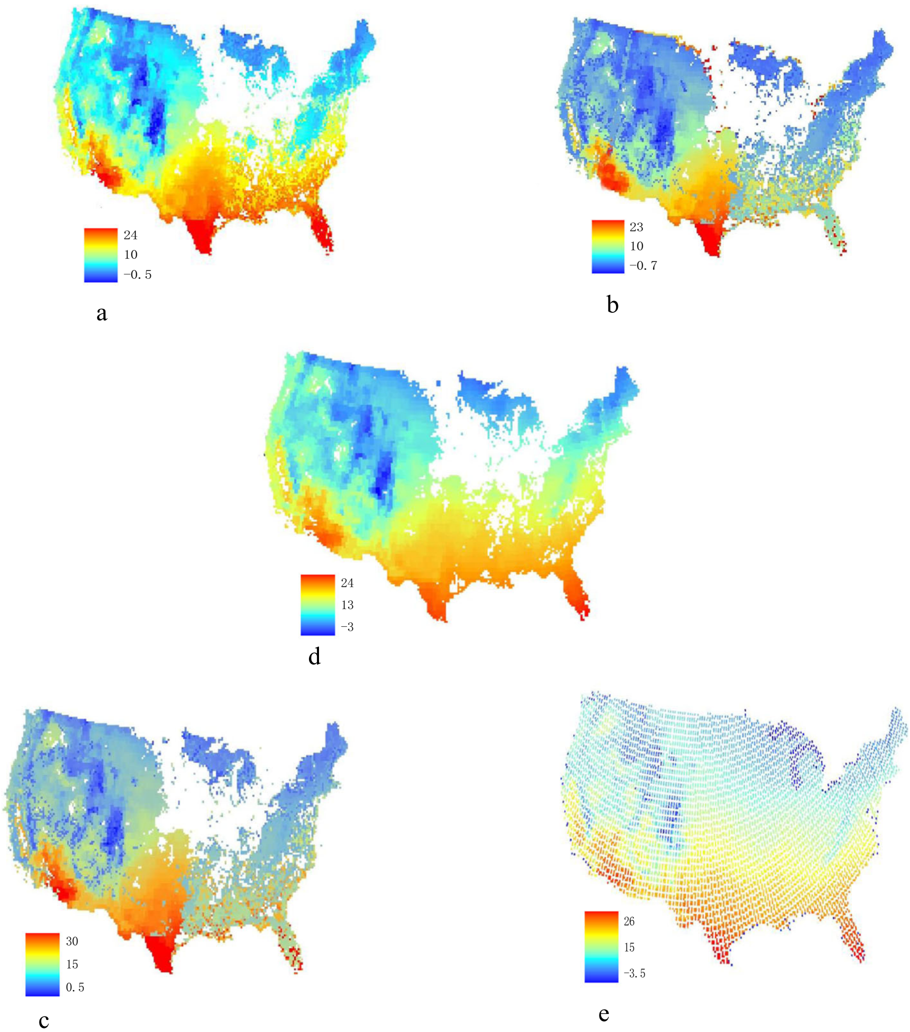

Fig. 3 Simulated annual mean soil temperature (°C) at depths: **a** 10 cm, **b** 20 cm, **c** 50 cm from 1948 to 2008. **d** Simulated average air temperature (°C) from 1948 to 2008. **e** Simulated annual mean soil temperature (°C) with 10 cm from NARR model

California experience the highest soil temperature. At depths of 20 and 50 cm, the lowest soil temperature distribution is the same as that at 10 cm. However, the highest soil temperature occurs in Texas, Oklahoma, and some coastal areas of California. These differences may be because that air temperature influences soil temperature differently at the surface layer and the deeper soil layers (Qian et al. 2011).

3.4 Comparison between simulated soil temperature and other studies

Soil temperature at shallow depths has been the source of deep soil temperature variations (Qian et al. 2011). Moreover, surface soil warming plays a great role in altering soil and plant processes affecting carbon storage in natural ecosystems and net carbon exchanges between the atmosphere and the Earth's surface. Therefore, we evaluated our simulations of soil temperature at 10 cm depth with other datasets. A dataset of soil temperature covering more than 30 years was from the National Climatic Data Center (NCDC) estimated with the NARR model at 0.3° (32 KM) resolution. We extracted monthly soil temperature at depth 10 cm from January 01, 1979 to December 31, 2008 and calculated the annual mean during those 30 years (Fig. 3). We find that the data of soil temperature at depth 10 cm are with a similar trend and are well correlated with the STM simulations (R^2=0.95, p<0.01, n=30). Both datasets show that soil temperature decreases gradually from north to south, and the highest and lowest temperatures are approximately 26 and −3.5 °C, respectively.

3.5 Soil thermal dynamics in different ecosystems

Soil temperature varies in different ecosystems (Table 2). Shrubland has the highest soil temperature intensity, and deciduous forest has the lowest. For shrubland and grassland ecosystems, soil temperature at depth of 50 cm is 2–4 °C higher than that at 10 and 20 cm. For savanna ecosystems, soil temperature at depth of 10 cm is approximately 1.5 °C higher than that at 20 and 50 cm. For deciduous forest ecosystems, the variation in soil temperature is smooth at depths from 10 to 50 cm. Among forest ecosystems, soil temperature in evergreen forests is higher than that of deciduous forests.

The simulated soil temperatures at depths of 10, 20, and 50 cm vary spatially from 1948 to 2008 (Fig. 4). In both summer and winter, soil temperatures in western areas show a warming trend and areas in the southeast experience a little change. Areas in Texas, Oklahoma, and Arkansas experienced weak soil temperature cooling (−0.02 °C $year^{-1}$) at all three depths in summer, and areas experiencing warming (0.06 °C $year^{-1}$) were located in Arizona, Nevada, and Oregon. In winter, areas of Mississippi, Alabama, and Georgia show a cooling trend and Montana, North Dakota, and South Dakota experience warming over the 61-year period. In summer, the overall spatial pattern of soil temperature trends is comparable to the 61-year air

Table 2 Annual Ts for each vegetation type in the conterminous US during 1948–2008

Vegetation type	Mean ANNUAL Ts(°C)	Mean annual Ts-10 cm(°C)	Mean annual Ts-20 cm(°C)	Mean annual Ts-50 cm(°C)
Shrubland	12.29	11.12	11.75	14.00
Deciduous forest	6.28	6.36	6.14	6.34
Evergreen forest	8.13	6.59	7.50	10.30
Grassland	10.38	7.99	10.00	13.16
Savanna	8.14	9.83	7.34	7.26

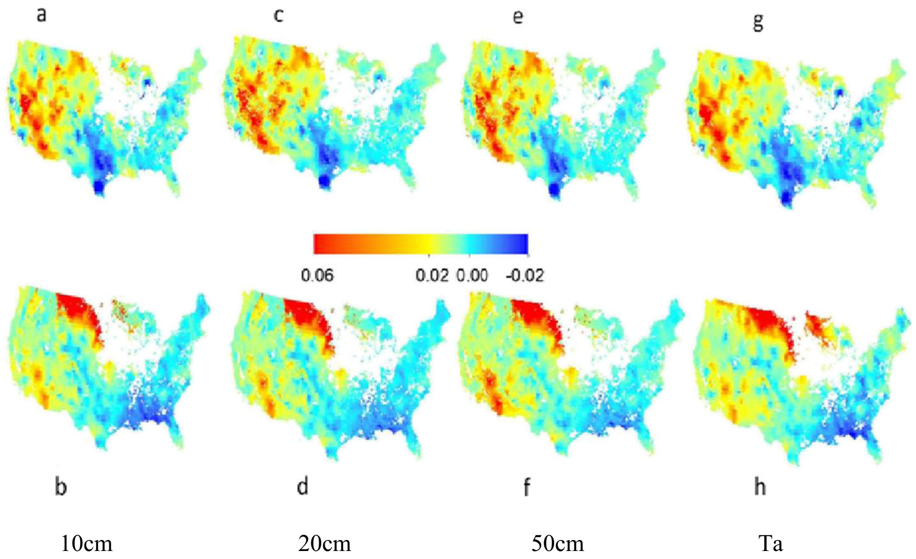

Fig. 4 Spatial patterns of temporal trends in the simulated mean seasonal soil temperature (°C/year) in both summer (**a**, **c**, **e**, **g**) and winter(**b**, **d**, **f**, **h**) at depths of 10 cm (**a**, **b**); 20 cm (**c**, **d**); 50 cm (**e**, **f**) and air temperature (**g**, **h**)

temperature trend based on the NCEP reanalysis product. In winter, however, the warming trend at 10, 20, and 50 cm differs in magnitude. The northeast area of Minnesota experienced an air temperature warming and weak soil temperature warming (0.02 °C $year^{-1}$). Some areas of Nevada and Arizona experienced a mild soil temperature warming trend (0.06 °C $year^{-1}$) and most areas of Nevada and Arizona experienced a soil temperature warming trend.

3.6 Effects of precipitation on soil thermal dynamics

Air temperature and precipitation can strongly modulate soil temperature through insulation and by modifying the evapotranspiration rate and soil thermal properties. Changes in precipitation and air temperature directly alter snow conditions and soil moisture, thereby changing soil temperature and hence the relationship between soil temperature and air temperature (Zhang et al. 2005). Figure 5 shows that precipitation decreased approximately 2 mm from 1948 to 2008 in summer months (June, July, and August); however, air temperature and soil temperature at 10, 20, and 50 cm increased approximately 0.24, 0.84, 0.76, and 0.74 °C, respectively. Mean annual air temperature is much higher, approximately 4–5 °C, than mean annual soil temperature (Fig. 6). Due to higher precipitation during summer months, surface wetness and soil moisture increase, which results in more energy consumption by evaporation cooling the ground surface and soils, which is the so-called soil moisture feedback (Yasunari et al. 1991; Sankar-Rao et al. 1996; Matsuyama and Masuda 1998). This soil moisture feedback may explain soil cooling during the summer months (June, July, and August), even if the air temperature increases several degrees Celsius over the same period.

In winter months (December, January, and February), snowfall decreases by approximately 3 mm from 1948 to 2008 (Fig. 5). Soil temperature at different depths decreases approximately 1, 0.8, and 0.78 °C during the 61-year period (Fig. 7). However, soil temperature is almost 1 °C higher than that of air temperature at different depths in winter, even when air temperature

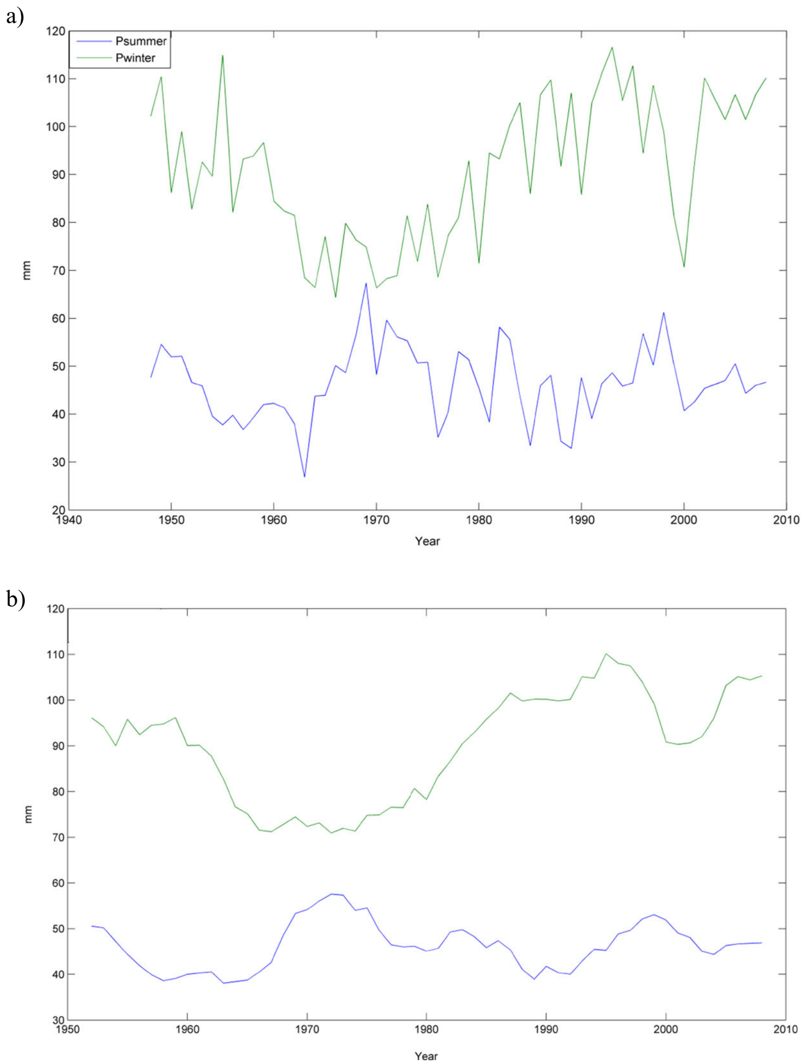

Fig. 5 **a** Mean annual precipitation (mm) in summer and winter during 1948–2008, **b** 5-year averages to show the trends

increased to approximately 0.48 °C. This implies that soil temperature was more sensitive to the effects of snowfall than air temperature.

In general, the seasonal distribution of changes in precipitation impacted soil temperature with the opposite effects of snowfall and evapotranspiration. This result is similar to other model results and numerical experiments (Zhang and Roger 2001; Hu and Feng 2005; Qian et al. 2011).

3.7 Possible uncertainties

The data used to drive STM and the parameterization are two major uncertainty sources. First, as indicated by Zhao et al. (2006), the NCEP reanalysis data overestimated solar radiation and

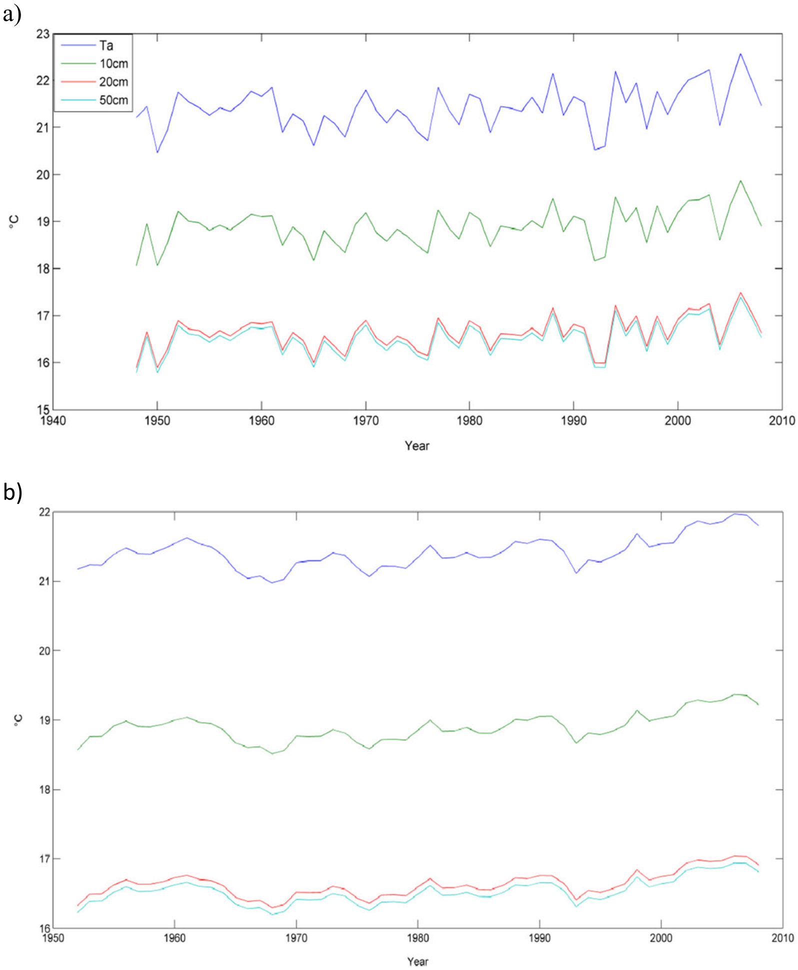

Fig. 6 **a** Air temperature and soil temperature at soil depths of 10, 20, and 50 cm in summer, **b** 5-year averages to show the trends.

underestimated temperature. The errors in air temperature may have introduced errors into soil temperature estimation as indicated by a significant positive correlation between Ts and Ta (Qian et al. 2011). As expected, the dynamics of snow, such as snowfall, snow depth, snow density, and the duration of snow cover on the ground, may have errors due to uncertain air temperature (Kongoli and Bland 2000), which will result in uncertain soil temperatures in winter.

Second, a limited number of quality ecosystem sites with respect to soil temperature observational data may also induce uncertainty. For example, weak shrubland parameter constraints in STM as a result of having only a few shrubland sites with sufficient observations may have biased the estimates for shrubland ecosystems. We suggest that more sites in the western US should be established. In addition, the significant uncertainty of eddy flux data (Richardson et al. 2008) and the uncertainties introduced by the gap-filling techniques (Moffat et al. 2007) might have also biased our parameterization and regional results.

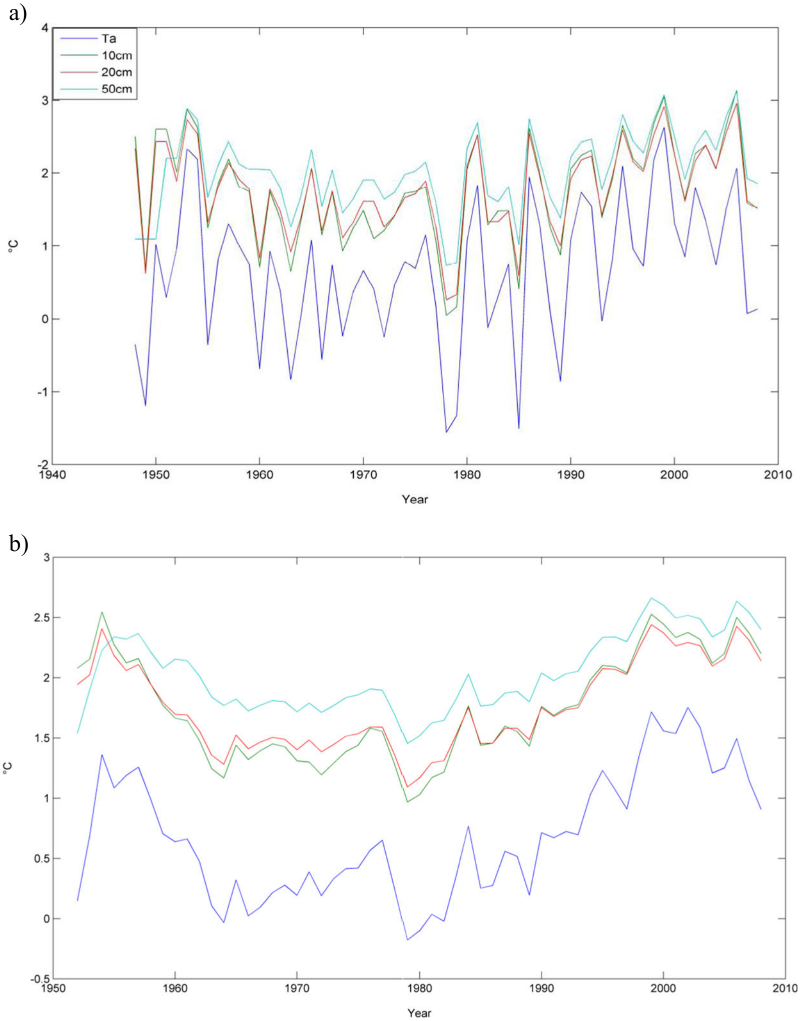

Fig. 7 **a** Air temperature and soil temperature at all soil depths (10, 20, and 50 cm) in winter during the 61-year period, **b** 5-year averages to show the trends.

Third, the parameterization itself may have introduced uncertainty to soil temperature estimates. For instance, uncertainty analysis under the normal climate scenario indicated that 30–80 % of the variance in monthly soil temperatures for the upper organic soil layer can be explained by uncertainty in a subset of the parameters, including moss thickness, moss thermal conductivity, and snow thermal conductivity (Zhuang et al. 2001).

4 Conclusions

Soil temperatures at various depths were estimated for the conterminous US for the period 1948–2008. This study is among the first to explore the spatial distribution of soil temperature in the USA. We find that the mean annual soil temperature increased approximately 0.2 °C at depths of 10 cm, 0.3 °C at 20 cm, and 1.2 °C at 50 cm during the 61-year period. Soil temperatures at 50 cm increased significantly and the mean annual soil temperature is the coolest at 20 cm. At depths of 10, 20, and 50 cm, the spatial pattern of the annual mean soil temperature is similar to that of air temperature. The lowest soil temperature values were found in the state of Colorado and at the junction of Wyoming, Idaho and Montana. The coastal areas, such as Texas, Florida, and California, experienced the highest soil temperature values. In both summer and winter, soil temperature in western regions showed a warming trend, but most areas of the southeast experienced a little change. In winter, dramatic changes in soil temperatures were occurred in shrubland and forests. Seasonal distribution and changes in precipitation impacted soil temperature differently and with the opposite effects of snowfall and evapotranspiration. This study makes use of the available AmeriFlux observation data of soil temperature at multiple sites covering major ecosystems to examine the soil temperature dynamics of terrestrial ecosystems in the USA. The findings shall have important implications to studying climate change in the region.

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