Simulated change in the near-surface soil freeze/thaw cycle on the Tibetan Plateau from 1981 to 2010

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Abstract The near-surface freeze/thaw cycle in cold regions plays a major role in the surface energy budget, hydrological activity, and terrestrial ecosystems. In this study, the Community Land Model, Version 4 and a suite of high-resolution atmospheric data were used to investigate the changes in the near-surface soil freeze/thaw cycle in response to the warming on the Tibetan Plateau from 1981 to 2010. The *in situ* observations-based validation showed that, considering the cause of scale mismatch in the comparison, the simulated soil temperature, freeze start and end dates, and freeze duration at the near-surface were reasonable. In response to the warming of the Tibetan Plateau at a rate of approximately 0.44 °C decade^{-1}, the freeze start-date became delayed at an area-mean rate of 1.7 days decade^{-1}, while the freeze end-date became advanced at an area-mean rate of 4.7 days decade^{-1}. The delaying of the freeze start-date, which was combined with the advancing of the freeze end-date, resulted in a statistically significant shortening trend with respect to the freeze duration, at an area-mean rate of 6.4 days decade^{-1}. Such changes would strongly affect the surface energy flux, hydrological processes, and vegetation dynamics. We also found that the rate of freeze-duration shortening at the near-

surface soil layer was approximately 3.0 days decade^{-1} lower than that at a depth of 1 m. This implied that the changes in soil freeze/thaw cycles at the near surface cannot be assumed to reflect the situation in deeper soil layers. The significant correlations between freeze duration and air temperature indicated that the shortening of the near-surface freeze duration was caused by the rise in air temperature, which occurred especially in spring, followed by autumn. These results can be used to reveal the laws governing the response of the near-surface freeze/thaw cycle to climate change and indicate related changes in permafrost.

1 Introduction

The Tibetan Plateau features some of the highest terrain on the globe, with an elevation averaging more than 4,000 m. Permafrost and seasonally frozen ground are common characteristics due to its high elevation. Seasonally soil freeze/thaw processes in the surface layers, accompanied by absorption and release of latent heat, result in variations in the surface wetness and heat balance. These variations strongly affect the Tibetan Plateau's seasonal transitions [1], surface energy flux [2–4], and circulation over East Asia [5], thus having profound implications for the following monsoon behavior and even global climate processes [6–9].

The near-surface soil freeze/thaw cycle is very sensitive to climate change [10, 11]. Significant warming of the climate has taken place on the Tibetan Plateau in recent decades [12], and this warming will necessarily result in

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changes in the near-surface soil freeze/thaw cycle. Such changes in turn regulate the period in which the soil experiences freeze/thaw processes, thus eventually affecting the surface energy flux, hydrological processes, and terrestrial ecosystems [2, 3, 13, 14]. On the other hand, the near-surface soil freeze/thaw cycle is a key parameter characterizing frozen ground conditions. Its long-term changes are important indicators of permafrost change [15]. Therefore, studying changes in the near-surface soil freeze/thaw cycle is of great importance for both our understanding of changes to the ecological environment, and for examining permafrost change on the Tibetan Plateau.

Previous work in this field has focused mainly on the annual cycle of freeze/thaw processes and the diurnal freeze/thaw cycle at the near-surface of a select few observational sites, mostly along the Qinghai–Tibet Highway [1, 10, 16–18]. There are few studies that have focused on the interannual and interdecadal changes of the soil freeze/thaw cycle at the near-surface on the regional scale, and thus these are many associated issues and problems that remain uninvestigated and unresolved. The shortage is essentially due to a paucity of long-term observational data. Nevertheless, based on observations at 10 sites along the Qinghai–Tibet Highway, Li et al. [19] recently studied changes in the freeze start-date, freeze end-date, and freeze duration of the active layer during different observational periods of the sites. Meanwhile, microwave remote sensing have also been employed to evaluate the landscape's freeze/thaw status [15, 20, 21], and we [11] have used a numerical simulation method with the Community Land Model Version 4 (CLM4) to examine changes in recent decades to the soil freeze/thaw cycle at a depth of 1 m on the Tibetan Plateau.

Considering the large effect that the near-surface soil freeze/thaw cycle has on the surface energy budget, hydrological activity, and terrestrial ecosystems, in the present reported study we expanded upon our previous work at a depth of 1 m by simulating plateau-scale changes in the near-surface soil freeze/thaw cycle in response to the warming on the Tibetan Plateau from 1981 to 2010. The numerical simulation was based on the CLM4, with a better ability to simulate permafrost [22, 23], as well as a suite of high-resolution atmospheric data [24, 25].

2 Data, model, experimental design, and methods

2.1 Data

A suit of gridded daily temperature grid data (CN05 data) were obtained from the China Meteorological Administration, and used for the evaluation of air temperature in the atmospheric forcing data. These data were developed by interpolating observations from 751 stations in China [26]. The data's spatial resolution is $0.5° \times 0.5°$ (longitude $\times$ latitude), covering a period of 1961–2009. The data are reliable and have been widely employed for validations of model performance [23, 27].

In this study we employed a suit of high-resolution atmospheric data to drive the CLM4. Because these data were developed by He (supervised by Kun Yang) [24] from the Hydrometeorological Research Group at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences, we refer to these data as "HY data". The HY data includes seven variables: air temperature, precipitation, wind speed, specific humidity, atmospheric pressure, downward shortwave radiation flux, and downward longwave radiation. The data cover the entire Chinese area and the period from 1981 to 2010, with a temporal and spatial resolution of 3 h and $0.1° \times 0.1°$ (longitude $\times$ latitude). More detailed information on the data can be found in the works of He [24] and Chen et al. [25]. Evaluations based on meteorological station observations and CN05 data, and their use in improving surface temperature modeling, have demonstrated that the HY data are highly accurate and suitable for land surface simulations on the Tibetan Plateau [11, 24, 25].

In situ observations of soil temperature at a depth of 0.04 m were obtained from the Global Energy and Water Cycle Experiment/Asian Monsoon Experiment (GAME/Tibet) and the Coordinated Enhanced Observing Period/Asia–Australia Monsoon Project on the Tibetan Plateau (CAMP/Tibet), which were used to validate the model in this study. Data at only six sites were collected due to the following two reasons: (1) borehole observations for frozen ground are sparse on the Tibetan Plateau; (2) only near-surface and daily data were required for this study. The six sites were distributed along the Qinghai–Tibet Railway (Fig. 1). Information regarding the geography and the types
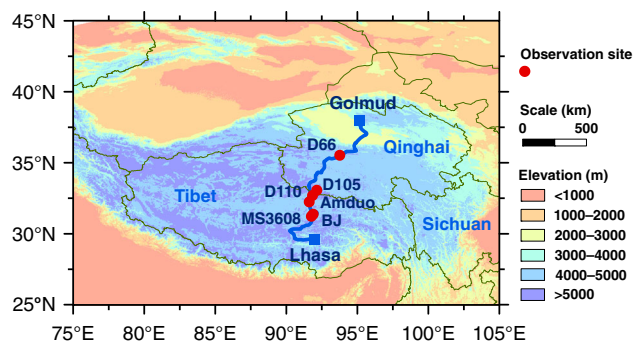

Fig. 1 Modeling domain and location of the observation sites. The blue line represents the Qinghai–Tibet Railway. Qinghai represents Qinghai Province. Sichuan represents Sichuan Province. Tibet represents the Tibet Autonomous Region

of frozen ground at the observation sites, as well as the observational periods, is given in Table 1. Detailed information on the data, such as the observational methods, can be found in the works of Yang et al. [1], Guo et al. [2, 3], and Guo and Wang [11]. These observations have been used previously in research on soil temperature characteristics, freeze/thaw processes, and model validations [1–3, 11].

2.2 Model and experimental design

In this study we employed CLM4, which is an improved version developed from CLM3.5 [28]. In CLM4, frozen ground processes, soil organic matter's thermal and hydrothermal properties, and the deep soil column (approximately 50 m; 15 ground layers) are explicitly treated. These treatments make CLM4 better at simulating permafrost and seasonally frozen ground [22, 29–31]. In our own previous work [11], we further indicated that the CLM4 is suitable for simulating the frozen ground on the Tibetan Plateau.

A regional simulation was carried out from January 1981 to December 2010, driven by the HY data. The region covered was (20°–45°N, 70°–105°E) (Fig. 1). The temporal and spatial resolutions of the output results of the simulation were 24 h and 0.31° × 0.23° (longitude × latitude), respectively. The spin-up period involved running the model for 400 years driven by the output results of RegCM3 from 1951 [27], and for a continuous 100 years driven by the HY data from 1981. The restart file on 1 January, 1981 was then saved and used to initialize the simulation.

2.3 Methods

Previous studies have indicated the near-surface soil at a depth of 0.02 m displays significant freeze/thaw cycles [2, 3, 10]. Therefore, in this study we used the depth of 0.02 m to represent the near-surface. Because the model does not directly yield soil temperature at this depth, we estimated the soil temperature using simple linear interpolation between the known temperatures in all soil layers of

CLM4. The freeze start-date, freeze end-date, and freeze duration, used to express the changes in the freeze/thaw cycle, were calculated by determining whether daily soil temperature was below or above zero. To avoid the influence of random changes in soil temperature on the calculation of freeze start and end dates, we assumed that if three consecutive day met the criterion (soil temperature was below or above zero), the first day of these three days was then considered as the freeze start- or end-date. Trends in the parameters of the freeze/thaw cycle were taken as the slope of the linear fit, derived using ordinary least-squares regression. A nonparametric test was employed to assess the significance of trends [32, 33], within which the >95 % significance level was used to judge the significance.

3 Results

3.1 Validation of the model

Owing to the scarcity of soil temperature observations at a depth of 0.02 m, we performed a validation at the relatively close depth of 0.04 m (Fig. 2). Specifically, the simulated soil temperature at 0.04 m depth was estimated using simple linear interpolation between the known temperatures that were directly calculated by the model. For all six sites, the mean bias between the simulated soil temperature and the site observations ranged from 0.6 to 3.1 °C, with a mean of −2.0 °C (Fig. 2a).

Relatively low simulated soil temperatures were likely caused by the mismatch of scale in the comparison, which was based on grid-mean simulations and individual site observations. The observation sites were mostly located in lower-altitude plains, basins, and valleys, where soil temperatures are higher than those in adjacent areas of higher altitude. Therefore, in a grid containing both an observation site and adjacent high-altitude terrain, the mean temperature would be lower than at the observation site. Moreover, such a mismatch is likely to be more marked on the Tibetan Plateau given the highly rugged and varied nature of its topography.

Table 1 Summary of observation sites at a depth of 0.04 m

| Station name	Latitude (°N)	Longitude (°E)	Elevation (m)	Period of observations	Freeze conditions
D66	35.52	93.78	4,560	1998, 2004–2006	Permafrost
D105	33.06	92.16	5,020	2002–2005	Permafrost
D110	32.69	91.86	5,000	1998–1999, 2003–2005	Permafrost
Anduo	32.24	91.62	4,710	1998–2000, 2005	–
BJ	31.37	91.90	4,509	2001–2005	Seasonally frozen ground
MS3608	31.23	91.78	4,610	1998–2000, 2003–2005, 2007–2008	Seasonally frozen ground
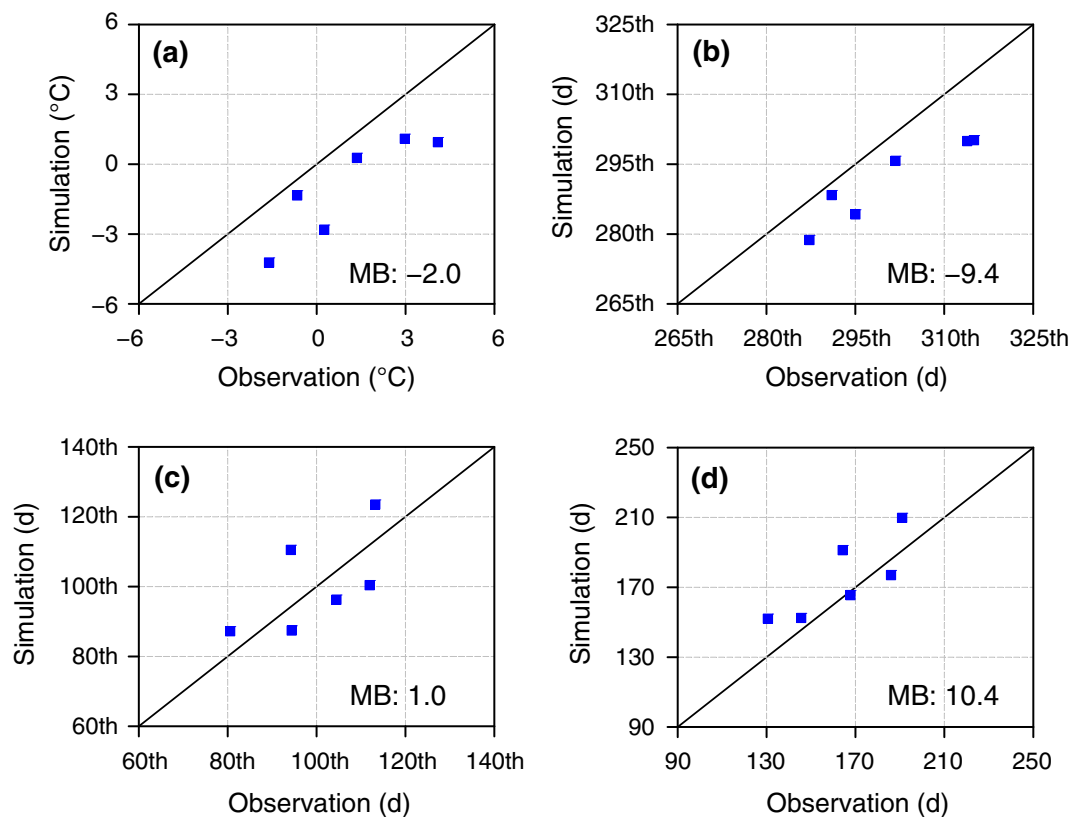
Fig. 2 Comparison of the simulated annual-mean soil temperature (**a**), freeze start date (**b**), freeze end date (**c**), and freeze duration (**d**) with the corresponding site observations at a depth of 0.04 m over 1996–2006 (for the sites with shorter observation periods, over their own recorded period). *MB* mean bias

In order to validate the suitability of CLM4 to be applied to the Tibetan Plateau, a single-point simulation was performed at BJ site based on observational atmospheric forcing data from CAMP/Tibet. The surface data (e.g., leaf area index and soil texture) used were similar to those in Guo et al. [2]. The simulation period only covered a year, from 1 August 2002 to 31 July 2003, due to the scarcity of the forcing data. The results showed that the mean bias between simulated and observed soil temperature was −0.48 °C at a depth of 0.04 m, indicating the model to be suitable for the simulation of soil temperature on the Tibetan Plateau. In addition, this bias was obviously smaller than the cold bias of −3.12 °C between simulated grid-mean soil temperature and corresponding site observations at BJ site. This provided further confirmation that the majority of the cold bias between simulated grid-mean soil temperature and corresponding site observations was likely due to the mismatch of scale in the comparison.

Underestimated soil temperature basically resulted in an earlier freeze start-date, a later freeze end-date, and a longer freeze duration in the simulation relative to site observations. For all six sites, the mean biases between simulations and site observations were −9.4, 1.0, and 10.4

d for freeze start-date, freeze end-date, and freeze duration, respectively (Fig. 2b–d). Bearing in mind the issue of scale mismatch in the comparison, we considered these simulated near-surface soil freeze/thaw cycle parameters to be reasonable.

3.2 Current (1981–2000) near-surface soil freeze/thaw status in CLM4.0

Over the entire Tibetan Plateau area, the freeze start-date mostly ranged from the 258th to the 349th d (Fig. 3a). Basically, the freeze start-date was earlier in the northwestern Tibetan Plateau, with a range from approximately the 258th to the 288th d, and later in the southeastern Tibetan Plateau, with a range from approximately the 288th to the 349th d. The area-averaged value over the entire Tibetan Plateau was the 290th d (Table 2).

The spatial distribution patterns of the simulated freeze end-date and freeze duration were similar to that of the freeze start-date (Fig. 3b, c). For the freeze end-date, the northwestern Tibetan Plateau had later values, ranging from approximately the 106th to the 152nd d, while the southeastern Tibetan Plateau had earlier values, ranging
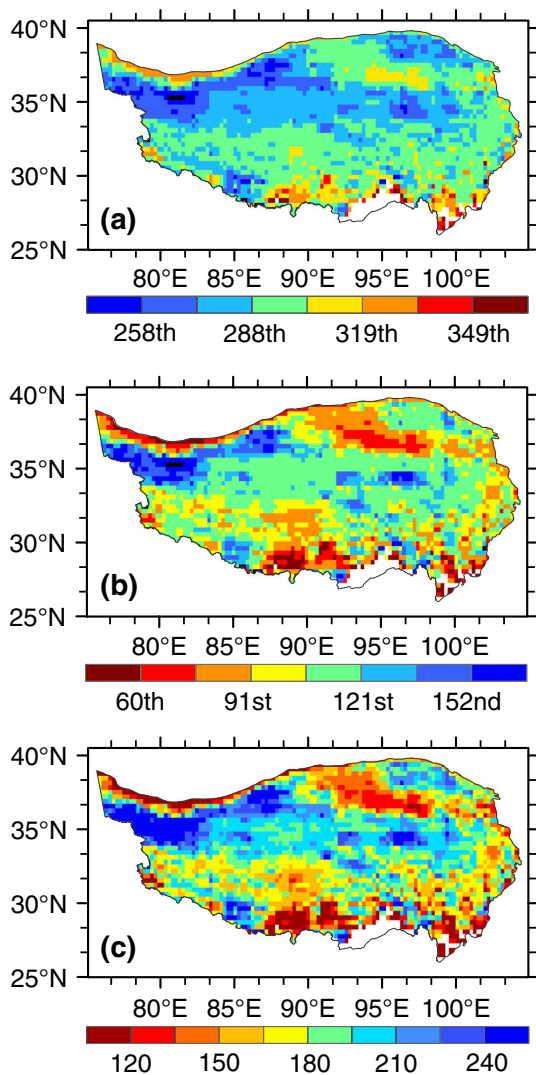
Fig. 3 Spatial distributions of the simulated annual-mean freeze start-date (**a**, units: d), freeze end-date (**b**, units: d), and freeze duration (**c**, units: d) at the near-surface soil, averaged over 1981–2000. *Black* grids in (**a**) and (**b**) refer to the areas where the near-surface soil always freezes over the course of the year. *White* grids in the southern Tibetan Plateau represent unfrozen ground

Table 2 Simulated values of the near-surface freeze/thaw cycle parameters, averaged over their own areas

Parameters	Current (1981–2000)	Change in 1981–2010 (per decade)
Freeze start-date (day)	290th	1.7
Freeze end-date (day)	107th	−4.7
Freeze duration (day)	182	−6.4

from approximately the 60th to the 106th d. The area-averaged value over the entire Tibetan Plateau was the 107th d (Table 2). For freeze duration, the northwestern

Tibetan Plateau had longer values, ranging from approximately 180 to 365 d, while the southeastern Tibetan Plateau had shorter values, ranging from approximately 60 to 180 d. The area-averaged value over the entire Tibetan Plateau was 182 d (Table 2).

The spatial distribution patterns of these freeze/thaw cycle parameters were similar to that of air temperature (not shown). The spatial correlation coefficients between freeze start-date, freeze end-date, and freeze duration and air temperature were 0.90, −0.86, and −0.90, respectively. These results indicate a close relationship between the freeze/thaw cycle and air temperature, which in turn implies a degree of rationality regarding the simulation of the current freeze/thaw status.

3.3 Changes in the near-surface soil freeze/thaw cycle during 1981–2010

The simulated freeze start-dates for the majority of the grids displayed a delaying trend, except for some grids located in the central Tibetan Plateau (Fig. 4a). However, the grids with a statistically significant trend were relatively less in number and mostly distributed in the western, northern, and southeastern Tibetan Plateau. The trends in freeze start-date ranged from −6.2 to 13.6 days decade^{-1}, with an area-averaged value of 1.7 days decade^{-1} (Table 2). The time series of the area-averaged freeze start date over the entire Tibetan Plateau showed a statistically significant increasing trend, which had a strong correlation with the area-averaged annual air temperature, with a correlation coefficient of 0.70 (Fig. 4b).

The simulated freeze end-dates for the majority of the grids displayed a statistically significant advancing trend, except for some grids in the southwestern part, southeastern part, and northwestern corner of the Tibetan Plateau, where a statistically insignificant advancing trend was found (Fig. 4c). The trends in freeze end date ranged from −21.0 to 13.0 days decade^{-1}, and the area-averaged value was −4.7 days decade^{-1} (Table 2). A statistically significant decreasing trend was found in the time series of the area-averaged freeze-end (Fig. 4d). The trend was closely related to the rise in area-averaged annual air temperature, and the correlation coefficient between them was 0.80.

The spatial distribution pattern of trends in freeze duration was similar to that of freeze end-date; the majority of the grids displayed a statistically significant shortening trend, which resulted from both the delayed freeze start-date and the advanced freeze end-date (Fig. 4e). For the entire Tibetan Plateau, most of the trends had a range from −12.0 to 0 days decade^{-1}, and the area-averaged value was −6.4 days decade^{-1} (Table 2). The area-averaged freeze duration shortened significantly from 1981 to 2010,
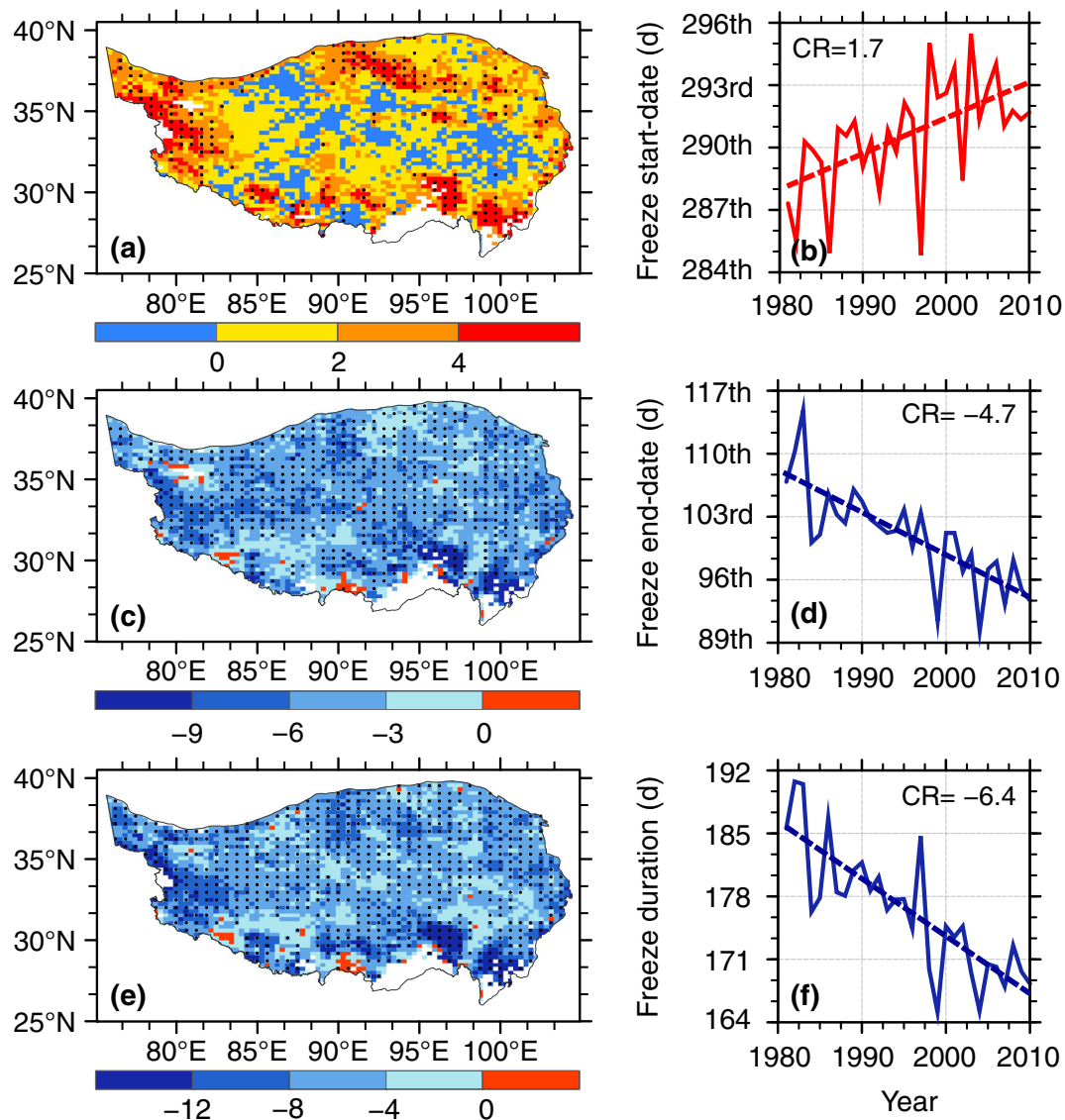
Fig. 4 Spatial distributions of the trends (units: day decade^{-1}) in the simulated freeze start-date (**a**), freeze end-date (**c**), and freeze duration (**e**) at the near-surface soil as well as their area-averaged time series (**b**, **d**, and **f**, respectively) over 1981–2010. CR denotes a change in rate. Areas with significance exceeding the 95 % level are denoted with *dots*. *White* grids in the northwestern corner of the Tibetan Plateau represent those areas where soil always freezes over the course of at least one year during 1981–2010. The *dashed line* in (**b**), (**d**), and (**f**) represents the trend line of the corresponding time series

with a correlation coefficient of 0.90 with the area-averaged annual air temperature (Fig. 4f).

The relationships between the trends in near-surface freeze duration and altitude and latitude are shown in Fig. 5. As can be seen, the shortening rate increased along with altitude increasing to 2,500 m above sea level, and then slowly declined up until the highest altitudes. This pattern is similar to the result based on Special Sensor Microwave/Imager (SSM/I) data, but with a discrepancy that the converted altitude was 3,500 m above sea level for the SSM/I data [15]. This discrepancy could be partially due to the different study periods between these two

studies. The shortening rate decreased as latitude increased from 27° to 31°N, and then became relatively stable with a decline near the highest latitudes. These results indicate a nonlinear relationship of the near-surface freeze-duration trends with altitude and latitude.

The degree of temporal correlation between the freeze duration and air temperature in all four seasons is shown in Fig. 6. In spring, the correlation coefficients were statistically significant over almost the entire Tibetan Plateau area, except for some small areas mostly located in the northwestern part. In autumn, the correlation coefficients were also statistically significant over most of the Tibetan
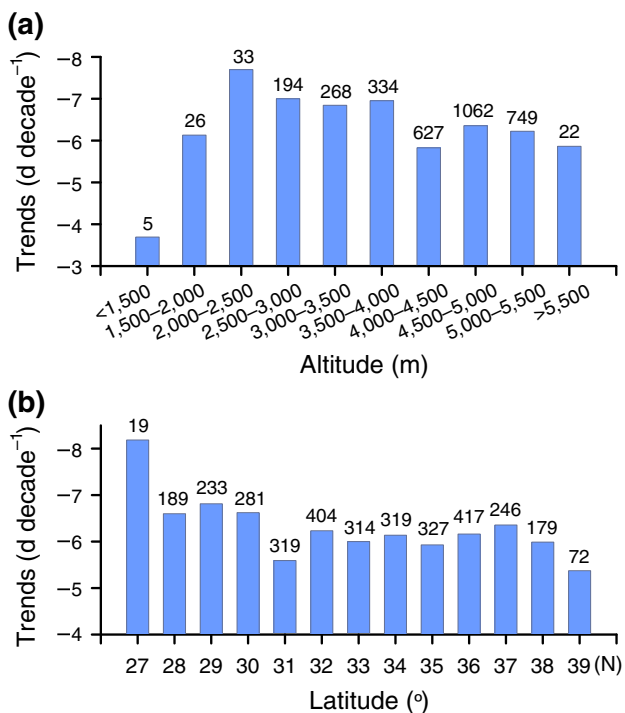
Fig. 5 Relationship between trends in the near-surface soil freeze duration and altitude (**a**) and latitude (**b**). The number above each *bars* is the number of simulation grids at each elevation range

Plateau, with the exception of the central Tibetan Plateau where the correlation coefficients did not pass the significance test. Relative to spring and autumn, the correlation coefficients were evidently low in summer and winter. However, overall, the significance of the correlation indicated that the increase in air temperature was largely responsible for the shortening of freeze duration, which primarily occurred in spring, followed by autumn.

4 Further analyses and discussion

4.1 Comparison with changes in the freeze/thaw cycle at a depth of 1 m

Studying the relationship between changes in the near-surface and deep freeze/thaw cycle changes is helpful to improving our understanding of the overall laws governing such changes. Based on the simulated results, we found that the shortening rate for the near-surface freeze duration was approximately 3 days decade^{-1} lower than that at a depth of 1 m. In other words, in response to a certain increase in air temperature, the deep freeze-duration shortened more rapidly than it did at the near-surface, indicating changes in the near-surface freeze/thaw cycle
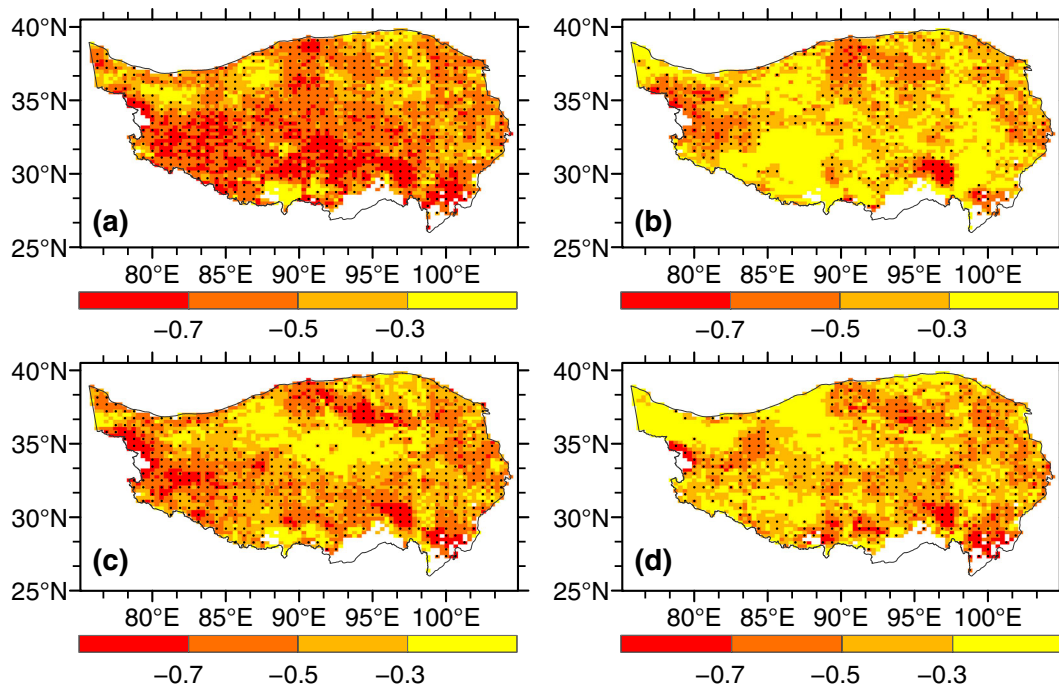

Fig. 6 Spatial distributions of the temporal correlation coefficients between near-surface soil freeze duration and air temperature in Spring (March–April–May) (**a**), Summer (June–July–August) (**b**), Autumn (September–October–November) (**c**), and Winter (December–January–February) (**d**) over 1981–2010. Areas with significance exceeding the 95 % level are denoted with *dots*

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change cannot be relied upon to reflect the situation in deeper layers of the soil. Incidentally, we previously found [11] that the changes in parameters of the freeze/thaw cycle at a depth of 1 m were smaller than those at the near-surface derived from SSM/I data. We discussed that the discrepancy between the two may be due to the difference in the soil depths, with an assumption that changes in the simulated freeze/thaw cycle at the near-surface might be larger than those at 1 m depth. From the present results, that discussion was not appropriate.

4.2 Comparison with the results from SSM/I data

The simulated changes in the parameters of the near-surface freeze/thaw cycle were compared to the results from SSM/I data reported in Li et al. [15]. The trends from SSM/I data were 5.0, −7.0, and −16.8 days decade^{-1} for the freeze start-date, freeze end-date, and freeze duration, respectively. These results were area-means averaged over only the area with statistically significant trends for the parameters. In addition, the period was from 1988 to 2007. In order to make our simulations comparable with the results based on SSM/I data, we calculated the simulated trends under the restrictions of the SSM/I data and obtained values of 6.7, −11.1, and −13.2 days decade^{-1} for the freeze start-date, freeze end-date, and freeze duration, respectively. These trends are basically similar to the results from SSM/I data, implying that the numerical simulation method can be used to successfully detect changes in the soil freeze/thaw cycle.

The reasons for discrepancies between these two sets of results may relate to the uncertainties in both the simulation and the results from SSM/I data. In terms of the simulation, uncertainties may have arisen due to inaccuracies in atmospheric and soil organic matter data and snow cover, which are discussed in detail in section 4.3. For SSM/I data, they derived soil freeze/thaw dynamics were limited to areas under snow cover [21], and thus uncertainties in the results may have occurred. This could be especially true for the Tibetan Plateau, which is characterized by irregular snow cover in the winter half of the year (September–June) [34]. Despite these analyses, more practical work is still required in the future to better understand the inconsistencies between the simulated- and SSM/I-based results.

4.3 Analysis of potential uncertainty

Air temperature is a meteorological element closely related to the simulation of the freeze/thaw cycle; its accuracy could significantly affect the simulated results. The spatial distribution pattern of the HY temperature trends, as well as a comparison of their annual area-mean time series with observations from meteorological stations, can be found in our earlier work [11]. The interannual changes of the area-mean HY temperature are consistent with observations, with their correlation coefficient being 0.95. However, their magnitudes differs because the observed values cover the eastern and central Tibetan Plateau, while the HY data cover the entire Tibetan Plateau. In a chosen equal area of (30°–36°N, 83°–100°E), the time series of the HY and CN05 temperature are also very consistent, with a mean bias of −0.22 °C. The area-mean trend in the HY temperature is 0.49 °C decade^{-1}, which is very close to the 0.52 °C decade^{-1} trend in the CN05 temperature from 1981 to 2008. Therefore, air temperature made little contributions to the uncertainty in this simulation. Precipitation used in this study was also reliable, according to our earlier evaluation [11]. However, the accuracy of other elements (e.g., radiation and wind speed) is not known, although they are generally thought to have a relatively small influence on simulations of changes in the freeze/thaw cycle. Nevertheless, the possibility of inaccuracies in these elements could have been a source of the uncertainties in this simulation.

In our previous work [11], we encountered a belt where the parameters of the simulated freeze/thaw cycle at a depth of 1 m differed distinctly from the near-grid value and largely deviated from site observations. This was related to soil organic matter content of those locations being distinctly larger than the near-grid value and changing slightly with soil depth. We thus pointed out that soil organic matter content might be inaccurate at those locations. Interestingly, the present results show that, at the near-surface, the belt was almost not visible (Figs. 3 and 4). This indicates that soil organic matter content may generally be reasonable at the near-surface, in spite of the possible inaccuracy at a depth of 1 m in the belt. However, since the global soil organic matter data in the model were developed based on few observations, perhaps they still deviate to some extent from the reality, which could have contributed to the uncertainty in the simulation.

Owing to its low thermal conductivity, snow cover insulates the soil surface from rapid and large air temperature variations [35–37]. A reasonable examination of snow cover in the model is therefore important for the simulation of the freeze/thaw cycle. There were many modifications to the snow model in CLM4 from the previous version; for example, the incorporation of a snow and ice aerosol radiation model, as well as new snow cover and snow burial fraction parameterizations [22]. These modifications greatly improved the estimation of snow cover [22], thus favoring the purpose of the present simulation. However, in the simulation, the total precipitation was inputted, which the model then divided them into liquid and/or solid form using an empirical formulation based on

air temperature. It is possible that some biases were produced in this process for snow cover, which may have resulted in some of the uncertainty in the simulation.

5 Concluding remarks

In this study we performed a numerical-simulation-based investigation of the changes in the near-surface freeze/thaw cycle on the Tibetan Plateau from 1981 to 2010. The results showed that the area-mean freeze start-date delayed by 5.1 d, and the freeze end-date advanced by 14.1 d, both of which resulted in a shortening of the freeze duration by 19.2 d from 1981 to 2010. These changes in the parameters of the freeze/thaw cycle were mostly caused by a rise in air temperature, which occurred especially in spring. In addition, the near-surface freeze duration trends showed a nonlinear relationship with altitude and latitude.

Further analyses and discussion revealed that the changes in the near-surface freeze/thaw cycle cannot sufficiently reflect the situation in deeper soil layers, where the magnitude of changes was smaller. The simulated changes in the near-surface freeze/thaw cycle changes were similar to those derived from SSM/I data, with the discrepancies possibly being due to uncertainties in the simulation and limitations of the SSM/I data; further investigations into these uncertainties and limitations are needed in the future. Possible inaccuracies in atmospheric elements (e.g., radiation and wind speed) and soil organic matter data and snow cover could be sources of the uncertainties in the simulation.

Finally, in addition to investigating model uncertainties and data limitations, another interesting and useful direction for future work would be to quantify the impacts of changes in the near-surface freeze/thaw cycle on the land–atmosphere interaction processes, hydrological processes, and ecosystems.

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