Numerical Simulation and Evaluation of Soil Temperature on the Qinghai-Xizang Plateau by the CLM4.5 Model

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Abstract

The CRUNCEP V7 dataset was used to drive the Community Land Model version 4.5 (CLM4.5) to simulate the spatiotemporal changes of soil temperature in the Qinghai-Xizang Plateau from 1981 to 2016. The simulation results were compared with observations, ERA-Interim and GLDAS-CLM soil temperature reanalysis data. The results show that: 1) CLM4.5 can accurately reproduce the dynamic changes in the observed soil temperature over time in two soil layers (0–10 cm and 10–50 cm) at most sites, with a significant positive correlation with the observations. 2) CLM4.5 can depict the spatial distribution of soil temperature in the plateau area, and the distribution characteristics are consistent with those of the reanalysis data. The soil temperature increases from north to south, and the values in the Qaidam Basin are significantly higher than those in the surrounding area. The CLM4.5 results are similar in value to the ERA-Interim product, while the GLDAS-CLM soil temperature values are generally higher. 3) The simulated value shows the trend of "+ - + -" ("increasing-decreasing-increasing-decreasing") from the west to the east in summer and autumn, while in winter and spring, the trend is generally increasing, but a decreasing trend is observed in some isolated locations. The temperature variation trends in the ERA-Interim data in winter and the GLDAS-CLM data in the middle of Sanjiangyuan in spring and the Qinghai Plateau in winter are consistent with that of the simulated data. The above results are all tested with 95% confidence. 4) During the period from 1981 to 2016, the soil temperature on the plateau showed a significant upward trend, especially in spring and autumn. The two layers of the plateau have obvious seasonal changes, with the whole year characterized by a "single peak shape". From March to September, the shallow soil temperature is higher than the deep soil temperature, and from October to February, the deep soil temperature is higher than the shallow soil temperature.

1 Introduction

The Qinghai-Xizang Plateau (hereinafter referred to as "the plateau") has an average elevation of more than 4,000 metres and is known as the Roof of the World. Its total area accounts for about a quarter of China's total land area (Chen et al., 2005) and has a special geographical location and complex terrain. The area includes the Northern Tibetan Plateau, the Qaidam Basin and Qinghai Plateau in the north, the Sanjiangyuan wetland in the middle, and the Tibetan Southern Valley and Sichuan-Tibet Alpine Valley in the south. The high elevation of the features of the plateau and the complex underlying surface play important roles in weather and climate change on the Asian continent. In addition, the fragile and sensitive ecosystems of the plateau are sensitive to global climate change (Zhang et al., 1998; Ma et al., 2001; Wu et al., 1999). Soil temperature can affect vegetation coverage, energy and material circulation in geophysical systems, change the ablation of the plateau permafrost, determine the surface energy cycle and water vapor phase transition process, and reflect soil thermal conditions. In addition, soil temperature is closely related to the transmission of radiant flux, sensible heat flux, latent heat flux and momentum flux in the near-surface layer. The heat exchange between the near-surface layer and the atmosphere directly affects the regional climate and the changes in atmospheric circulation in East Asia (Zhang et al., 2008). Therefore, studying the changes in soil temperature on the plateau is helpful for understanding the geo-gas interactions on the plateau (Chen et al., 2010) and has important significance for the study of plateau heat and dynamics and climatological characteristics of soil temperature. However, due to the geographical environment, extreme climatic conditions and high cost of experimentation on the plateau, the area has long been lacking ground observation sites (Robock et al., 2000) and lacking long-term soil temperature data sets (Vinnikov et al., 1996), making it difficult to study long-term changes in plateau soil temperature (Liu et al., 2015). Therefore, it is very important to obtain a set of representative data that can accurately describe the dynamic changes and distribution details of the plateau soil temperature.

As one of the land surface models with extensive development and great development potential in the world, the CLM can accurately and meticulously describe dynamic soil hydrothermal processes and reasonably reproduce the temporal and spatial distribution characteristics and trends of soil temperature and other surface parameters. The CLM is an effective way to obtain soil temperature data with high spatial resolution over a long period and across a broad scale in the plateau region by using land surface model simulation, which plays an important role in the study of climatological characteristics of plateau soil temperature (Wen et al., 2003). In recent years, a long-term observation network of various climatic conditions was established gradually on the plateau, providing valuable experimental data for the verification of the applicability of soil temperature products on the plateau (Li et al., 2012). Some scholars have evaluated the simulation ability of the CLM and found that it can reasonably simulate the spatial distribution and temporal variation of soil temperature on the plateau (Huang et al., 2004; Chen et al., 2010; Guo et al., 2017; Li et al., 2018), improve the water process transmission scheme in CLM4.0 and simulate the land surface process on the plateau. The results show that CLM4.0 can simulate not only the temporal and spatial distribution characteristics of soil temperature but also the changes in various energy fluxes between land and gas. Chen et al. (2017) used the observation data of the Maqu station in 2008–2009 and 2013–2014 to verify the applicability of CLM4.5, ERA-Interim, CFSR and JRA-55 reanalysis data in the source region of the Yellow River. The results show that the CLM4.5 data have higher finesse and can better describe the details of soil temperature changes in the source region of the Yellow River. Xie et al. (2017) used the soil temperature observation data of the Nagqu Climate Observatory Research Station of the Chinese Academy of Sciences to verify the simulation results with CLM4.5 and utilized the model to better reproduce the seasonal and daily cycle characteristics of surface soil heat flux. However, the simulation of the surface temperature during the freezing period in winter is low in comparison to the observation data. The above studies show that the CLM can reasonably reproduce the spatial and temporal distribution characteristics of soil temperature and thus can be used in studies to simulate surface parameters such as plateau soil temperature.

However, most previous numerical simulation experiments have focused on single-point experiments (Miller et al., 2007), and the main areas of research are concentrated in the eastern and central parts of the plateau. It is impossible to fully and objectively show the simulation results of the regional model results of the plateau soil temperature.

This paper used the 1981–2016 CRUNCEP V7 forcing field data to drive the CLM4.5 and obtain the soil temperature data set with a horizontal spatial resolution of 0.1°×0.1° on the plateau (25°N-40°N, 75°E-105°E). Soil temperature data were selected from representative regions of the plateau (Nagri, Shi quanhe, Nagqu, Maqu) (Fig. 1)and different vegetation cover types, and the simulation results were compared with observations and reanalysis data to verify that CLM4.5 depicts the effects of dynamic changes in the plateau soil temperature. At the same time, the temporal and spatial variation characteristics of soil temperature on the plateau were further analysed. The shortcomings of the CLM4.5 in simulating the plateau soil temperature were discussed, which provided a reference for the future parameterization scheme for improving the land model.

2 Model, Data And Methods

2.1 Introduction to CLM4.5

The CLM is a dynamic land surface module for the Common Earth System Model (CESM) and the Common Atmosphere Model (CAM). Established by the National Center for Climate Research (NCAR), the Department of Global Climate Dynamics and the Department of Earth Sciences, it is one of the most well-developed and most promising land-based models. It combines the Land model, which was established at the Institute of Atmospheric Physics (Chinese Academy of Sciences in 1994, IAP94) (Dai et al., 1997), Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1993) and the National Surface Atmospheric Research Center's Land Surface Model (LSM) (Bonan et al., 1996) and other gradual improvements of land surface process models, improving the parameterization scheme of physical processes in the model. The CLM4.5 land surface process model version recently released by the National Center for Atmospheric Research has improved the photosynthesis process plan and knowledge of the hydrological processes and wetland distribution in cold regions, soil carbon added due to bioturbation, low temperature disturbances and diffusion. It also has improved nitrogen vertical mixing (the mechanism of biological nitrogen fixation in the vertical direction of the soil) and methane emission model to correct the soil biogeochemical program. In addition, the new version of the CLM4.5 proposes new crop models, lake models, snow cover models, proportional parameterization schemes and various urban class categories. Minor changes include the transition of C3 Arctic grass and shrub phenology from deciduous to seasonal deciduous and changes in glacier albedo. Compared to CLM4.0, the forcing field data used by CLM4.5 is improved from the default Qian to the more time-scaled CRUNCEP V7 forcing field data with higher spatial resolution (Lawrence et al., 2011).

2.2 Introduction to the data

(1) Atmospheric forcing field and surface data

The test used CRUNCEP V7 data with a horizontal spatial resolution of 0.5°×0.5° as the forcing field data for driving the CLM4.5 land model. The forcing field data includes near-surface pressure, specific humidity, precipitation, temperature, wind speed, solar shortwave radiation and atmospheric longwave radiant flux data. Land surface data information such as topographical terrain, soil texture components, soil colour, and the classification of land use types are derived from the land surface property parameter data that come with the CLM4.5 model.

(2) Observation data

The observation data used in the study are from the plateau soil temperature monitoring network of the Northwest Institute of Ecology and Environmental Resources, Chinese Academy of Sciences, 2010–2016. The selected four stations (Nagri, Shi quanhe, Nagqu and Maqu) represent different climatic zones and vegetation cover types. Nagri is a temperate arid climate zone with sparse vegetation, Shi quanhe is a semi-desert and desert zone, and the underlying surface is mainly desert or bare land. Nagqu is a semi-arid and sub-arid climate zone, and the underlying surface type is Grassland. Maqu is a continental subtropical alpine zone with rich vegetation cover on the underlying surface of the semi-humid zone (Li Maoshan, 2004).

The main information about the sites is shown in Table 1-1:

Table 1
Basic information of the observation site

Site	Climatic characteristics	Vegetation coverage	NDVI
Nagri	Plateau temperate arid climate zone	Sparse vegetation	$0.1 \leq NDVI \leq 0.2$
Shi quanhe	Semi-desert and desert zone	Desert or bare land	$0 \leq NDVI \leq 0.1$
Nagqu	Sub-arid semi-arid climate zone	Grassland	$0.3 \leq NDVI \leq 0.4$
Maqu	Plateau continental high-altitude zone	Meadow with prosperous vegetation cover	$0.5 \leq NDVI \leq 0.6$
Note: NDVI (Normalized Difference Vegetation Index)			

Due to damage at some observation points in the soil temperature observation network, the data are not continuous. In this paper, some observation points with complete data and good time continuity are selected for the research work. To ensure the authenticity and reliability of the data, the missing data and error values are corrected in the data check (Chen et al., 2017). The data of the Nagri, Shi quanhe and Nagqu areas ranged from September 7, 2014, to August 10, 2016. The time range of the Maqu area was from May 17, 2010, to June 23, 2016. The details of CLM4.5 and reanalysed soil temperature data are shown in Table 2.

Table 2
Soil temperature data information

Data	Time resolution/h	Spatial resolution	Soil temperature level/cm
CLM4.5	24	0.1°×0.1°	0 1.75,1.75 4.51 4.51 9.06 9.06 16.55 16.55 28.91 28.91 49.29 49.29 82.89 82.89 138.28 138.28 229.61 380.19 628.45 628.45 1037.75 1037.75 1712.59 1712.59 2825.20 2825.20 4210.32
ERA-Interim	6	0.125°×0.125°	0 7,7 28 28 100 100 289
GLDAS-CLM	3	1°×1°	0 1.8,1.8 4.5 4.5 9.1 9.1 16.6 16.6 28.9 28.9 49.3 49.3 82.9 82.9 138.3 138.3 229.6 229.6 343.3

(3) Reanalysis data

a.ERA-Interim

ERA-Interim is a new global reanalysis from the European Centre for Medium-Range Weather Forecasts (Simmons et al., 2006) that has continuously updated in real time since 1979. The data assimilation system used to produce ERA-Interim is based on a 2006 release of the IFS(Cy31r2). The system includes a 4-dimensional variational analysis with a 12-hour analysis window. The surface fluxes in ERA-Interim are based on the land surface model TESSEL (Tiled ECMWF Surface Scheme for Exchange over Land, (van den Hurk et al., 2000)) forced by atmospheric analysis and short range forecasts. Land data assimilation constrains the model fields on the basis of short-range forecast errors; soil moisture and temperature are corrected using air temperature and relative humidity observations from SYNOP stations (Douville et al., 2000). The fluxes were obtained as monthly mean values in W/m2 at a resolution of 0.75°×0.75° (very close to the native ERA-Interim T255 Gaussian reduced grid)

b. GLDAS-CLM

The Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004) drives multiple off-line land surface models, integrating a large quantity of observation-based data enabled by the Land Information System (Kumar et al., 2006). It uses advanced surface modelling and data assimilation techniques to ingest satellite and ground observation data products to generate optimal surface conditions and flux fields. Currently, GLDAS drives four land surface models (Mosaic, Noah, CLM) and the Variable Infiltration Capacity (VIC), forcing them with satellite-derived precipitation and radiation data and atmospheric analysis model outputs (Jiménez et al., 2011). The CLM includes superior components from each of three contributing models: the NCAR Land Surface Model (Bonan, 1998), the Biosphere-Atmosphere Transfer Scheme (Dickinson et al., 1986), and the LSM of the Institute of Atmospheric Physics of the Chinese Academy of Sciences (Dai et al., 1997). Both of the first two “frozen” versions of the CLM are included in the GLDAS.

2.3 Method

2.3.1 Basic processing of site data

In this paper, the observed data are used to analyse the applicability of the CLM4.5-simulated values of the corresponding time periods on the plateau. Since the observed data are different from the spatial and temporal resolution of the simulated output, this paper uses the daily average processing method to unify the time resolution of the data and the neighbouring grid method to spatially match the reanalysis data and the observations. By comparing the results of the neighbour lattice matching method and the bilinear interpolation method, it is found that the data obtained by the neighbour lattice matching method at most sites has a smaller standard error. (Liu et al., 2015).

2.3.2 Soil stratification

The CLM4.5 data are the average value of the soil layer with a certain thickness, which differs from the layered soil depth. Therefore, when the comparative analysis is carried out, the data are divided into two layers. For the first layer, the CLM4.5 data from 0 to 9.06 cm (average of 0-1.75 cm, 1.75–4.51 cm, and 4.51–9.06 cm) were compared with the 0–10 cm depth in the observed values. For the second layer, the data from 9.06 to 49.29 cm (average of 9.06 to 16.55 cm, 16.55 to 28.91 cm, and 28.91 to 49.29 cm) in CLM4.5 were compared with the observed values at depths of 10–50 cm.

2.3.3 Method for calculating error metrics

This paper selects six common error metrics to quantify the consistency between CLM4.5, reanalysis and observational data: R (correlation coefficient), RMSE (root-mean-square error), Bias (mean bias), ubRMSE (unbiased RMSE) (Entekhabi et al., 2010), SDV (standard deviations) and E (Albergel et al., 2013).

SDV is the normalized standard deviation, which is the ratio between the soil temperature product and the standard deviation of the observed values and represents the relative magnitude of the change in soil temperature with time. An SDV close to 1 indicates that the magnitude of the change in soil temperature is close to the observed value. E represents the distance from the point represented by each product to this point and can be used to quantify the comprehensive level of R and SDV in the model change. The smaller the value of E, the larger the correlation coefficient and the closer the change is between the products and the observed value (Entekhabi et al., 2010).

3 Analysis Of The Applicability Of Clm4.5-simulated Soil Temperature On The Qinghai-xizang Plateau

To eliminate the influence of the initial state of soil moisture changes, the 1981–2016 CRUNCEP forcing field data are used as the atmospheric forcing driving model to integrate for 36 years. The result is then used as the initial field of CLM4.5, and the atmospheric forcing is used to integrate for 36 years. Finally, the soil moisture process is fully balanced, and the output is the integration of results from 1981–2016 with a spatial resolution of 0.1°×0.1° and a time resolution of daily and monthly averages. By studying the time-varying characteristics of soil temperature in the CLM4.5, observing and reanalysing the four sites, and then calculating the error quantities used to quantify the accuracy of each product, the applicability of the CLM4.5 data on the plateau can be verified.

3.1 Comparative analysis of CLM4.5, reanalysis data and observations

Figure 2 is a time-dependent plot of the observed, CLM4.5 and reanalysis data of the two-layer daily average temperature. It can be seen from the figure that the CLM4.5 model can reasonably reproduce the seasonal periodic variation characteristics of the soil temperature observations at each site and is consistent with the changes in the ERA-Interim and GLDAS-CLM. The seasonal values at different depths are consistent, and the soil temperature changes in the 0–10 cm layer are slightly larger than in the deep layer, which may be due to the influences of solar radiation, wind speed, precipitation and other factors on the shallow soil temperature. In addition, the Nagqu area has a higher altitude, the climate is cold and dry, and the surface cover type is grassland, resulting in a significantly lower temperature than the Shi quanhe and Maqu areas (Fig. 2c). The Maqu area is a sub-humid area of the plateau continental high-cold belt. The meadow covers the surface with prosperous vegetation, and the soil temperature is higher than that in other areas. (Fig. 2d; Table 3). What is the relationship between soil temperature and vegetation cover in the area? Studies have shown that temperature and precipitation have a certain impact on vegetation growth, and the change in vegetation cover is dominated by the cumulative effect of temperature (Li et al., 2002). In addition, there is a positive correlation between the soil temperature at a depth of 2 m and at the soil surface at each site. The positive correlation shows that soil temperature is closely related to vegetation growth (Liang et al., 2010).

Table 3
Soil temperature at different levels in different climate zones of the Qinghai-Xizang Plateau.

Soil temperature (°C)	Nagri	Shi quanhe	Nagqu	Maqu
0-10cm	4.41	6.40	5.50	6.32
10-40cm	4.28	6.96	3.87	7.05
Average	4.345	6.68	4.685	6.685

Figure 3 is a Taylor's plot of the CLM4.5, reanalysis and observation data of the two-layer daily average soil temperature that shows the distribution of the correlation and variation between the simulated and observed values. It can be seen from the figure that the simulated and observed temperature values for the first layer of soil has a significant positive correlation at each site ($R > 0.955$), and the correlation coefficient of the ERA-Interim data at each site is greater than 0.928. The correlation between the GLDAS-CLM and observed soil temperature values at Maqu station is only 0.854. All of the above results pass the 99% confidence test. In terms of the magnitude of change (SDV), the simulated values in the Maqu and Ngari regions are closer to the observed values (Chen et al., 2012), and in the Shi quanhe area, the SDV is large, ($SDV < 0.75$). The ERA-Interim value is closest to the observation value at Shi quanhe station; the variation range of GLDAS-CLM at the Maqu station is the closest to the observed value. Based on the results of the comprehensive variation, the correlation coefficient and E, it can be seen that the simulated value performs best at the Maqu station; the integrated SDV, R and E error metrics show that the CLM4.5 simulation results in the Maqu and Nagqu areas are good. The ERA-Interim analysis data have a good effect on the soil temperature at Shi quanhe station. The GLDAS-CLM data have a good effect at the Nagri station (Fig. 3a). When combining the second-layer soil temperature change range, the correlation coefficient and E, it can be seen that the simulation value has the best description effect at Maqu station. GLDAS-CLM has a good reproduction effect on the soil temperature at Naqu station, while the simulation effect of CLM4.5 at Naqu station is only second to that of GLDAS-CLM (Fig. 3b).

Nagri is an area of sparse vegetation (NDVI = 0.1), the Shi quanhe surface cover type is desert and bare land (NDVI = 0.05), and the land cover types of Nagqu and Maqu are plateau grassland (NDVI = 0.3) and plateau meadow (NDVI = 0.5) (Liang et al., 2004; Wang et al., 2014). These results show that the CLM4.5 model has a better effect on the variation in soil temperature in Naqu and Maqu in the vegetation coverage area than in the desert area simulation.

Table 4 is a statistical table of the measured values of the daily average soil temperature simulated values and observed values at each site. It can be seen from the table that for the first layer of soil temperature, the CLM4.5 simulation value is systematically smaller than the observed value (Bias < 0), and the simulated soil temperature in the Nagqu area is the closest to the observed value (Bias=-1.6). The soil temperature of GLDAS-CLM is close to that at the observations at Nagri, Shi quanhe and Maqu stations, with a large difference between the GLADAS-CLM and the observations at Naqu station (Bias = 5.906). The soil temperature values of ERA-Interim in Nagri, Shi quanhe and Maqu stations differed from the observed values by 10.021°C. In terms of RMSE and ubRMSE, CLM4.5 has the best simulation results for the observed soil temperature in Nagqu and Nagri, with a higher accuracy. The error measures between the simulated and observed values in the Nagqu area is RMSE = 3.26 and ubRMSE = 2.63, and in the Nagri area they are RMSE = 4.002 and ubRMSE = 3.17. The reproducibility of CLM4.5 on the soil temperature in the Shi quanhe area is worse than that of other stations; the RMSE and ubRMSE of GLDAS-CLM data at the Nagri, Shi quanhe and Maqu stations are small, and the reproduction effect of observation values is good.

For the second layer soil temperature, the CLM4.5-simulated soil temperature values of each site are consistent with those of the shallow layer, and the error value is the smallest in the Nagqu area. The results are better than the GLDAS-CLM and ERA-Interim reanalysis data, as the correlation coefficients of the ERA-Interim data at the Nagri, Shi quanhe and Maqu stations are higher than 0.956. The error metrics of GLDAS-CLM in Nagri, Shi quanhe and Maqu are all optimal, and the CLM4.5 simulation results are second only to GLDAS-CLM. CLM4.5 deviates greatly from the observed values in some areas due to the quality of the forcing field data set of the driving mode, the difference between the accuracy of the land data and the actual surface condition of the model, and the description of the physical processes such as hydrology and heat conduction in the model. (Lai et al., 2014).

Table 4
Daily average soil temperature observations and reanalysis product error metrics for each site. RMSE (root mean square error), Bias (mean deviation), ubRMSE (unbiased RMSE) and R (correlation coefficient).

Site	Date	0-10cn						10-50cm					
		RMSE	Bias(°C)	ubRMSE	R	SDV	E	RMSE	Bias(°C)	ubRMSE	R	SDV	E
Nagri	ERA-Interim	9.604	-8.663	8.674	**0.975***	1.419	0.704	10.068	-8.540	8.567	**0.956***	1.731	0.910
	GLDAS-CLM	**3.573**	**2.354**	**2.915**	0.957*	**1.097**	0.567	**3.699**	**2.345**	**2.712**	0.954*	**1.281**	0.667
	CLM4.5	4.002	-3.02	3.17	0.965*	1.151	0.375	4.360	-2.778	3.52	0.933*	1.331	0.536
Shi quanhe	ERA-Interim	10.514	-10.021	10.010	0.959*	**0.997**	0.535	10.778	-10.608	10.618	**0.985***	1.076	0.649
	GLDAS-CLM	**3.005**	**0.160**	**2.467**	**0.974***	1.394	0.691	**2.456**	**-0.887**	**2.006**	0.979*	**1.008**	0.738
	CLM4.5	6.63	-5.24	5.33	0.955*	0.744	0.364	6.485	-5.660	5.65	0.968*	0.425	0.598
Nagqu	ERA-Interim	5.444	-4.459	4.587	0.928*	0.748	0.643	5.287	-3.782	4.452	0.922*	0.707	0.666
	GLDAS-CLM	6.740	5.906	5.975	0.930*	**0.904**	0.606	7.056	6.467	6.460	**0.943***	**0.877**	0.582
	CLM4.5	**3.26**	**-1.6**	**2.63**	**0.960***	0.865	0.296	**3.37**	**-0.87**	**2.85**	**0.943***	0.817	0.355
Maqu	ERA-Interim	4.811	-4.443	4.444	**0.963***	0.746	0.588	5.149	-4.940	4.938	**0.971***	0.695	0.604
	GLDAS-CLM	**3.760**	**1.033**	**2.819**	0.872*	**1.062**	0.725	**3.275**	**0.337**	**2.514**	0.854*	**1.035**	0.742
	CLM4.5	4.336	-3.810	3.85	0.960*	1.076	0.303	4.716	-4.386	4.38	0.963*	1.049	0.283
Note: * indicates that the 99% confidence test has passed.													

A comprehensive analysis of the two-layer soil temperature changes shows that CLM4.5 can accurately and reasonably reproduce the dynamic process characteristics and spatial distribution characteristics of two-layer soil temperature over time in various regions (Xie et al., 2017). However, it is found in this study that the land model has different simulation effects on soil temperature in different regions. For example, the CLM4.5 simulation value is better in the characterization of the soil temperature in Nagqu and Nagri than in the Shi quanhe region. This difference may be related to the accuracy of the model forcing field precipitation data, the choice of the physical process parameterization scheme, the vegetation coverage of each region and the actual change in vegetation type. The research results are consistent with the conclusions reached by prior researchers (Zeng et al., 2015).

3.2 Comparative analysis of the spatial distribution and variation trends of soil temperature in CLM4.5 simulation and reanalysis

3.2.1 Spatial distribution characteristics of soil temperature

Figure 4 is a spatial distribution of 0–10 cm soil temperature on the plateau from 1981 to 2016. It can be seen from the figure that the spatial distribution characteristics of the CLM4.5 data are consistent with those of the other data, except for the numerical values. In the past 36 years, the soil temperature of the plateau presented obvious seasonal cycle changes and increased from north to south (Zhang et al., 2008). Due to the special geographical environment and high altitude of the plateau, the overall soil temperature of the plateau is significantly lower than that of the surrounding areas; in the Qaidam Basin, the overall soil temperature is significantly higher than that in the surrounding areas, which is related to its own special geographical environment. There, the underlying surface type is mainly desert, covering saline desert soil and gypsum desert soil, and the ground vegetation is sparse and of a single type, making the soil temperature more susceptible to the influence of solar radiation and air temperature (Zhou et al., 2004).

It can be seen that the soil temperature of all soil moisture products on the plateau is positive in the summer and negative in the winter, which reasonably reproduces the variation in soil temperature by season on the plateau (Chen et al., 2017). In all four seasons, the CLM4.5 values are lower than the ERA-Interim values, and the GLDAS-CLM soil temperature values are the highest throughout the year. The simulation results of CLM4.5 on the plateau soil temperature are more elaborate than those of ERA and GLDAS and can accurately depict the distribution of plateau waters. However, due to their low resolution, ERA-Interim and GLDAS-CLM cannot describe the distribution characteristics of soil temperature in different climatic regions and the distribution of rivers and lakes on the plateau.

Figure 5 shows the spatial distribution of soil temperature in the 10–50 cm layer on the plateau from 1981 to 2016. It can be seen from the figure that the temporal and spatial distribution characteristics of the soil temperature in the second layer of the plateau are consistent with those of the first layer. The soil temperature has significant seasonal characteristics, and there is no significant difference in the soil moisture content between the two layers (Zhang et al., 2008). From the beginning of spring to the end of summer, the high soil temperature region gradually expands from the south to the north. From the early autumn to the end of winter, the area of the plateau with high soil temperature is substantially reduced from north to south. The spatial distribution of soil temperature throughout the plateau generally shows the step-like variation in the high temperature in the northernmost part of the plateau. It can be seen from the numerical values that the soil temperature from the CLM4.5 and ERA-Interim are similar, while the soil temperature from the GLDAS-CLM is higher than that from the CLM4.5 and ERA-Interim.

3.2.2 Variations in soil temperature

Since the CLM4.5, ERA-Interim and GLDAS-CLM temperature data at soil depths of 0–10 cm and 10–50 cm exhibit nearly the same trends, the data from 10–50 cm are omitted. Figure 6 shows the soil temperature changes from 0 to 10 cm in all four seasons on the plateau from 1981 to 2016. It can be seen from the figure that in spring, the CLM4.5 temperature data show distribution characteristics of “+ - +” from west to east in the plateau region, while the ERA-Interim temperature data show distribution characteristics of “- + -” from north to south. The GLDAS-CLM data show that the temperatures is significantly warming in the Sanjiangyuan area and exhibits a “+ - +” distribution from west to east, which is similar to the distribution of CLM4.5. However, the observed range of temperature reduction in the northern Tibetan Plateau is larger than the simulated range, and the range of temperature is much higher than that from CLM4.5.

In summer, CLM4.5 has a warming trend in most areas, although it is reduced locally in the Qinghai Plateau (Guo et al., 2017). ERA-Interim has the distribution characteristics of “+ - + -” from northeast to southwest, and the Qinghai Plateau has significantly increased temperature, while GLDAS-CLM has the characteristics of “- + -” from south to north. In the autumn, CLM4.5 showed the spatial variation characteristics of “+ - + -” from west to east in the plateau region, but the distribution of CLDAS-CLM was reversed. In winter, CLM4.5 has a declining trend in the southwestern plateau, northern Tibetan Plateau and Qinghai Plateau (Yang et al., 1999), in other areas has increased significantly. ERA-Interim has obvious warming trend in most areas, although there are declining trends in the Kunlun Mountains, the middle of the Sanjiangyuan, the Qinghai Plateau and the Sichuan-Tibet Alpine Valley. The temperature variation trend of GLDAS-CLM in the northeastern part of the plateau is consistent with the distribution of CLM4.5, while the rest of the regions have opposing trends with the simulated values.

In summary, between 1981 and 2016, the CLM4.5 soil temperature of the plateau showed a strip-like change in the summer-autumn season, and the soil temperature in winter and spring showed an overall warming trend (Guo et al., 2017), while the local temperature decreased. The ERA-Interim products in winter are consistent with the CLM4.5 results, and the other seasons show opposite temperature changes. The GLDAS-CLM temperature values in the Sanjiangyuan region in spring and their variation in the Qinghai Plateau in winter are consistent with the simulated values (Wang et al., 2003). The temperature changes in the other seasons are opposite to those obtained by the CLM4.5, and the overall variation is much higher than the simulated value.

3.3 Variation characteristics of soil temperature in CLM4.5

3.3.1 Interannual variation in soil temperature

Figure 7 is a time series diagram of the interannual variation in two-layer standardized soil temperature on the plateau. It can be seen from the figure that the deep soil temperature is about the same as that of the shallow layer. From the 1980s to the beginning of the 21st century, the soil temperature of the two layers of the plateau showed an upward trend (Zhang et al., 2008; Chen et al., 2017), after which the two soil temperature values began to decline. The average annual soil temperatures of the plateau occurred between the 1980s and the 1990s, while the highest soil temperatures occurred between 2000 and 2009. It is indicated that during the period of 1981–2016, the plateau soil temperature experienced a "rise-down" change process.

To further study the long-term variation characteristics of soil temperature at different depths, this paper calculated the climatic tendency rate of soil temperature at different depths in the four seasons of the Plateau from 1981 to 2016 and performed a significance level test. As shown in Table 5, it can be seen from the table that between 1981 and 2016, the two-layer soil temperature in the plateau has the same long-term upward trend in the four seasons, deemed significant at a 95% confidence level. This is especially true in spring and autumn, the soil temperature rises significantly (Xie et al., 2005).

Table 5
Statistical table of climate variation trends of soil temperature (units: °C/a) at different depths of the Tibetan Plateau.

Soil layer	Statistics	Spring	Summer	Autumn	Winter
0–10 cm	Climate tendency rate	0.399	0.305	0.397	0.298
	R^2	0.246	0.314	0.582	0.113
	F	11.087*	15.570*	47.320*	4.327*
10–50 cm	Climate tendency rate	0.370	0.274	0.346	0.296
	R^2	0.244	0.277	0.600	0.133
	F	10.997*	13.052*	50.894*	5.207*
Note: * indicates that the 99% confidence test has passed.					

3.3.2 Monthly variation in soil temperature

Figure 8 shows the monthly variation in soil temperature in the two layers of the plateau from 1981 to 2016. It can be seen that the soil temperature in the two layers of the plateau has obvious seasonal variation characteristics and that the soil temperature throughout the whole year is "monomodal" (Wang et al., 2009). This change is consistent with the cyclical changes in solar radiation and atmospheric temperature. From March to September, the shallow soil temperature in the plateau is higher than the deep soil temperature. From October to February, the deep soil is wetter than the shallow soil. The shallow soil is more susceptible to surface heat changes than the deeper soil layer. In addition, the deep soil temperature has a certain hysteresis to the solar radiation received by the surface, and the temperature changes slowly with depth. At the same time, when there is snow on the ground in winter, snow can act as an insulation layer, which can maintain deep soil temperature for a certain period of time. The internal heat of the earth can also transfer heat to the surface to a certain extent, but because of the poor thermal conductivity of the earth's crust, compared with the heating effect of solar radiation on the soil temperature, the influence of the heat inside the earth on the soil temperature is not obvious (Liu et al., 1991; Chen et al., 2009).

4 ��

In this paper, CRUNCEPV7 forcing field data were used to drive CLM4.5 to simulate the temporal and spatial variation of soil temperature in the plateau from 1981 to 2016. The simulation results were compared with observations and ERA-Interim and GLDAS-CLM products and then the CLM4.5 model simulation results were comprehensively evaluated to depict the dynamic changes in soil temperature on the plateau. The temporal and spatial variation characteristics of soil temperature in the plateau are further analysed. The research results are as follows:

(1) CLM4.5 can accurately describe the dynamic process and changes in the two layers of soil temperature over time at the observation site. In late summer and early autumn, the soil temperature gradually decreases, reaching its lowest value in February of the following year. After the spring air temperature increased, the soil temperature began to increase slowly, reaching a peak in August. The seasonal variation in soil temperature at different depths was generally consistent.

(2) The spatial distribution characteristics of the two layers of soil temperature between the CLM4.5 data and the two sets of reanalysis data are consistent, although there are differences in the numerical values. CLM4.5 can describe the spatial distribution of soil temperature in the plateau region in more detail. Spatially, the overall soil temperature of the plateau increases stepwise from north to south. The southern part of the plateau is the high soil temperature zone, the northern part of the plateau is the low soil temperature zone, and the soil temperature in the northern Qaidam

Basin is significantly higher than the surrounding area. Numerically, the CLM4.5 and ERA-Interim soil temperature values are similar, while the GLDAS-CLM soil temperature values are generally higher than the simulated values and ERA-Interim values.

(3) During the period from 1981 to 2016, the simulated soil temperature of the plateau showed a trend of “+ - + -” in the summer and autumn. The soil temperature in winter and spring showed a trend of increasing temperature, although in some isolated locations, the temperature decreased. The temperature trend of ERA-Interim products in winter is consistent with the simulated values, while the temperature trends in GLDAS-CLM in the Sanjiangyuan area in spring and the Qinghai Plateau in winter are consistent with the simulated values. All of the above results were tested by 95% confidence.

(4) During the period from 1981 to 2016, the plateau soil temperature experienced a “rise-descent” change process, and the overall trend showed a significant upward trend (through a 95% significance level), especially in spring and autumn when the soil temperature increased significantly.

(5) Through the study of the monthly variation of soil temperature in the plateau region, it is concluded that the soil temperature in the two layers of the plateau has obvious seasonal changes. The soil temperature in January has an upward trend, and the soil temperature gradually decreases after reaching a peak in July, resulting in a unimodal type of variation characteristics. The shallow soil temperature of the plateau from March to September is higher than the deep soil temperature, and the deep soil is higher than the shallow soil temperature from October to February.

Although the simulation results of the CLM4.5 model can reflect the seasonal variations of soil temperature and moisture at different depths, the simulation results are less accurate in some areas. Errors may be the result of a combination of factors, especially in a plateau with complex underlying conditions. Possible reasons include: accuracy of the soil temperature sensor at the observation site; unit conversion error between the temperature product and observation data of each soil temperature (K, °C); spatial observation scale mismatch between the observation site and the soil temperature product; and differences in the sampling depths (Table 1 for the sampling depth difference). A few causes of error that are especially true of the positioning of fixed stations include: the spatial resolution of the data output is different; the observation station may not be at the corresponding grid point; and the site data obtained by spatial interpolation or adjacent site matching methods cannot completely represent the real observation value of the site

On the one hand, for soil temperature products, the selected numerical prediction model, model driving field data, physical process parameterization scheme and output assimilation scheme will make the difference in soil temperature and moisture results, especially in the plateau where the terrain is complex, the altitude is high, and the climate is extreme. Are the parameters adjusted in consideration of the special conditions of the plateau? In addition, factors such as soil texture used in the simulation process, inaccurate vegetation cover information and whether constant parameters are applicable to the plateau area are also the reasons for the deviation of soil temperature products in the plateau.

On the other hand, due to the sparse observation sites in the plateau, the time continuity of observation data is poor, and the observation data of some observation points are seriously deficient, rendering it impossible to compare the simulated values and reanalysis data for long times and over large areas. However, the longest time range of soil temperature and humidity studied in this paper is only 6 years, so whether the selected reanalysis data and simulation results have the ability to describe long-term climate change in this region is still questionable. Is it possible to improve the accuracy of soil temperature and moisture in the plateau by improving the accuracy of vegetation cover on the plateau, adding more accurate soil texture information, and reducing the difference between the observation site and the underlying surface of the model grid? Further research is needed (Chen et al., 2017).

5 Declarations

Conflict of Interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the position presented in, or the review of, the manuscript entitled, “Numerical Simulation and Evaluation of Soil Temperature on the Qinghai-Xizang Plateau by the CLM4.5 Model”.

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Author's Contribution

Ding X: data analysis/interpretation, statistical analysis, experimental studies , manuscript preparation,

Lai X: provided data, study concepts, study design, manuscript revision/review, manuscript final version approval, supervision, project administration, funding acquisition.

Fan GZ: manuscript revision/review , manuscript final version approval, supervision, project administration, funding acquisition.

All authors read and approved the final manuscript.

Availability of data and material

The datasets used or analysed during the current study are available from the corresponding author on reasonable request.

Code availability

The codes of the data in this current study are available from the corresponding author on reasonable request.

Ethics approval

The authors have the responsibility about the methodology and the novelty, research, ethical standards, and professional guidelines in this contribution.

Consent to participate

We as the research team in this current contribution have voluntarily agreed to participate in this research study.

Consent for publication

We would like to give consent for the publication of identifiable details including text, material and methods, figures, and tables.

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Figures

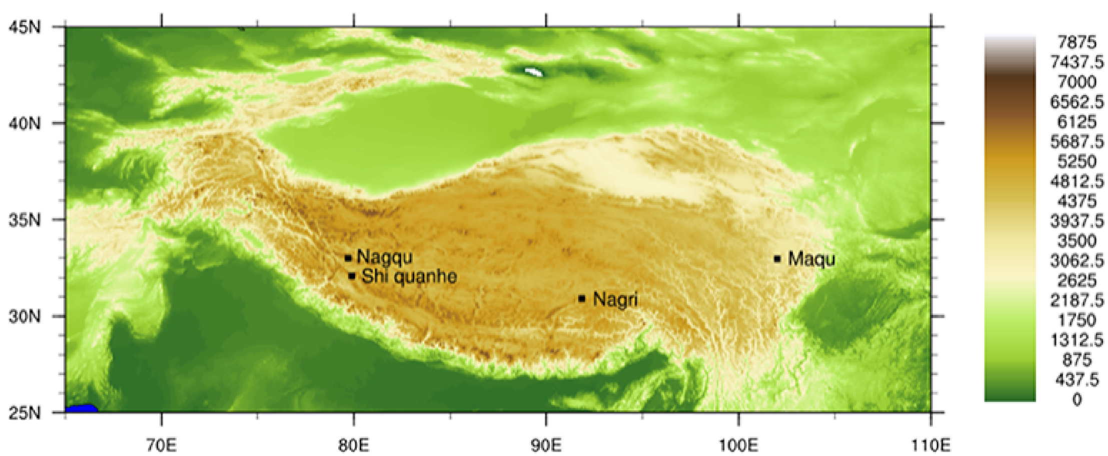

Figure 1

Geographical distribution map of the observation site on the plateau.

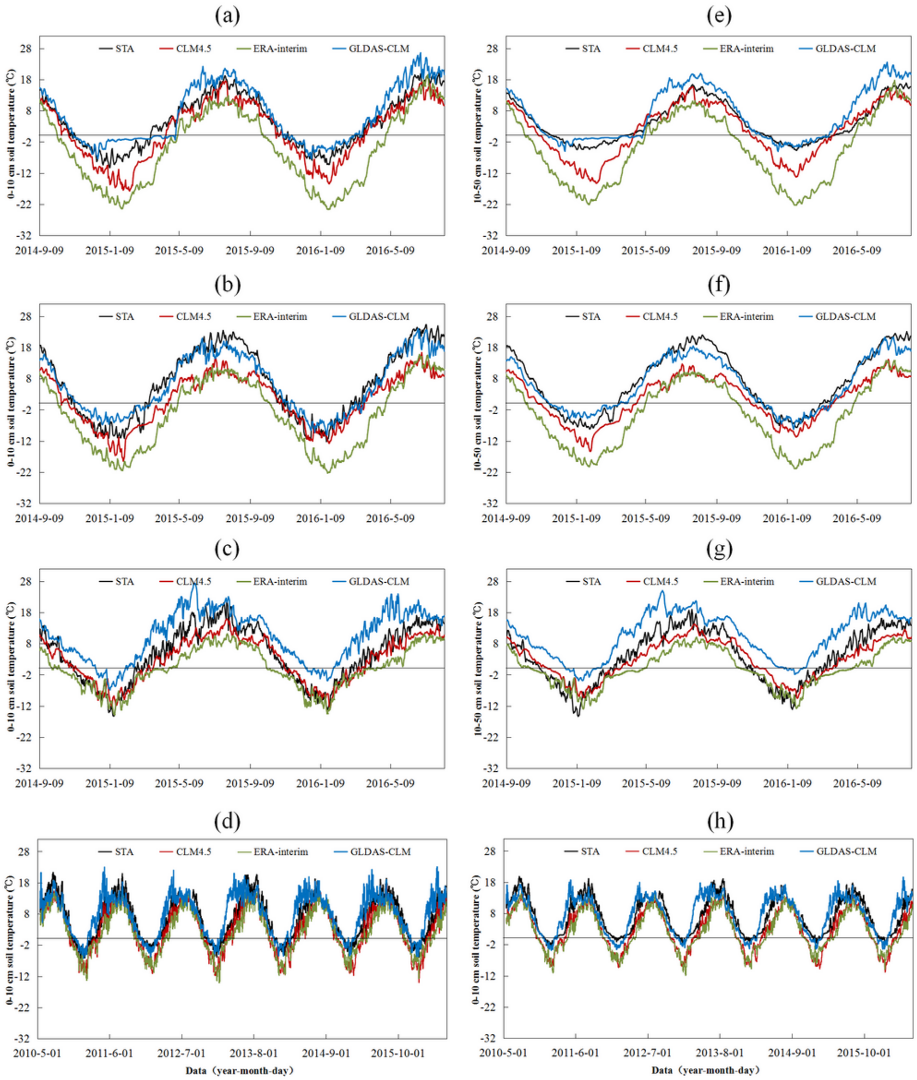

Figure 2

Comparison of the two-layer daily average soil temperature (unit: °C) between the CLM4.5 data, the reanalysis data and the observations. The left side is the first layer (0-10 cm), and the right side is the second layer (10-50 cm). (a)(e) Nagri, (b)(f) Shi quanhe, (c)(g) Nagqu, and (d)(h) Maqu.

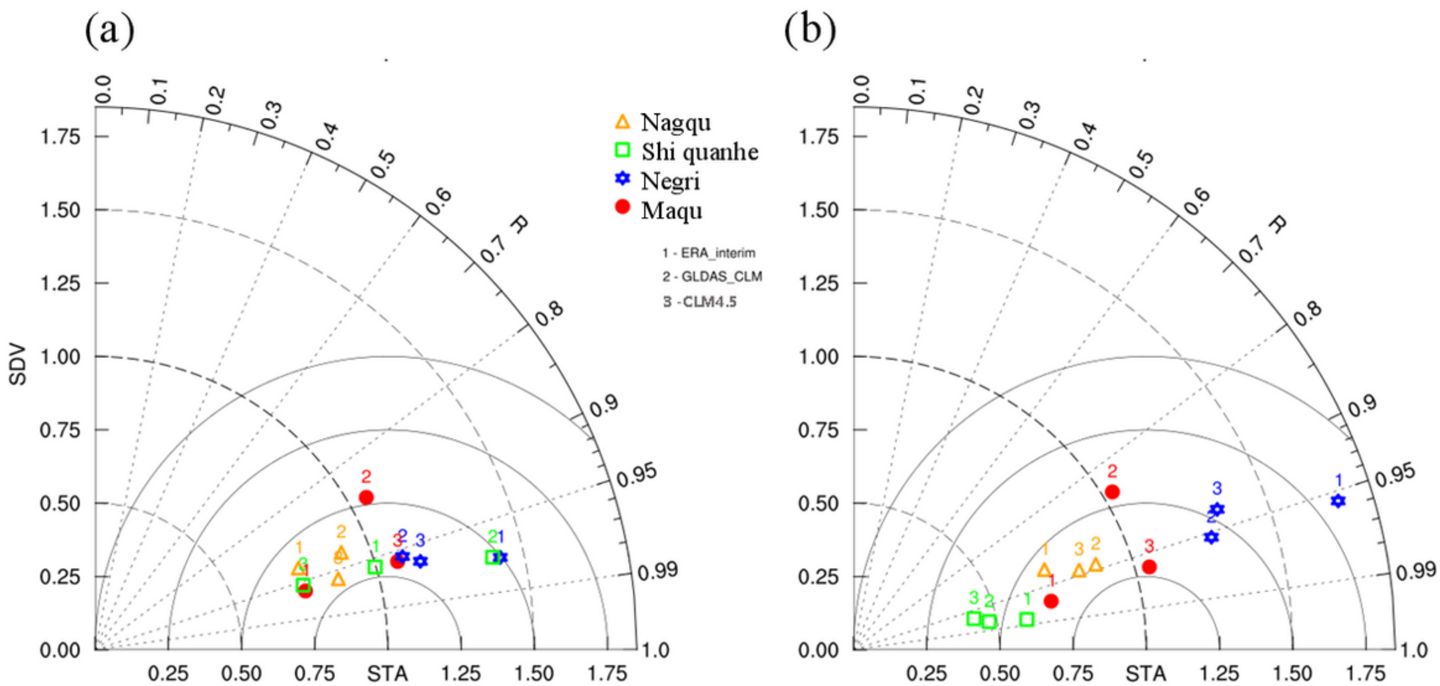

Figure 3

Taylor's plot of the average daily temperature of two layers of CLM 4.5 and observations. (a) the first layer (0-10 cm), (b) the second layer (10-50 cm).

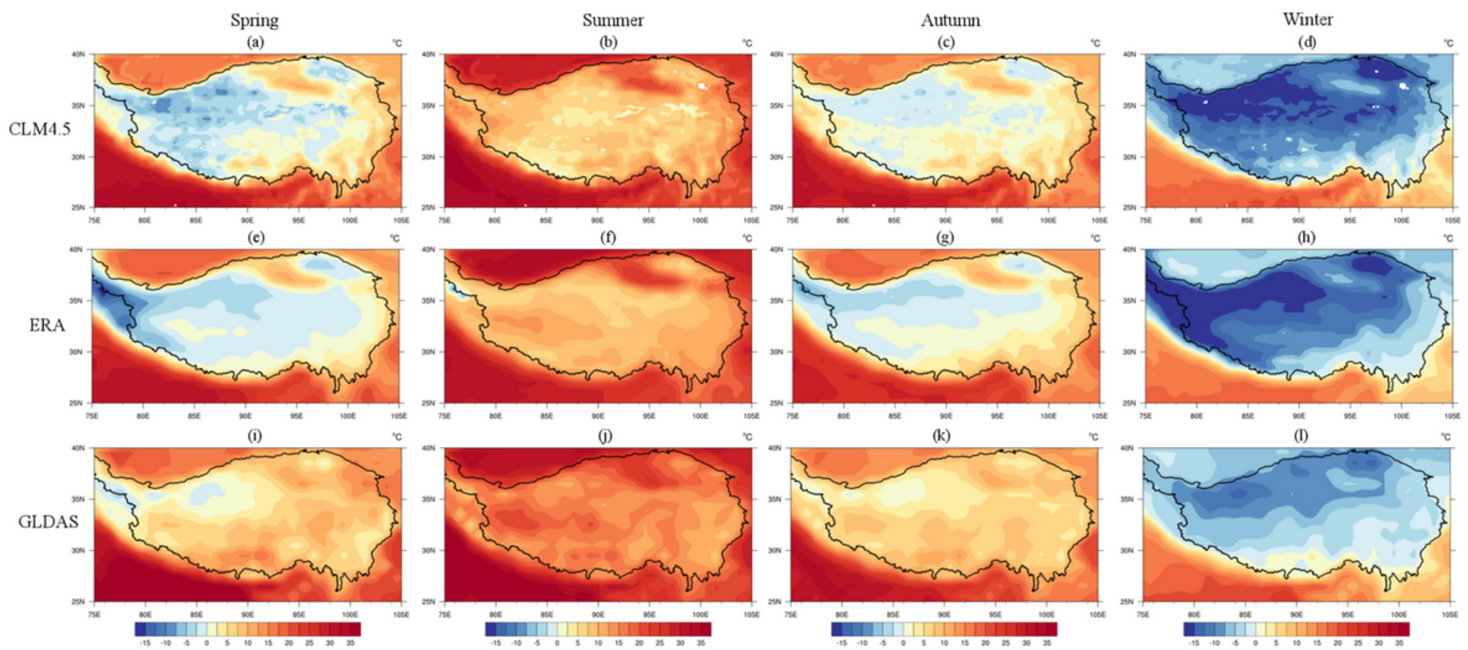

Figure 4

Spatial distribution of soil temperature (units: °C) of 0-10 cm on the plateau from 1981 to 2016. (a) (e) (i) Spring, (b) (f) (j) Summer, (c) (g) (k) Autumn, (g) (h) (b) Winter. (a)(b)(c)(d) CLM4.5, (e)(f)(g)(h) ERA-Interim, and (i)(j)(k)(l) GLDAS-CLM.

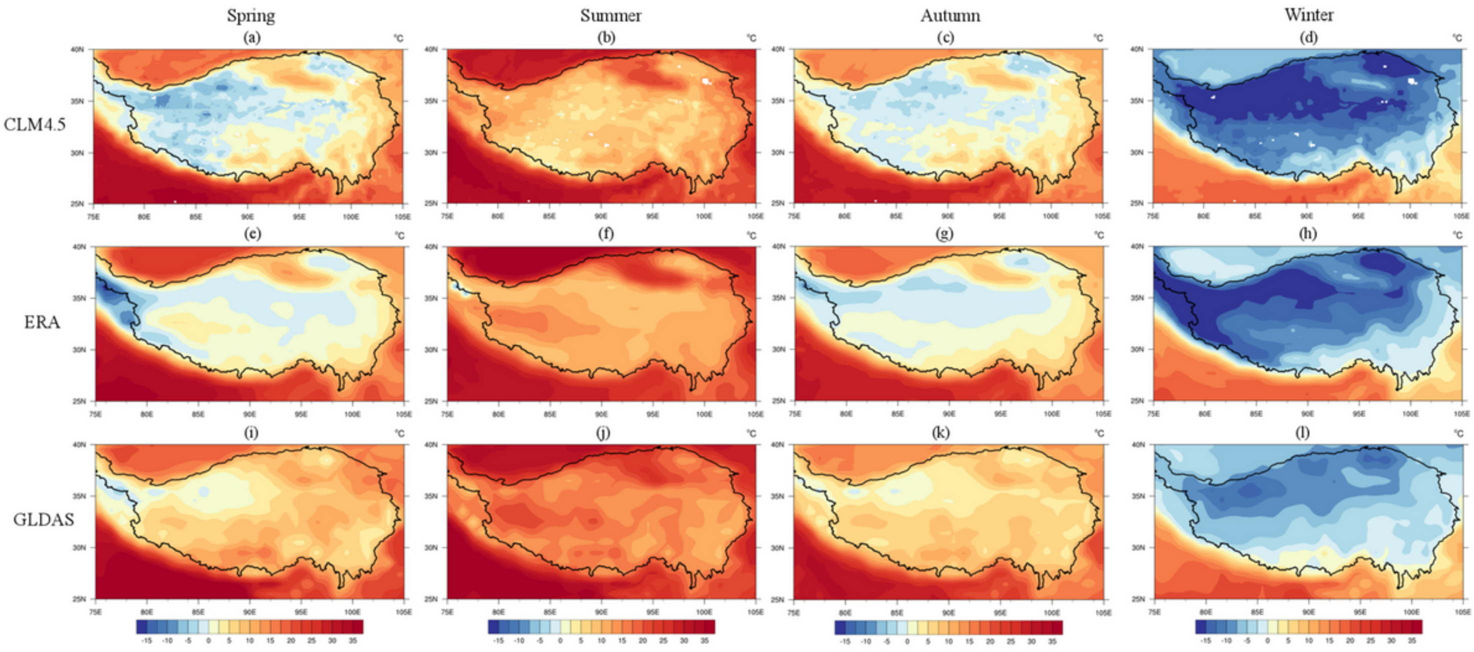

Figure 5

Spatial distribution of soil temperature (units: °C) of 10-50 cm on the plateau from 1981 to 2016. (a) (e) (i) Spring, (b) (f) (j) Summer, (c) (g) (k) Autumn, (g) (h) (b) Winter. (a)(b)(c)(d) CLM4.5, (e)(f)(g)(h) ERA-Interim, and (i)(j)(k)(l) GLDAS-CLM.

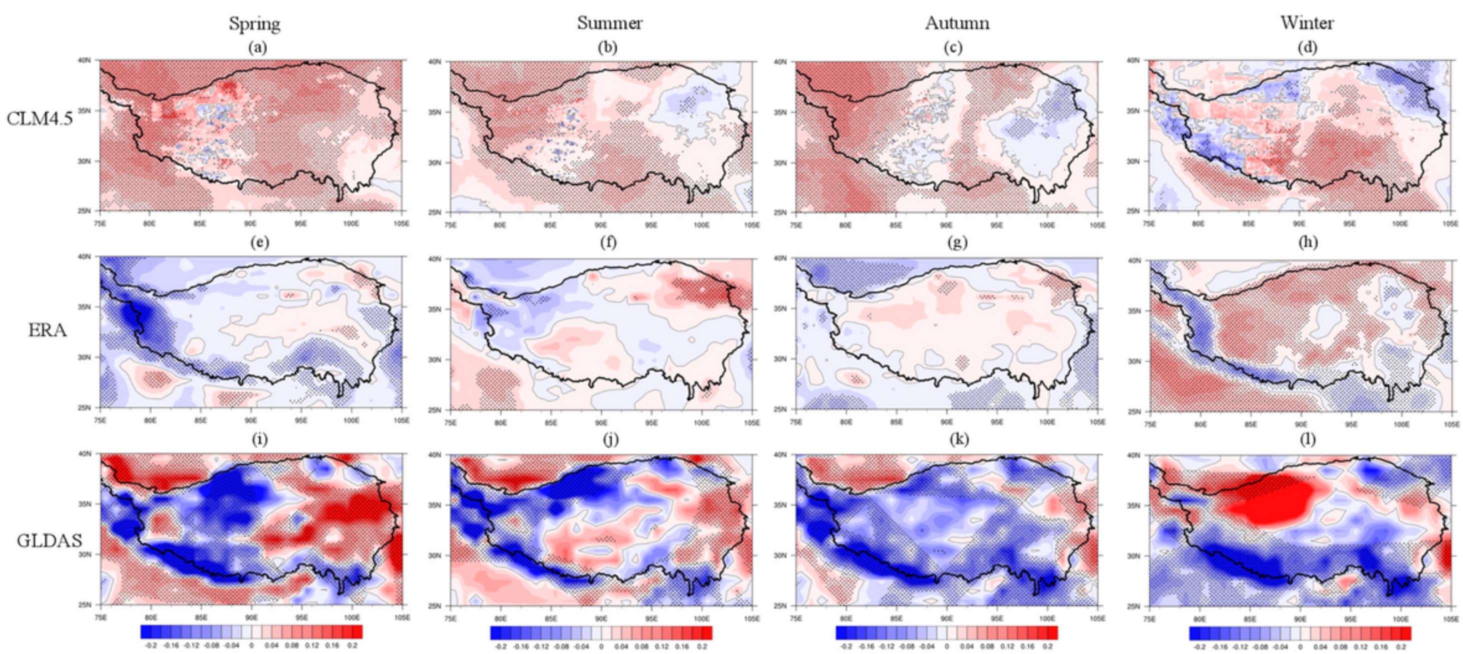

Figure 6

Variation trend of 0-10 cm soil temperature in the four seasons of the plateau from 1981 to 2016 (units: °C/a). (a) (e) (i) Spring, (b) (f) (J) Summer, (c) (g) (k) Autumn, (g) (h) (b) Winter. (The dot area represents passing the 95% confidence level). (a) (b) (c) (d) CLM4.5, (E) (f) (g) (h) Era interim, and (i) (J) (k) (l) GLDAS CLM.

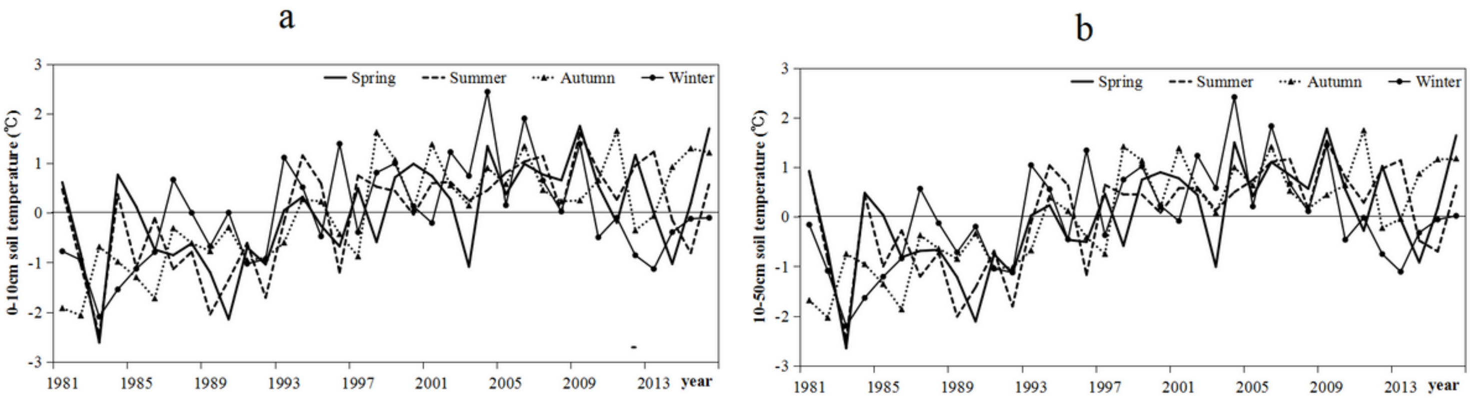

Figure 7

Time series of the interannual variation of two-layer standardized soil temperature in the plateau. (a) 0-10 cm, (b) 10-50 cm.

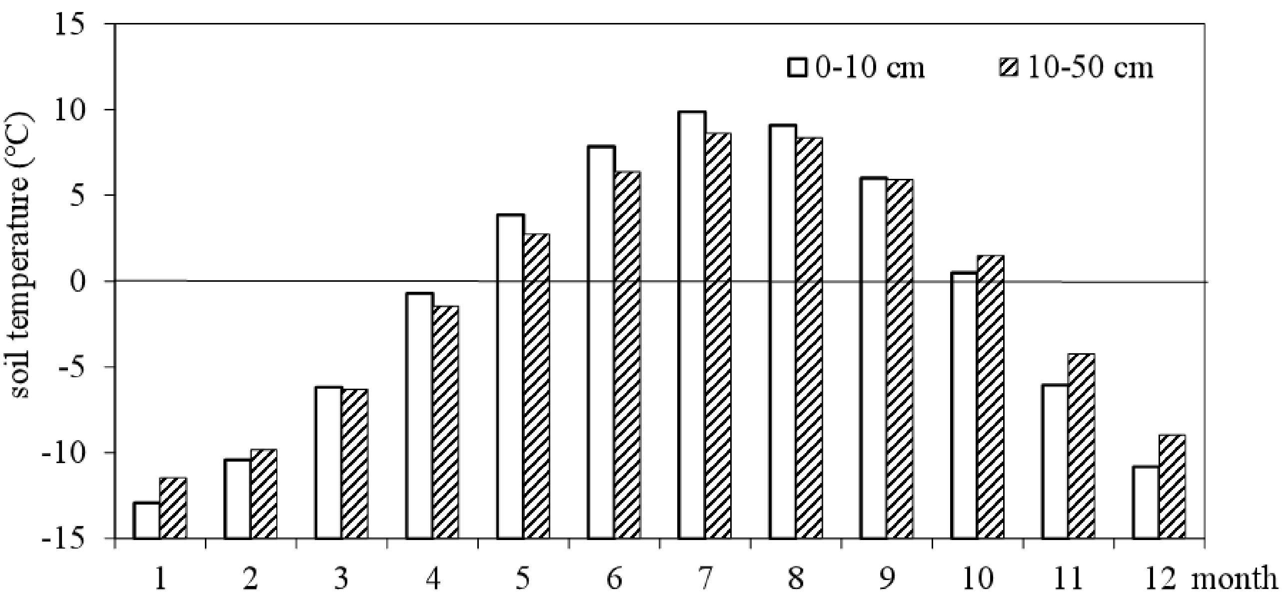

Figure 8

Monthly variation of soil temperature (unit: °C) on the plateau from 1981 to 2016.