Analysis on the Temporal and Spatial Characteristics of the Shallow Soil Temperature of the Qinghai-Tibet Plateau

Yujie Li

Northwest Institute of Eco-Environment and Resources

Cunjie Zhang

China Meteorological Administration

Zhenchao Li

Northwest Institute of Eco-Environment and Resources

Liwei Yang

Northwest Institute of Eco-Environment and Resources

Xiao Jin

Northwest Institute of Eco-Environment and Resources

Xiaoqing Gao (✉ xqgao@lzb.ac.cn)

Northwest Institute of Eco-Environment and Resources <https://orcid.org/0000-0003-0806-2014>

Research Article

Keywords: Qinghai-Tibet Plateau, Shallow soil, Soil temperature, Climate change, Land surface process, land-atmosphere interaction

Posted Date: March 7th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-904007/v2>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Analysis on the Temporal and Spatial Characteristics of the Shallow

Soil Temperature of the Qinghai-Tibet Plateau

Yujie Li^{1,2} • Cunjie Zhang³ • Zhenchao Li¹ • Liwei Yang^{1,2} •

Xiao Jin¹ • Xiaoqing Gao^{1*}

¹Key Laboratory of Land Surface Process and Climate Change in Cold and Arid Regions of Chinese Academy of Sciences, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, 320, Donggang West Road, Lanzhou, Gansu, 730000, China.

²University of Chinese Academy of Sciences, Beijing 100049, China.

³China Meteorological Administration, National Climate Center, Beijing, China

Corresponding author: Xiaoqing Gao, xqgao@lzb.ac.cn

Acknowledgment.

We thank the editors and reviewers for the constructive comments. We thank China Meteorological Administration, National Climate Center for the observational data. This research supported by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP), Grant No. 2019QZKK010303; Numerical Simulation Research on the Influence of Soil Temperature on Precipitation Forecast, Grant No. QHMS2019015; Key Talent Projects of Gansu Province in 2021. All authors declare that there is no conflict of interest.

Declarations

Conflict of interest The authors declares that they have no competing interest.

Abstract

Shallow soil refers to the soil layer within 50 cm underground. Shallow soil temperature (ST) directly or indirectly affects many processes in the soil, such as seed germination, plant growth, water evaporation. Shallow ST is also affected by solar radiation, atmospheric circulation, air temperature and precipitation changes. Therefore, the study of shallow ST is of great significance in understanding surface energy, water cycle, ecology and climate change. This work collected the observational data from 141 meteorological stations on the Qinghai-Tibet Plateau from 1981 to 2020, analyzed the ST as well as its temporal and spatial change characteristics at different levels. The results show that: 1) The shallow ST has a gradually increasing trend from north to south, from west to east. From the perspective of time characteristics, the increasing trend is obvious. The temperature increase of 0-20cm (the surface layer of the shallow soil) is roughly the same. The average annual ST is 9.15-9.57 °C, the interdecadal variabilities are 0.49-0.53 K/10a. The average annual ST of 40cm (the bottom layer) is 8.69 °C, the interdecadal variability reaches by 0.98 K/10a; 2) Considering the 7 regions, the warming trend is obvious, and there are certain regional differences. The average annual ST in different regions ranges from 5.2°C (Northeast of the Plateau) to 17.1°C (Western Sichuan Plateau), with a difference of nearly 12K; the standard deviation ranges from 0.40K (Western Sichuan Plateau) to 0.61K (Qiangtang Plateau), with a difference of 0.21K. This work is significant for understanding the characteristics of the ST evolution and the land-atmosphere interaction on the Qinghai-Tibet Plateau.

Keywords: Qinghai-Tibet Plateau · Shallow soil · Soil temperature · Climate change · Land surface process · land-atmosphere interaction

1. Introduction

The Qinghai-Tibet Plateau (QTP) is located in western China, including Tibet, Qinghai, southern Xinjiang, western Sichuan, southern Gansu, and northwestern Yunnan. The QTP spans more than 2500 km from east to west, and is about 1,000 kilometers from north to south. The total area is nearly $2.5 \times 10^6 \text{ km}^2$, accounting for about one-fourth of China's total area. It has an average elevation of 4000 m, which accounts for almost one-third of the thickness of the troposphere. The QTP, often

referred to as the *Roof of the World* or *Third Pole*, is known for its complex terrain and high altitude (Yang et al. 2014). QTP plays an important role in climate change and land-atmosphere interaction (Tang et al. 1979; Liu et al. 2000; Ma et al. 2011), its climate and ecological environment are jointly affected by westerly winds and Asian monsoons. In turn, the Qinghai-Tibet Plateau has also affected the regional and global climate change (Zhou et al. 2009). For example, the snow cover in winter and spring on the Qinghai-Tibet Plateau has a profound impact on temperature and precipitation in China and even in Asia (Wang et al. 2017; Wu et al. 2003). Changes in summer heat sources on the Qinghai-Tibet Plateau have a key impact on the evolution of the Asian monsoon (Duan et al. 2013; Park et al. 2012; Jiang et al. 2016). Many studies have shown that QTP is one of the most sensitive regions to global climate change (Su et al. 2011; Zhao et al. 2010).

Global temperature has increased rapidly in recent decades. Climate change, as a hot issue discussed in today's society, has attracted much attention. The IPCC Fifth Assessment Report (AR5) pointed out that the global surface temperature increased by 0.85°C from 1880 to 2021 (IPCC5, 2013; Qin and Stocker 2014). Global warming affects changes in a range of ecological processes and has the potential to alter the stability of ecosystems. Many scholars have also investigated the response of various ecosystem processes to temperature rise from the aspects of global warming's impact on atmospheric circulation (Collins et al. 2010; Hu et al. 2000; Chen et al. 2016; Power and Kociuba 2011), hydrology (Miller and Russell 1992; Rosenberg et al. 1999), agriculture (Rose et al. 2016; Lobell and Field 2007; Wurr et al. 1995), energy (Hernandez and von Storch 2012), and forests (Torn and Fried, 1992). However, there are relatively few studies on soil changes and their effects on subsurface processes (Zhang et al. 2016).

As an important part of the underlying surface of the land, soil is the lower boundary of material and energy exchange in the earth-atmosphere system (Dickinson 1995). Soil temperature (ST) is one of the important parameters to characterize the thermal properties of soil, and it plays an important role in the research of many related fields (Huang et al. 2014). In terms of energy cycle, ST affects climate change by

affecting changes in surface energy. Therefore, the diagnosis and prediction of ST are important scientific and technical issues in land surface process models, numerical weather prediction and short-term climate prediction (Holmes et al. 1998). In terms of water cycle, ST greatly affects the process of sensible heat, latent heat and surface evapotranspiration. Changes in ST can further affect the temperature and precipitation of the Qinghai-Tibet Plateau and East Asia through the exchange of water between the atmosphere and the surface (Wang et al. 2013; Yang et al. 2007). In agricultural research, ST is a driving environmental factor that affects crop growth, fertilizer decomposition and organic matter accumulation (Mackay et al. 1984; Kirschbaum 1995). Considering meteorological research, the change of ST is a reliable indicator reflecting climate change. For example, the increase of ST in permafrost regions is an important indicator of permafrost degradation (Cheng et al. 2007; Luo et al. 2018b; Peng et al. 2016). The shallow ST is also one of the key factors of precipitation. Because the heat in the shallow soil can be easily released into the atmosphere, the abnormality of the shallow ST will affect the short-term weather process (Hu et al. 2005).

Because of the importance of ST, many scholars have done a lot of work. Tang et al. (1987) conducted a series of research on the relationship between ST and precipitation, whose studies have shown that there is a good corresponding relationship between ST and later precipitation, and the ST at different levels has different continuity. The work of Qin et al. (2020) showed that the increasing trend of shallow ST in the Qinghai-Tibet Plateau in spring and summer is greater than that of deep soil; the temperature increase rate of shallow soil in autumn and winter is significantly lower than that of deep soil; the significant positive growth trend of the annual average ST indicates that the Qinghai-Tibet Plateau has responded to climate warming in the past few decades, and it is also regarded as one of the important indicators of permafrost degradation on the Qinghai-Tibet Plateau. Studies have shown that ST is one of the key factors affecting soil respiration in ecosystems such as forests, grasslands, and farmland (Bouma et al. 1997; Phillips et al. 2011; Tang et al. 2006). The sensitivity of soil respiration rate to the changes of ST is also an important link in the carbon cycle of terrestrial ecosystems (Liu et al. 2008). Considering the different effects of ST on

climate and ecology, scholars have also conducted regional analysis of ST.

Due to the synergy of many factors such as solar radiation, atmospheric circulation, and precipitation, there is a complex energy exchange between soil and atmosphere. This formed the periodic diurnal and seasonal changes of ST, and also formed different regional characteristics of ST (Bond-Lamberly et al. 2005). Studying the regional differentiation characteristics of ST is helpful to reveal the influence of ST on agricultural production and ecological environment (Zhang et al. 2009). Research on regional differences in ST and its influencing factors began at the end of the 20th century. Zhang et al. (2005) studied the change of ST in Canada in the 20th century and found that it has a complex response relationship with air temperature and precipitation, this response has an impact on climate change. Lu et al. (2006) used the ST at a depth of 0.8m in China from 1954 to 2001, found that the variation trends of ST in different regions were different. Bai et al. (2020) pointed out that the previous division of ST was mostly based on administrative and mechanical grid, but changes in ST have potential effects on vegetation growth, so ST division based on vegetation area is very meaningful. Research shows that the spatial distribution of shallow ST in China varies greatly during plant growth seasons. The spatial distribution of shallow ST in eastern China is mainly distribution from northeast to southwest, while it is complex in the west, which is mainly affected by altitude. Meanwhile, Wang et al. (2020) analyzed the memory of ST at different levels based on 8 vegetation growth regions in China, and found that each level showed a similar spatial pattern. Generally, the spatial distribution of the memory of ST has a northwest to southeast gradient. In some seasons, the arid and semi-arid regions of northwestern China have longer memory periods than the humid and sub-humid regions of southeastern China. Besides, Gao et al. (2016) used fuzzy C-means clustering to classify ST at 1.6 m in China into four categories, the cold region ($\bar{T}_{1.6} \leq 9^{\circ}\text{C}$), including Northeast China and the Qinghai-Tibet Plateau; sub-cold region ($9^{\circ}\text{C} \leq \bar{T}_{1.6} \leq 15^{\circ}\text{C}$), mainly including Northwest China; sub-warm region ($15^{\circ}\text{C} \leq \bar{T}_{1.6} \leq 18^{\circ}\text{C}$), including Huaihe Basin area; warm region ($\bar{T}_{1.6} \geq 18^{\circ}\text{C}$), including the middle and lower reaches of the Yangtze River and southern China. Zhou

et al. (2020) used the fuzzy C-means clustering method to classify ST at 3.2 m depth from 113 sites in China, and divided them into 10 regions. The research shows that there are obvious regional differences in the increasing rate of the 3.2m ST. The northeast and northwest China had the largest temperature increase, about 0.57K/10a, and the other regions were all below 0.36K/10a. However, there are few studies on the zoning of soil temperature on the Qinghai-Tibet Plateau.

As one of the most sensitive areas of global climate change, the Qinghai-Tibet Plateau is an indispensable part of understanding the degradation of frozen soil, ecological environment and climate change. So far, most studies on ST in the Qinghai-Tibet Plateau are based on model results or reanalysis data from different sources. However, due to the harsh environmental conditions and the complex topography of the Qinghai-Tibet Plateau, the model parameters of the Qinghai-Tibet Plateau are not accurate enough. The ST data obtained from the model has limitations and uncertainties (Guo et al. 2016; Wu et al. 2018b). The reanalysis data from different sources, because of the use of different assimilation systems, also differs from each other. So, the model results and reanalysis data need to be verified by the site observation data. In this study, the shallow ST observation data from 141 meteorological stations on the Qinghai-Tibet Plateau from 1981 to 2020 are used to analyze the ST and its temporal and spatial change characteristics at different levels of the Qinghai-Tibet Plateau, using fuzzy C-means clustering, linear fitting and linear regression. This work is of great significance for understanding the evolution characteristics of ST and its climatic effects.

2. Data and methods

2.1. Data selection

The observational data in this work are the daily ST of 141 stations on the Qinghai-Tibet Plateau during the period of January 1, 1981, to December 31, 2020 by the National Climate Centre. The dataset has eight soil layers with depths of ground surface, 5, 10, 20, 40, 80, 160, and 320cm. In the northwestern part of the Qinghai-Tibet Plateau, there are fewer ST observation sites.

Considering the unique geographical conditions and underlying surface types of the

176 Qinghai-Tibet Plateau, the altitude, underlying surface types and observation sites of
177 the Qinghai-Tibet Plateau in Fig. 1 are given.

178
179 Fig. 1 The altitude, underlying surface types and observation sites of the Qinghai-
180 Tibet Plateau

181 (a) is the altitude, (b) is the underlying surface type and observation sites

182 2.2. Method

2.2.1 Fuzzy C-means algorithm (FCM)

In this paper, the fuzzy C-means algorithm (FCM) is used to classify the annual average soil temperature of 141 ST observation sites in 20cm on the Qinghai-Tibet Plateau from 1981 to 2020. Clustering is a method which divides a collection of abstract objects into different classes or clusters according to a certain standard (such as distance criterion, that is, the distance between different data), so that the similarity of data objects in the same cluster and the difference between different clusters is as great as possible (Saxena et al. 2017). The main idea of FCM is to divide a number of L-dimensional vectors into C fuzzy groups, determine the degree of membership of each category by distance, and continuously update the membership degree as well as clustering center of image pixels to minimize the objective-function and complete pixel classification and image segmentation (Bezdek et al. 1984). The pixel membership degree is used to describe the degree to which the pixel belongs to a certain category, and the value range is [0,1]. The objective-function and restriction of the FCM algorithm are:

$$J_{FCM} = \sum_{i=1}^C \sum_{j=1}^N u_{ij}^m d_{ij}^2(x_j, v_i), \quad \sum_{i=1}^C u_{ij} = 1 \quad (1)$$

$u_{ij} = u_j(x_j)$ represents the degree to which the pixel gray x_j belongs to category i , m is the fuzzy weighting coefficient, often taken as 2, $v_i = \{v_1, \dots, v_c\}$ represent the i -th cluster centers, $d_{ij}(x_j, v_i) = ||x_j - v_i||^2$ represents the shortest distance from the gray level of the j -th pixel to the i -th cluster center.

Using the Lagrangian multiplier method to find the minimum value of the objective function,

$$J_{\lambda} = \sum_{i=1}^C \sum_{j=1}^N u_{ij}^m d_{ij}^2(x_j, v_i) + \lambda \left(\sum_{j=1}^N u_{ij} - 1 \right) \quad (2)$$

$$v_i = \frac{\sum_{j=1}^N u_{ij}^m x_j}{\sum_{j=1}^N u_{ij}^m} \quad (i = 1, \dots, C) \quad (3)$$

$$u_{ij} = \frac{1}{\sum_{k=1}^N \left(\frac{d(x_j, v_i)}{d(x_j, v_k)} \right)^{2(m-1)}} \quad (4)$$

The standard FCM algorithm is superior in simple image segmentation. In recent years, FCM has been widely used in research fields such as climate region division, pattern recognition, data analysis and image processing, showing that the FCM can clearly represent the continuous spatial distribution of natural phenomena (Lee 2009).

2.2.2 Mann-Kendall mutation analysis

The change of ST is synergistically affected by many factors, so it can show the characteristics of trend change. Mann-Kendall (M-K) (Mann 1945; Kendall 1975) test is not affected by the sample value, distribution type, etc., and further analyzes the changing of variables by deeply mining the hidden information within the time series. Therefore, it is widely used in the research of time analysis of natural variables. MK mutation analysis is a non-parametric statistical test method, which is not only easy to calculate, but also can identify the time when the mutation starts and point out the region of the mutation time period.

Given the time series variables $(X_1, X_2, \dots, X_n)$, where n is the length of X , define the rank of the series as follows:

$$s_k = \sum_{i=1}^k r_i \quad (5)$$

where r_i can be expressed as:

$$r_i = \begin{cases} +1, & \text{if } x_i > x_j \\ 0, & \text{else} \end{cases} \quad (6)$$

It can be seen that s_k is the accumulation of the number of values at the $i - th$ time greater than the $j - th$ time.

Under the assumption of random independence of the time series, define the statistics:

$$UF_k = \frac{[s_k - E(s_k)]}{\sqrt{Var(s_k)}} \quad (k = 1, 2, \dots, n) \quad (7)$$

Among them, $UF_1 = 0$, $E(s_k)$ and $Var(s_k)$ are the mean and variance of the accumulated number s_k . When $X_1, X_2, \dots, X_n$ are independent of each other and have the same continuous distribution, then there is

$$E(s_k) = \frac{n(n-1)}{4}, \quad Var(s_k) = \frac{n(n-1)(2n+5)}{72}$$

UF_k is a standard normal distribution, which is a series of statistics calculated in the

order of time series $X_1, X_2, \dots, X_n$. Given a significance level α , if $|UF_k| > U_\alpha$, it means that the series has obvious trend changes.

The time series is generated into its corresponding inverse sequence $X_n, X_{n-1}, \dots, X_1$, and the above calculation process is repeated. Meanwhile, $UB_k = -UF_k$, $k = n, n-1, \dots, 1$, $UB_1 = 0$.

To summarize the brief computational steps for Mann-Kendall (M-K) mutation analysis:

1) Calculate the rank column of the sequential time series, and calculate UF_k according to the rank;

2) Calculate the rank column of the reverse time series, and calculate UB_k according to the rank;

3) Given a significance level, such as $\alpha = 0.05$, for the critical value $U_{0.05} = \pm 1.96$, if UF or UB is greater than 0, it indicates that the sequence is in an upward trend; else, it is in a downward trend; if it exceeds the critical value, the upward or downward trend is significant; if there is an intersection between UF and UB , and the intersection is between the critical lines, the intersection is the moment when the mutation begins.

2.2.3 Moving Surface Spline Interpolation Algorithm Based on Green's Function

The data of 141 ST observation stations on the Qinghai-Tibet Plateau are interpolated by *Moving Surface Spline Interpolation Algorithm Based on Green's Function*. Compared with Shepard (IDW interpolation), Bivariate Cubic Polynomial Fitting, Local Neighborhood Kriging, Ordinary Kriging, Moving Surface Spline Interpolation, etc., this method has higher accuracy and better continuity when dealing with complex terrain and different underlying surface conditions (Deng and Tang 2011). The solution of Green's functions implies that the surface $s(x)$ can be expressed as

$$s(x) = T(x) + \sum_{j=1}^n w_j g(x, x_j) \quad (8)$$

where x is the output position vector of the unknown data point, $g(x, x_j)$ is the Green's function, x_j is the j -th data constraint, and w_j are the associated unknown

weight relative to x . $T(x)$ is the trend function (Wessel 2009). The weight w_j are determined by requiring (1) to be accurately satisfied in n data positions,

$$s(x_i) = \sum_{j=1}^n w_j g(x_i, x_j), i = 1, 2, \dots, n. \quad (9)$$

$$g(x_i, x_j) = |x_i, x_j|^2 \ln(|x_i, x_j|) \quad (10)$$

The steps of the Moving Surface Spline Interpolation Algorithm Based on Green's Function are as follows:

Part 1. Assuming a surface has total n known points, the desired output node is p_0 . The number of points nearest to p_0 used for interpolation is k . The distance from point p_0 to other known points should be calculated first by

$$r_{0i} = |x_i, x_0|, i = 1, 2, \dots, n \quad (11)$$

Where r_{0i} is the distance between the point p_0 and the i -th known data point, x_0 is the position vector of p_0 , and x_i is the position vector of the i -th known data point.

Part 2. Setting the coordinate matrix $X = [x_1 x_2 \dots x_k]^T$, $Y = [y_1 y_2 \dots y_k]^T$, attribute matrix $Z = [z_1 z_2 \dots z_k]^T$, $k \times k$ Green's function matrix G is:

$$G = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1k} \\ d_{21} & d_{22} & \dots & d_{2k} \\ \vdots & \vdots & \ddots & \vdots \\ d_{k1} & d_{k2} & \dots & d_{kk} \end{bmatrix} \quad (12)$$

$$d_{ij} = \begin{cases} 0 & r_{ij} = 0 \\ [\ln(r_{ij}) - 1.0] r_{ij}^2 & r_{ij} \neq 0 \end{cases} \quad i = 1, \dots, k, j = 1, \dots, k \quad (13)$$

where $r_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$. the weight matrix W can be calculated as

$$W = G^{-1}Z \quad (14)$$

Part 3. Computing $1 \times k$ Green's function matrix G_p of point p_0

$$G_p = [d_{01} d_{02} \dots d_{0k}] \quad (15)$$

where $d_{01}, d_{02}, \dots, d_{0k}$ are calculated by (13). The attribute value of point p_0 is

$$z_p = G_p W \quad (16)$$

Part 4. Repeat Parts (1)-(3) to calculate the interpolation z_{pi} of other points p_i .

3. Results

3.1. Temporal and spatial distribution of shallow layers ST on the Qinghai-Tibet Plateau

3.1.1 The spatial distribution

Fig. 2 shows the spatial distribution of the annual average ST in the shallow layers of the Qinghai-Tibet Plateau (surface, 5cm, 10cm, 15cm, 20cm, 40cm). It can be seen from the figure that the shallow ST of the Qinghai-Tibet Plateau has a gradually increasing trend from north to south, but there is a relatively high ST area in Golmud, Qinghai, with an average of 5-10 °C. In the vast areas of the Northern Qiangtang Plateau and the Southern Qiangtang Plateau, the shallow ST is basically below 5 °C. The temperature in the southeastern Tibet and the western Sichuan plateau is high, reaching above 20 °C.

Fig. 2. Spatial distribution of shallow ST on the Qinghai-Tibet Plateau (unit: °C)

3.1.2 Temporal characteristics

Fig. 3 and 4 show the interannual variation of ST anomalies in shallow layer (surface, 5cm, 10cm, 15cm, 20cm, 40cm) of the Qinghai-Tibet Plateau and their MK tests. It can be seen that from 1981 to 2020, ST at the six levels has shown a significant upward trend, but the rising amplitudes of each level are quite different. From the MK tests in

Fig. 4, it can be seen that 5cm, 10cm, 15cm, and 20cm have insignificant mutation points near 2008. Besides, 40cm and the surface have mutations near 2002. Table 1 is the statistical information of the annual and seasonal temperature of the shallow soil on the Qinghai-Tibet Plateau, including the average, standard deviation, and interdecadal variability. On an annual scale, the average annual ST of 0-20cm is 9.15-9.57 °C, and that of 40cm is 8.69 °C. The interdecadal variability of 0-20cm is 0.49-0.53 K/10a, and the interdecadal variability of 40cm reaches 0.98 K/10a, which is much higher than other levels. From the seasonal perspective, the interdecadal variability of ST in winter and spring is relatively high, with 40cm even reaching more than 1 K/10a. In addition, the 40cm interannual and seasonal ST standard deviation (1.13-1.44 K) is much larger than other layers ($\sigma < 1$ K), indicating that ST in 40cm varies more greatly. This result is reflected in the mutation point in 2002-2006 of Fig. 3(e1) and 2002 of Fig. 4(e). The analysis shows that the temperature of the shallow soil on the Qinghai-Tibet Plateau has a clear increasing trend. The temperature increase of 0-20cm (the surface layer of shallow soil) is roughly the same, which is quite different from that of 40cm (the bottom layer of shallow soil).

Fig. 3. Interannual variation of shallow ST anomaly in the Qinghai-Tibet Plateau (unit: K)

Fig. 4. MK analysis of shallow ST on the Qinghai-Tibet Plateau

UF and *UB* are the statistics of the MK analysis

Table 1. Statistical information of annual average and interannual variations in various seasons on the Qinghai-Tibet Plateau from 1981 to 2020

	5cm			10cm		
	μ	σ	Trend	μ	σ	Trend
	(°C)	(K)	(K/10a)	(°C)	(K)	(K/10a)
Spring	10.19	0.78	0.55**	9.74	0.85	0.61**
Summer	18.42	0.65	0.39**	18.15	0.70	0.45**
Autumn	9.42	0.77	0.51**	9.81	0.75	0.50**
Winter	-1.43	0.93	0.63**	-0.96	0.83	0.55**
Annual	9.15	0.71	0.52**	9.19	0.72	0.53**
	15cm			20cm		
	μ	σ	Trend	μ	σ	Trend
	(°C)	(K)	(K/10a)	(°C)	(K)	(K/10a)
Spring	9.27	0.74	0.48**	9.05	0.83	0.60**
Summer	17.87	0.63	0.37**	17.62	0.67	0.45**

Autumn	10.28	0.71	0.49**	10.41	0.68	0.46**
Winter	-0.30	0.70	0.62**	-0.17	0.71	0.48**
Annual	9.28	0.66	0.49**	9.22	0.67	0.50**
	40cm			surface		
	μ	σ	Trend	μ	σ	Trend
	(°C)	(K)	(K/10a)	(°C)	(K)	(K/10a)
Spring	7.65	1.51	1.14**	11.17	0.75	0.51**
Summer	16.46	1.13	0.84**	19.51	0.61	0.30**
Autumn	10.58	1.17	0.87**	9.38	0.75	0.51**
Winter	0.06	1.44	1.06**	-1.79	0.96	0.66**
Annual	8.69	1.29	0.98**	9.57	0.66	0.49**

μ mean, σ standard deviation

**Denotes trends statistically significant at $\alpha = 0.001$

3.1.3 Characteristics of spatial changes in shallow soils on the Qinghai-Tibet Plateau

Fig. 5 shows the interdecadal distribution of ST in shallow layer (surface, 5cm, 10cm, 15cm, 20cm, 40cm) of the 141 observation sites on the Qinghai-Tibet Plateau from 1981 to 2020, results are significant at 99% ($\alpha = 0.01$) confidence level. As shown in the figure, the interdecadal variabilities of 5-20cm (the surface layer of the shallow soil) is basically the same. In the central Tibet, the southern and southwestern parts of the Qinghai-Tibet Plateau, ST has a significant cooling trend, and the interdecadal variabilities are as low as -1 K/10a. In the northwestern part of the Qinghai-Tibet Plateau, ST is warming obviously. Compared with other layers, 40cm (the bottom layer of shallow soil) is quite different. On the whole, the temperature increase trend of 40cm is more obvious than that of other layers. The cooling trend still exists in central Tibet, the warming trend in the northwestern Qinghai-Tibet Plateau has slightly weakened, while the cooling trend of ST in southwestern Tibet has turned into a warming trend, and the Qaidam Plateau has a significant warming trend. The surface of the Qinghai-Tibet Plateau has a warming trend, but the temperature change does not have the obvious regional differentiation like other levels.

Fig. 5. Distribution of interdecadal variability of ST in shallow soil on the Qinghai-Tibet Plateau from 1981 to 2020 (unit: K/10 a, $\alpha = 0.01$)

3.2. Analysis of 20cm ST characteristics of the Qinghai-Tibet Plateau

3.2.1 Regionalization of 20cm ST

The ST at 20cm depth was chosen as the research object, because: 1) 20cm is basically the same as 5cm, 10cm, and 15cm, and 20cm is the boundary layer between the shallow soil surface and the shallow soil bottom layer (Yan et al. 2017); 2) the ST at a depth of 20cm is greatly affected by climate factors such as air temperature and precipitation, but is less affected by geothermal, so the response to climate change is more obvious; 3) the 20cm ST directly affects the growth and distribution of soil organisms (Zhang et al. 2009).

Fig. 6 shows the 20cm ST division of the Qinghai-Tibet Plateau, using fuzzy C-means algorithm (FCM). In the process of FCM clustering, choosing the appropriate fuzzy index m and the number of categories C is the most critical. According to the research of Liu et al. (2014), the expected clustering effect can be achieved when $m =$

2. The choice of category number C is related to the change of entropy (δH , $H_c - H_{c+1}$) and the change of distribution coefficient (δF , $F_c - F_{c+1}$). When the change of distribution coefficient is the smallest and the change of entropy is the largest, C is determined. Using FCM, based on 20cm ST at 141 sites on the Qinghai-Tibet Plateau, 7 regions were clustered. The classification results are shown in Fig. 7, and the environmental parameters of the cluster centers are shown in Table 2.

The Qinghai-Tibet Plateau is divided into 7 regions according to the characteristics of 20cm ST, namely the Northeastern of Plateau, Southern Tibet, Xining Plateau, Qiangtang Plateau, Western Sichuan Plateau, Eastern Tibet Plateau and the vast Central Plateau. Lin et al. (1981) pointed out that the Northeastern of Plateau is a sub-arctic semi-humid climate zone, with an average altitude of about 4000-4600m, less than 50 days with a temperature $\geq 10^\circ\text{C}$, and an average temperature of 8-10 $^\circ\text{C}$ in the warmest month. In Table 2, the average temperature of 20cm soil is the lowest, which is 5.2 $^\circ\text{C}$; Southern Tibet is a temperate and semi-arid climate zone, and a large area is a wide river valley. The middle and upper reaches of the Yarlung Zangbo River are located in it, with an average altitude of 3500-4500m. The number of days when the temperature is $\geq 10^\circ\text{C}$ ranges from 50 to 150 days. The average temperature of the warmest month is 10-15 $^\circ\text{C}$, while the average temperature of the 20cm soil is relatively slightly higher, at 10.9 $^\circ\text{C}$; Xining Plateau is a temperate and semi-arid climate zone, located in the eastern part of Qinghai Province, with complex terrain. The altitude of the valley area is below 2200m, the average altitude is 2700-3300m, the number of days with temperature $\geq 10^\circ\text{C}$ ranges from 50 to 150 days, and the average temperature of the warmest month is 11 -13 $^\circ\text{C}$, the average ST of 20cm is 8.9 $^\circ\text{C}$; Qiangtang Plateau is a frigid semi-arid climate zone with gentle terrain fluctuations, the average altitude is 4300-5100m, less than 50 days with a temperature $\geq 10^\circ\text{C}$, and an average temperature of 8-10 $^\circ\text{C}$ in the warmest month. The average ST of 20cm is 7.6 $^\circ\text{C}$; Western Sichuan Plateau is a temperate humid climate zone, located on the eastern edge of the Qinghai-Tibet Plateau. The terrain fluctuates greatly, while the average altitude is 1500-3400m. The number of days when the temperature is $\geq 10^\circ\text{C}$ ranges from 120 to 180 days. The average ST of 20cm is the highest, which reaches to 17.1 $^\circ\text{C}$; Eastern Tibetan Plateau is

a temperate semi-humid climate zone, with an altitude of about 2700-4000m, about 50 days when the temperature is $\geq 10^{\circ}\text{C}$, the average temperature of the warmest month is $13-16^{\circ}\text{C}$, and the average of 20cm ST is 11.6°C ; The Central of Plateau is a vast area, including most of Tibet and Xinjiang, with an average altitude of 4500-4800m, less than 50 days with a temperature $\geq 10^{\circ}\text{C}$, the average temperature of the warmest month is $6-10^{\circ}\text{C}$, and the average of 20cm ST is also low, which is 6°C . It can be seen from the above analysis that the 20cm ST is greatly affected by air temperature, and the response to climate change is obvious.

Fig. 6. When $m = 2.0$, the entropy and distribution coefficient change with the number of categories (C)

Fig. 7. 20cm ST division of the Qinghai-Tibet Plateau (7 regions)

The points are divided into four categories, from small to large: $<6^{\circ}\text{C}$ (cold region), $6-11^{\circ}\text{C}$ (sub-cold region), $11-16^{\circ}\text{C}$ (sub-warm region), $>16^{\circ}\text{C}$ (warm region)

Table 2. Environmental parameters of the region center

Region Number	Region name	Longitude ($^{\circ}\text{E}$)	Latitude ($^{\circ}\text{N}$)	μ ($^{\circ}\text{C}$)	σ (K)	Trend (K/10a)	number of observation sites
Region 1	Northeastern of Plateau	99.9	35.4	5.2	0.60	0.46	25
Region 2	Southern Tibet	90.6	29.3	10.9	0.56	0.38	19
Region 3	Xining Plateau	101.9	34.9	8.9	0.48	0.33	22
Region 4	Qiangtang Plateau	81.1	32.6	7.6	0.61	0.61	4
Region 5	Western Sichuan Plateau	102.4	29.7	17.1	0.40	0.25	25
Region 6	Eastern Tibet Plateau	100.0	30.5	11.6	0.42	0.24	26
Region 7	Central of Plateau	93.8	32.4	6.0	0.49	0.35	20

3.2.2 The characteristics of interannual variation of 20cm ST on the different regions of Qinghai-Tibet Plateau

Fig. 8 shows the interannual variation of the 20cm ST anomaly in 7 regions of the

Qinghai-Tibet Plateau. According to Fig. 8 and Table 2, from 1981 to 2020, ST of 20cm in 7 regions showed an obvious rising trend, but the rise of each region was quite different. Linear fitting of ST for each region shows that the interdecadal variability of region 1 is 0.46K/10a, region 2 is 0.38 K/10a, region 3 is 0.33 K/10a, region 4 is 0.61 K/10a, region 5 is 0.25 K/10a, region 6 is 0.24 K/10a, region 7 is 0.35 K/10a. And the correlation coefficients with the month are 0.61, 0.51, 0.48, 0.64, 0.38, 0.38, 0.59, all of which passed the confidence level t test with $\alpha = 0.001$. The average values of different regions range from 5.2 °C (region 1, Northeastern of Plateau) to 18.1 °C (region 5, Western Sichuan Plateau), and the average difference is nearly 12 K. The standard deviation of different regions ranges from 0.40 K (region 5, Western Sichuan Plateau) to 0.61 K (region 4, Qiangtang Plateau). Because the Western Sichuan Plateau is located in a humid climate area, the shallow ST changes little, while the Qiangtang Plateau is located in an arid climate area, and the seasonal temperature difference is larger, so the shallow ST changes greatly, which is consistent with the obtained results. The results above indicate that the 20cm ST increase trend of the Qinghai-Tibet Plateau is obvious, and there are significant regional differences.

Fig. 8. Interannual variation of 20cm ST anomalies in 7 regions of the Qinghai-Tibet Plateau (unit: K)

3.3 Spatial variation characteristics of 20cm ST on the Qinghai-Tibet Plateau

Fig. 9 shows the spatial distribution of 20cm ST anomalies in the Qinghai-Tibet Plateau from 1981 to 2020. It can be seen from the figure that since 1981-2000, most

437 areas of the Qinghai-Tibet Plateau have been in the cold stage, and the northwestern
438 part of the Qinghai-Tibet Plateau is a strong and obvious center of 20cm negative ST,
439 especially from 1981 to 1986. This negative anomaly center lasted for almost 20 years.

440 In addition, from 1981 to 2000, there were also four positive anomaly centers in the
441 Qinghai-Tibet Plateau, namely the eastern part of the Qinghai-Tibet Plateau, the central-
442 eastern part of the Qinghai-Tibet Plateau, the southern part of the Qinghai-Tibet Plateau,
443 and the southwestern part of the Qinghai-Tibet Plateau. Among them, the positive
444 anomaly of southwestern part of the Qinghai-Tibet Plateau was strong in some years
445 (such as 1984, 1999), reaching above 2 K, and in some years (such as 1991, 1997), it
446 was weak, below 0.5 K, or even disappear. In most years from 1981 to 2000, the positive
447 anomaly of 20cm ST in the southern part of the Qinghai-Tibet Plateau was strong,
448 reaching above 2.5 K, while in some years (such as 1990 and 1991), it was relatively
449 weak, near 0.5-1 K.

450 In 1986 and 1993, there was an obvious positive anomaly center in the north-central
451 Qinghai-Tibet Plateau. From 1981 to 1986, the ST of 20cm in central and northern Tibet
452 had an obvious trend of rapid temperature decrease and then rapidly increase. The
453 annual temperature reached -1.5-2.5 K. The ST of 20cm changed significantly from
454 1990 to 1995, and its annual temperature change rate reached -1.5-1.5 K.

455 From 2001 to 2005, there was a negative anomaly center of about -1 K in central
456 Tibet. The positive anomaly center in southwestern Tibet disappeared, while the
457 positive anomaly center in southern Tibet remained strong. In 2002, the 20cm ST in
458 southern Tibet reached a positive anomaly, up to 2 K or more. In addition, the strong
459 positive anomaly center in the eastern part of the Qinghai-Tibet Plateau disappeared in
460 2005 after having remained for 24 years (1981-2004). The strong positive anomaly
461 center of ST in central and eastern part of the Qinghai-Tibet Plateau, having existed for
462 22 years (1981-2003, except 2002), disappeared in 2004.

463 Based on the interannual variation of the 20cm ST anomaly in Figure 3(d1), the 20cm
464 ST anomaly across the Qinghai-Tibet Plateau has changed from a negative value to a
465 positive value since 2006. It can also be seen from Figure 9 that since 2006, the negative
466 ST anomaly of 20cm in most parts of the Qinghai-Tibet Plateau has begun to rise.

467 Except for the scattered negative anomaly centers, ST anomalies in most parts of the
468 Qinghai-Tibet Plateau have changed between -0.5 K and 0.5 K.

469 It is worth noting that since 1981, the vast northwestern part of the Qinghai-Tibet
470 Plateau has disappeared from the strong negative anomaly center that lasted for nearly
471 20 years. In the southern part of the Qinghai-Tibet Plateau, the positive and negative
472 anomaly centers appear at intervals. For example, a strong positive anomaly center
473 appeared in 2006, followed by a negative anomaly center that lasted for 7 years (2007-
474 2013). Afterwards, the positive anomaly center that has been in existence for 7 years
475 (2014-2020) appeared. A relatively weak positive anomaly center appeared in the
476 northeastern part of the Qinghai-Tibet Plateau for 17 years (2004-2020). The intensity
477 was 0.5-1 K during 2004-2012, and it slightly strengthened after 2012. The 20cm ST
478 anomaly varies between 1-1.5 K.

479 The above analysis shows that the ST of 20cm in the Qinghai-Tibet Plateau has
480 significant temporal and spatial changes. From 1981 to 2000, most areas of the Qinghai-
481 Tibet Plateau were in the cold stage; especially the northwestern region was a strong
482 negative ST anomaly. Since 2006, the 20cm ST anomaly has changed from a negative
483 value to a positive value. From the perspective of spatial distribution, there was a strong
484 negative ST anomaly center in the northwestern region from 1981 to 2000. Four
485 positive anomalous centers generally exist in the Qinghai-Tibet Plateau, namely the
486 eastern part of the Qinghai-Tibet Plateau (24 years, 1981-2004), the central-eastern part
487 of the Qinghai-Tibet Plateau (22 years, 1981-2003, except 2002), and the southern part
488 of the Qinghai-Tibet Plateau (continued 26 years, 1981-2006), the southwestern
489 Qinghai-Tibet Plateau (19 years, 1981-1999). In addition, since 2004, there has been a
490 weaker positive anomaly center in the northeastern part of the Qinghai-Tibet Plateau
491 that lasted for 17 years (2004-2020).

Fig. 9. Spatial distribution of 20cm ST anomalies in the Qinghai-Tibet Plateau from 1981 to 2020 (unit: K)

4. Discussion and conclusion

4.1 Discussion

Soil is an important component of the Earth's ecosystem (Oelke and Zhang 2004). Shallow soil refers to the soil layer within 50cm underground. Shallow soil is also the main layer of life activities of animals, plants and microorganisms. The thermal properties of soil are key variables for the growth and decomposition of above-ground and below-ground biomass (Abramoff and Finzi 2015; Munir et al. 2015; Wang et al. 2013; Xu et al. 2013). Changes in soil thermal properties can alter soil enzyme activity, plant productivity, nitrogen uptake, and the living conditions of soil microorganisms (Luo et al. 2009; Rustad et al. 2001). As one of the most important thermal properties of soil, soil temperature (ST) not only affects the chemical and biological processes of carbon and nitrogen in soil, but also determines the quality of soil resources (Shi and Deng 1993; Kang et al. 2000). Shallow ST and its temporal and spatial changes directly or indirectly affect many processes occurring in soil, such as seed germination, root elongation, evaporation, storage and movement activities of microorganisms, nutrient cycling, and many other dynamic processes of soil (Beltrami, 2001; Citakoglu, 2017; Qian et al. 2011). Therefore, the analysis of shallow ST is very meaningful in the study of local ecological conditions and environmental characteristics. Nowadays, most studies on shallow ST on the Qinghai-Tibet Plateau are based on model results or reanalysis data from different sources. However, the Qinghai-Tibet Plateau has many deficiencies in the simulation and reanalysis results due to its complex geographical features and underlying surface conditions (Guo et al. 2016; Wu et al. 2018b). There are also many difficulties in the collection of observational data due to the harsh geographical environment. This work collected shallow ST observation data from 1980 to 2020 from most counties and districts on the Qinghai-Tibet Plateau. The data are relatively complete and abundant, the time span is also long. Using the fuzzy C-means clustering method, 20cm ST was divided into 7 regions, namely the Northeastern of Plateau, Southern Tibet, Xining Plateau, Qiangtang Plateau, Western Sichuan Plateau, Eastern Tibet Plateau and the vast Central of Plateau. The meteorological elements of these seven regions are quite different, and the geographical conditions are also different. The seven regions are typical and representative on the plateau, and play an

important role in grasping the changing trend of shallow ST as a whole and understanding the impact of current climate warming on soil. However, this work also has certain shortcomings. For example, due to the geographical factors of the Qinghai-Tibet Plateau, there are fewer stations in the western part of the plateau, which brings certain errors to our understanding and characterization of the western part of the plateau. On the other hand, the shallow ST also has a certain influence and indicative significance on air temperature and precipitation, which also need to be considered in future work.

4.2 conclusion

Based on observational data and reanalysis data, this work studies the abnormal conditions of the shallow ST of the Qinghai-Tibet Plateau from 1981 to 2020, and further analyzes the temporal as well as spatial characteristics of the 20cm ST, draw the following conclusions:

The 20cm ST on the Qinghai-Tibet Plateau gradually decreases from south to north, and from east to west. The average ST in the Western Sichuan Plateau, located in the southeast of the Qinghai-Tibet Plateau is the highest, with $T_{20cm} = 18.1\text{ }^{\circ}\text{C}$. The temperature in the central and northern part of the Qinghai-Tibet Plateau is the lowest, with $T_{20cm} = 4.9\text{ }^{\circ}\text{C}$. The temperature increase of 0-20cm (the surface layer of shallow soil) is roughly the same, which is quite different from that of 40cm (the bottom layer of shallow soil). The average annual ST of 0-20cm is 9.15-9.57 $^{\circ}\text{C}$, and the interdecadal variability of 0-20cm is 0.49-0.53 K/10a. The average annual ST of 40cm is 8.69 $^{\circ}\text{C}$, and the interdecadal variability of 40cm reaches 0.98 K/10a.

In terms of spatial distribution, there was a strong negative ST anomaly center in the northwestern part of the Qinghai-Tibet Plateau from 1981 to 2000. Four positive anomalous centers generally exist in the Qinghai-Tibet Plateau, namely the eastern part of the Qinghai-Tibet Plateau (24 years, 1981-2004), the central-eastern part of the Qinghai-Tibet Plateau (22 years, 1981-2003, except 2002), and the southern part of the Qinghai-Tibet Plateau (26 years, 1981-2004). Years, 1981-2006), Southwestern Qinghai-Tibet Plateau (19 years, 1981-1999). In addition, since 2004, there has been a

weaker positive anomaly center in the northeastern part of the Qinghai-Tibet Plateau that lasted for 17 years (2004-2020).

Considering the 7 regions of 20cm ST, the warming trend is obvious, and there are certain regional differences. The average annual ST in different regions ranges from 5.2°C (Northeast of the Plateau) to 17.1°C (Western Sichuan Plateau), with a difference of nearly 12K; the standard deviation ranges from 0.40K (Western Sichuan Plateau) to 0.61K (Qiangtang Plateau), with a difference of 0.21K.

Data availability statement

The observational data in this work are come from the National Climate Centre, we thank Cunjie Zhang provided this dataset. Cun Jie Zhang's email is: zhangcj@cma.gov.cn.

References

- Abramoff RZ, Finzi AC (2015) Are above- and below-ground phenology in sync? *New Phytol* 205: 1054–1061. <https://doi.org/10.1111/nph.13111>
- Bai X, Zhang LH, He CS, Zhu Y (2020) Estimating Regional Soil Moisture Distribution Based on NDVI and Land Surface Temperature Time Series Data in the Upstream of the Heihe River Watershed, Northwest China. *Remote Sens* 12: 2414. <https://doi.org/10.3390/rs12152414>
- Beltrami H (2001) On the relationship between ground temperature histories and meteorological records: A report on the Pomquet station. *Glob Planet Chang* 29: 327–348. [https://doi.org/10.1016/S0921-8181\(01\)00098-4](https://doi.org/10.1016/S0921-8181(01)00098-4)
- Bezdek JC, Ehrlich R, Full W (1984) FCM: the fuzzy C-means clustering algorithm. *Comput Geosci* 10: 191-203. [https://doi.org/10.1016/00983004\(85\)90094-9](https://doi.org/10.1016/00983004(85)90094-9)
- Bond-Lamberty B, Wang CK, Gower ST (2005) Spatiotemporal measurement and modeling of stand-level boreal forest soil temperatures. *Agric For Meteorol* 131: 27–40. <https://doi.org/10.1016/j.agrformet.2005.04.008>
- Bouma TJ, Nielsen KL, Eissenstat DM, Lynch JP (1997) Estimating respiration of

roots in soil: Interactions with soil CO₂, soil temperature and soil water content.
 Plant Soil 195: 221-232. <http://dx.doi.org/10.1023/A:1004278421334>
 Chen CA, Yu JY, Chou C (2016) Impacts of Vertical Structure of Convection in
 Global Warming: The Role of Shallow Convection. J Clim 29: 4665-4684.
<http://dx.doi.org/10.1175/JCLI-D-15-0563.1>
 Cheng GD, Wu TH (2007) Responses of permafrost to climate change and their
 environmental significance, Qinghai-Tibet Plateau. J Geophys Res Earth Surf 112:
 F02S03. <https://doi.org/10.1029/2006JF000631>
 Citakoglu H (2017) Comparison of artificial intelligence techniques for prediction of
 soil temperatures in Turkey. Theor Appl Climatol 130: 545–556.
<https://doi.org/10.1007/s00704-016-1914-7>
 Collins M, An SI, Cai WJ, Ganachaud A, Guilyardi E, Jin FF, Jochum M, Lengaigne
 M, Power S, Timmermann A (2010) The impact of global warming on the tropical
 Pacific Ocean and El Nino. Nature Geoscience 3: 391-39.
<http://dx.doi.org/10.1038/NGEO868>
 Deng XS, Tang ZA (2011) Moving surface spline interpolation based on Green's
 function. Math Geosci 43: 663-680. <https://doi.org/10.1007/s11004-011-9346-5>
 Dickinson RE (1995) Land-atmosphere interaction. Rev Geophys 33: 917-922.
<https://doi.org/10.1029/95RG00284>
 Douville H, Colin J, Krug E, Cattiaux J, Thao S (2016) Midlatitude daily summer
 temperatures reshaped by soil moisture under climate change. Geophys Res Lett
 43: 812–818. <https://doi.org/10.1002/2015gl066222>
 Duan AM, Wang MR, Lei YH, Cui YF (2013) Trends in Summer Rainfall over China
 Associated with the Tibetan Plateau Sensible Heat Source during 1980-2008. J
 Climate 26: 261-275. <https://doi.org/10.1175/JCLI-D-11-00669.1>
 Gao N, Gao XQ, Yang LW, Zhou Y (2016) Spatial and temporal characteristics of soil
 temperature at 1.6m depth in mainland of China from 1981 to 2000. Plateau
 Meteorol 35: 686-692.
<https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFDLAST2016&filename=GYQX201603012&uniplatform=NZKPT&v=yY6okyLCBdc4qb>

9qsbG-X1vhqmnfgGDEcOUb6BhsqafBGv_IeOCtocXTRXrh7bjM

Guo DL, Wang HJ (2016) Permafrost degradation and associated ground settlement estimation under 2 °C global warming. *Clim Dyn* 49: 2569–2583.

<https://doi.org/10.1007/s00382-016-3469-9>

Hernandez DD, von Storch JS (2012) Impact of warming pattern on global energetics. *J Clim* 25: 5223-5240. <http://dx.doi.org/10.1175/JCLI-D-11-00468.1>

Holmes TRH, Owe M, De Jeu RAM, Kooi H (2008) Estimating the soil temperature profile from a single depth observation: A simple empirical heatflow solution.

Water Resour Res 44: W02412. <https://doi.org/10.1029/2007WR005994>

Hu Q, Feng S (2005) How have soil temperatures been affected by the surface temperature and precipitation in the Eurasian continent? *Geophys Res Lett* 32: 57-76. <https://doi.org/10.1029/2005GL023469>

Hu ZZ, Bengtsson L, Arpe K (2000) Impact of global warming on the Asian winter monsoon in a coupled GCM. *J Geophys Res: Atmos* 105: 4607-4624.

<http://dx.doi.org/10.1029/1999JD901031>

Huang F, Zhan WF, Ju WM, Wang ZH (2014) Improved reconstruction of soil thermal field using two-depth measurements of soil temperature. *J Hydrol* 519: 711-719.

<https://doi.org/10.1016/j.jhydrol.2014.08.014>

IPCC (2013) *Climate Change 2013: The physical basis science*. USA: Cambridge University Press.

Jiang XW, Li YQ, Yang S, Yang K, Chen JW (2016) Interannual Variation of Summer Atmospheric Heat Source over the Tibetan Plateau and the Role of Convection around the Western Maritime Continent. *J Climate* 29: 121-138.

<https://doi.org/10.1175/JCLI-D-15-0181.1>

Kang S, Kim, Oh S, Lee D (2000) Predicting spatial and temporal patterns of soil temperature based on topography, surface cover and air temperature. *For Ecol*

Manag 136: 173-184. [https://doi.org/10.1016/S0378-1127\(99\)00290-X](https://doi.org/10.1016/S0378-1127(99)00290-X)

Kang SC, Xu YW, You QL, Flügel WA, Pepin N, Yao TD (2010) Review of climate and cryospheric change in the Tibetan Plateau. *Environ Res Lett* 5: 015101.

<http://dx.doi.org/10.1088/1748-9326/5/1/015101>

- Kendall M (1975) *Rand Correlation Methods*. London: Charles Griffin, pp 13-26
- Kirschbaum MUF (1995) The temperature-dependence of soil organic-matter decomposition, and the effect of global warming on soil organic-C storage. *Soil Biol Biochem* 27: 753-760. [https://doi.org/10.1016/0038-0717\(94\)00242-S](https://doi.org/10.1016/0038-0717(94)00242-S)
- Krarti M, Lopez-Alonzo C, Claridge DM, Kreider JF (1995) Analytical model to predict annual soil surface temperature variation. *J Sol Energy Eng* 117: 91–99. <https://doi.org/10.1115/1.2870881>
- Kunkel V, Wells T, Hancock GR (2016) Soil temperature dynamics at the catchment scale. *Geoderma* 273: 32–44. <https://doi.org/10.1016/j.geoderma.2016.03.011>
- Lee M (2009) Improvement of the Fuzzy C-Means Clustering Algorithm with Adaptive Learning of the Dissimilarities among Categorical Feature Values. 2009 IEEE-Int Conf Fuzzy Syst 1-3: 403-408. <https://doi.org/10.1109/FUZZY.2009.5277209>
- Liang LL, Riveros-Iregui DA, Emanuel RE, McGlynn BL (2014) A simple framework to estimate distributed soil temperature from discrete air temperature measurements in data-scarce regions. *J Geophys Res: Atmos* 119: 407–417. <https://doi.org/10.1002/2013jd020597>
- Lin ZY, Wu XD (1981) Climate Regionalization of the Qinghai-Xizang Plateau. *Acta Geographica Sinica* 36: 22-32. <https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD7984&filename=DLXB198101002&v=FO8T6pExVyGBpcx%25md2B0QDpHTdHB33RO7F8jQPjRVpNe6raxGyWMI8bwvdaq7FxyiY5>
- Liu HS, Liu HJ, Wang ZP, Xu M, Han XG, Li LH (2008) The temperature sensitivity of soil respiration. *Prog Geogr* 27: 52-60. <https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2008&filename=DLKJ200804008&uniplatform=NZKPT&v=ZcnwbccUiiXEC10b80eFCz9G-hjK4PH9GqWxNL-hb9bjoGwudPBueg67hJO-ycHT>
- Liu WD, You HL, Ren GY, Yang P, Zhang BZ (2014) AWS precipitation characteristics based on K-means clustering method in Beijing area. *Meteorol Monogr* 40: 844–851. <https://doi.org/10.7519/jissn1000-0526.2014.07.008>

- Liu XD, Chen BD (2000) Climatic warming in the Tibetan Plateau during recent decades. *Int J Climatol* 20: 1729-1742. [https://doi.org/10.1002/1097-0088\(20001130\)20:14<1729::AIDJOC 556>3.0.CO;2-Y](https://doi.org/10.1002/1097-0088(20001130)20:14<1729::AIDJOC 556>3.0.CO;2-Y)
- Liu XS, Luo TX (2011) Spatiotemporal variability of soil temperature and moisture across two contrasting timberline Ecotones in the Sergyemla Mountains, Southeast Tibet. *Arct Antarct Alp Res* 43: 229–238. <https://doi.org/10.1657/1938-4246-43.2.229>
- Liu YQ, Avissar R (1999) A study of persistence in the land-atmosphere system with a fourth-order analytical model. *J Climate* 12: 2154-2168. [https://doi.org/10.1175/1520-0442\(1999\) 012<2154:ASOPIT>2.0.CO;2](https://doi.org/10.1175/1520-0442(1999) 012<2154:ASOPIT>2.0.CO;2)
- Lobell DB, Field CB (2007) Global scale climate - crop yield relationships and the impacts of recent warming. *Environ Res Lett*: 014002. <http://dx.doi.org/10.1088/1748-9326/2/1/014002>
- Lu XB, Xu HM, Sun CH, He JH (2006) Characteristics of soil temperature variations in China in recent 50 years (in Chinese). *J Nanjing Inst Meteorol* 29: 706-712. <https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2006&file name=NJQX200605018&uniplatform=NZKPT&v=WExG0hwm47ImGFOJzkkAohB9P2sPPtMFFpNKCqcS7pDJg7HSEW4Ni031bej0K8Pf>
- Luo DL, Jin HJ, Jin XY, He RX, Li XY, Muskett RR, Marchenko SS, Romanovsky VE (2018b) Elevation-dependent thermal regime and dynamics of frozen ground in the Bayan Har Mountains, northeastern Qinghai-Tibet Plateau, southwest China. *Permafr Periglac Process* 29: 257-270. <https://doi.org/10.1002/ ppp.1988>
- Luo GJ, Kiese R, Wolf B, Butterbach-Bahl K (2013) Effects of soil temperature and moisture on methane uptake and nitrous oxide emissions across three different ecosystem types. *Biogeosciences* 10: 305–321. <https://doi.org/10.5194/bg-10-3205-2013>
- Luo YQ, Sherry R, Zhou XH, Wan SQ (2009) Terrestrial carbon-cycle feedback to climate warming: Experimental evidence on plant regulation and impacts of biofuel feedstock harvest. *Glob Change Biol Bioenerg* 1: 62–74. <https://doi.org/10.1111/j.1757-1707.2008.01005.x>

- Ma WQ, Ma YM, Su B (2011) Feasibility of retrieving land surface heat fluxes from Aster data using SEBS: a case study from NamCo Area of the Tibetan Plateau. *Arct Antarct Alp Res* 43: 239-245. <https://doi.org/10.1657/1938-4246-43.2.239>
- Mackay AD, Barber SA (1984) Soil-temperature effects on root-growth and phosphorus uptake by corn. *Soil Sci Soc Am J* 48: 818-823. <https://doi.org/10.2136/sssaj1984.03615995004800040024x>
- Mann HB (1945) Nonparametric tests against trend. *Econom* 13: 245-259. <https://doi.org/10.2307/1907187>
- Mellander PE, Löfvenius MO, Laudon H (2007) Climate change impact on snow and soil temperature in boreal scots pine stands. *Clim Chang* 85: 179–193. <https://doi.org/10.1007/s10584-007-9254-3>
- Miller JR, Russell GL (1992) The impact of global warming on river runoff. *J Geophys Res: Atmos* 97: 2757-2764. <http://dx.doi.org/10.1029/91JD01700>
- Munir TM, Perkins M, Kaing E, Strack M (2015) Carbon dioxide flux and net primary production of a boreal treed bog: Responses to warming and water-table-lowering simulations of climate change. *Biogeosciences* 12: 1091–1111. <https://doi.org/10.5194/bg-12-1091-2015>
- Oelke C, Zhang TJ (2004) A model study of circum-Arctic soil temperatures. *Permafrost Periglacial Process* 15: 103–121. <https://doi.org/10.1002/ppp.485>
- Park HS, Chiang JCH, Bordoni S (2012) The Mechanical Impact of the Tibetan Plateau on the Seasonal Evolution of the South Asian Monsoon. *J Climate* 25: 2394-2407. <https://doi.org/10.1175/JCLI-D-11-00281.1>
- Paul KI, Polglase PJ, Smethurst PJ, O'Connell AM, Carlyle CJ, Khanna PK (2004) Soil temperature under forests: a simple model for predicting soil temperature under a range of forest types. *Agric For Meteorol* 121: 167–182. <https://doi.org/10.1016/j.agrformet.2003.08.030>
- Peng XO, Frauenfeld W, Cao B, Wang K, Wang H, Su H, Huang Z, Yue D, Zhang T (2016) Response of changes in seasonal soil freeze/thaw state to climate change from 1950 to 2010 across China. *J Geophys Res Earth Surf* 121: 1984–2000. <https://doi.org/10.1002/2016JF003876>

- Phillips CL, Nickerson N, Risk D, Bond BJ (2011) Interpreting diel hysteresis between soil respiration and temperature. *Glob Change Biol* 17: 515-527. <http://dx.doi.org/10.1111/j.1365-2486.2010.02250.x>
- Power SB, Kociuba G (2011) The impact of global warming on the Southern Oscillation Index. *Clim Dyn* 37: 1745-1754. <http://dx.doi.org/10.1007/s00382-010-0951-7>
- Qian B, Gregorich EG, Gameda S, Hopkins DW, Wang XL (2011) Observed soil temperature trends associated with climate change in Canada. *J Geophys Res* 116: 1–16. <https://doi.org/10.1029/2010JD015012>
- Qin DH, Stocker J, 259 authors and TSU (2014) Highlights of the IPCC working group I fifth assessment report. *Clim Change Res* 10: 1-6. <http://dx.doi.org/10.3969/j.issn.1673-1719.2014.01.001>
- Qin YH, Liu W, Guo Z, Xue S (2020) Spatial and temporal variations in soil temperatures over the Qinghai-Tibet Plateau from 1980 to 2017 based on reanalysis products. *Theor Appl Climatol* 140: 1055-1069. <https://doi.org/10.1007/s00704-020-03149-9>
- Rose G, Osborne T, Greatrex H, Wheeler T (2016) Impact of progressive global warming on the global-scale yield of maize and soybean. *Clim Change* 134: 417-428. <http://dx.doi.org/10.1007/s10584-016-1601-9>
- Rosenberg NJ, Epstein DJ, Wang D, Vail L, Srinivasan R, Arnold JG (1999) Possible impacts of global warming on the hydrology of the Ogallala aquifer region. *Clim Change* 42: 677-692. <http://dx.doi.org/10.1023/A:1005424003553>
- Rustad LE, Campbell JL, Marion GM, Norby RJ, Mitchell MJ, Hartley AE, Hartley AE, Cornelissen JHC (2001) A meta-analysis of the response of soil respiration, net nitrogen mineralization, and aboveground plant growth to experimental ecosystem warming. *Oecologia* 126: 543–562. <https://doi.org/10.1007/s004420000544>
- Samadianfard S, Asad E, Jarhana S, Kazemi H, Kheshtgar S, Kisi O, Sajjadi S, Manaf AA (2018) Wavelet neural networks and gene expression programming models to predict short-term soil temperature at different depths. *Soil Tillage Res* 175: 37–

50. <https://doi.org/10.1016/j.still.2017.08.012>

Shi XZ, Deng XH (1993) Soil temperature region in China. In Gong ZT (ed) Research on Chinese soil taxonomy (in Chinese). Beijing: Science Press, pp 353-360

Saxena A, Prasad M, Gupta A, Gupta A, Bharill N, Patel OP, Tiwari A, Er MJ, Ding W, Lin C (2017) A review of clustering techniques and developments.

Neurocomputing 267: 664-681. <https://doi.org/10.1016/j.neucom.2017.06.053>

Su Z, Wen J, Dente L, van der Velde R, Wang L, Ma Y, Yang K, Hu Z (2011) The Tibetan Plateau observatory of plateau scale soil moisture and soil temperature (Tibet-Obs) for quantifying uncertainties in coarse resolution satellite and model products. Hydrol Earth Syst Sci 15: 2303-2316. <https://doi.org/10.5194/hess-15-2303-2011>

Tang MC, Shen ZB, Chen YY (1979) On climatic characteristics of the Xizang Plateau monsoon. Acta Geograph Sin 34: 34-42.

<https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD>

&dbname=CJFD7984&filename=DLXB197901003&v=D1IdnHEP13%25mmd2BCJBTcGum5zBGAFUD6q0LpjSI0XT%25mmd2BH%25mmd2FFriKAu5%25mmd2FDw6eEDSKgJOkXR

Tang MC, Wang JX, Zhang J (1987) A primary method for predicting the spring rainfall by the winter soil temperature depth 80cm. Plateau Meteorol 6: 244-255.

<https://kns.cnki.net/>

[kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD8589&filename=GYQX198703005&v=CrUDrXz03wBIDGdBU%25mmd2B92QXLeRxs14Z1lguvAaeIHVIU0VJFMxTFyK0lq8EbVBSmc](https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD8589&filename=GYQX198703005&v=CrUDrXz03wBIDGdBU%25mmd2B92QXLeRxs14Z1lguvAaeIHVIU0VJFMxTFyK0lq8EbVBSmc)

Tang XL, Zhou GY, Liu SG, Zhang DQ, Liu SZ, Li J, Zhou CY (2006) Dependence of soil respiration on soil temperature and soil moisture in successional forests in southern China. J Integr Plant Biol 48: 654-663. <http://dx.doi.org/10.1111/j.1744-7909.2006.00263.x>

Torn MS, Fried JS (1992) Predicting the impacts of global warming on wildland fire.

Clim Change 21: 257-274. <http://dx.doi.org/10.1007/BF00139726>

Wang CH, Yang K, Li YL, Wu D, Bo Y (2017) Impacts of Spatiotemporal Anomalies

of Tibetan Plateau Snow Cover on Summer Precipitation in Eastern China. *J Meteorol Res* 30: 885-903. <https://doi.org/10.1175/JCLI-D-16-0041.1>

Wang GB, Zhou Y, Xu X, Ruan HH, Wang JS (2013) Temperature sensitivity of soil organic carbon mineralization along an elevation gradient in the Wuyi mountains, China. *PLoS One* 8: e53914. <https://doi.org/10.1371/journal.pone.0053914>

Wang XQ, Chen RS, Han CT, Yang Y, Liu JF, Liu ZW, Guo SH, Song YX (2020) Soil temperature change and its regional differences under different vegetation regions across China. *Int J climatol* 41: E2310-E2320. <https://doi.org/10.1002/joc.6847>

Wang YH, Chen W, Zhang JY, Nath D (2013) Relationship Between Soil Temperature in May over Northwest China and the East Asian Summer Monsoon Precipitation. *J Meteorol Res* 27: 716–724. <https://doi.org/10.1007/s13351-013-0505-0>

Wessel P (2009) A general-purpose Green's function-based interpolator. *Comput Geosci* 35: 1247-1254. <https://doi.org/10.1016/j.cageo.2008.08.012>

Wu TW, Qian ZA (2003) The relation between the Tibetan winter snow and the Asian summer monsoon and rainfall: An observational investigation. *J Climate* 16: 2038-2051. [https://doi.org/10.1175/1520-0442\(2003\)016<2038:TRBTTW>2.0.CO;2](https://doi.org/10.1175/1520-0442(2003)016<2038:TRBTTW>2.0.CO;2)

Wu W, Tang XP, Guo NJ, Yang C, Liu HB, Shang YF (2013) Spatiotemporal modeling of monthly soil temperature using artificial neural networks. *Theor Appl Climatol* 113: 481–494. <https://doi.org/10.1007/s00704-012-0807-7>

Wu XB, Nan ZT, Zhao SP, Zhao L, Cheng GD (2018b) Spatial modeling of permafrost distribution and properties on the Qinghai-Tibet Plateau. *Permafr Periglac Process* 29: 86–99. <https://doi.org/10.1002/ppp.1971>

Wundram D, Pape R, Löffler J (2010) Alpine soil temperature variability at multiple scales. *Arct Antarct Alp Res* 42: 117–128. <https://doi.org/10.1657/1938-4246-42.1.117>

Wurr DCE, Fellows JR, Hambidge AJ (1995) The potential impact of global warming on summer/autumn cauliflower growth in the UK. *Agric For Meteorol* 72: 181-193. [http://dx.doi.org/10.1016/0168-1923\(94\)02169-K](http://dx.doi.org/10.1016/0168-1923(94)02169-K)

Xu X, Sherry RA, Niu SL, Li DJ, Luo YQ (2013) Net primary productivity and rain-use efficiency as affected by warming, altered precipitation, and clipping in a

826 mixed-grass prairie. *Glob Change Biol* 19: 2753–2764.

827 <https://doi.org/10.1111/gcb.12248>

828 Yan D, Li JQ, Pei JM, Cui J, Nie M, Fang CM (2017) The temperature sensitivity of
829 soil organic carbon decomposition is greater in subsoil than in topsoil during
830 laboratory incubation. *Sci Rep* 7: 5181. [https://doi.org/10.1038/s41598-017-](https://doi.org/10.1038/s41598-017-05293-1)
831 05293-1

832 Yang K, Wu H, Qin J, Lin CJ, Tang WJ, Chen YY (2014) Recent climate changes
833 over the Tibetan Plateau and their impacts on energy and water cycle: a review.
834 *Glob Planet Chang* 112: 79-91. <https://doi.org/10.1016/j.gloplacha.2013.12.001>

835 Yang MX, Yao TD, Gou XH, Tang HG (2007) Water recycling between the land
836 surface and atmosphere on the northern Tibetan Plateau—a case study at flat
837 observation sites. *Arct Antarct Alp Res* 39: 694–698. [https://doi.org/10.1657/1523-](https://doi.org/10.1657/1523-0430(07-509)[YANG]2.0.CO;2)
838 0430(07-509)[YANG]2.0.CO;2

839 Zhang H, Wang EL, Zhou DW, Luo ZK, Zhang ZX (2016) Rising soil temperature in
840 China and its potential ecological impact. *Sci Rep* 6: 35530.
841 <http://dx.doi.org/10.1038/srep35530>

842 Zhang HZ, Shi XZ, Yu DS, Wang HJ, Zhao YC, Sun WX, Huang BR (2009) Seasonal
843 and regional variations of soil temperature in China. *Acta Pedol Sinica* 2009: 228-
844 234.
845 [https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2009&](https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2009&filename=TRXB200902006&uniplatform=NZKPT&v=ZVnzs2Bhs4gDDdLLYKe-NXvWcHoR3F6tE63m4gWLehiB6e1xRt6bCJvMwvOC2yt2)
846 [filename=TRXB200902006&uniplatform=NZKPT&v=ZVnzs2Bhs4gDDdLLYKe](https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2009&filename=TRXB200902006&uniplatform=NZKPT&v=ZVnzs2Bhs4gDDdLLYKe-NXvWcHoR3F6tE63m4gWLehiB6e1xRt6bCJvMwvOC2yt2)
847 [-NXvWcHoR3F6tE63m4gWLehiB6e1xRt6bCJvMwvOC2yt2](https://kns.cnki.net/kcms/detail/detail.aspx?dbcode=CJFD&dbname=CJFD2009&filename=TRXB200902006&uniplatform=NZKPT&v=ZVnzs2Bhs4gDDdLLYKe-NXvWcHoR3F6tE63m4gWLehiB6e1xRt6bCJvMwvOC2yt2)

848 Zhang Y, Chen WJ, Smith SL, Riseborough DW, Cihlar J (2005) Soil temperature in
849 Canada during the twentieth century: Complex responses to atmospheric climate
850 change. *J Geophys Res: Atmos* 110: D3. <https://doi.org/10.1029/2004JD004910>

851 Zhao L, Wu QB, Marchenko SS, Sharkhuu N (2010) Thermal State of Permafrost and
852 Active Layer in Central Asia during the International Polar Year. *Permafr Periglac*
853 *Process* 21: 198-207. <https://doi.org/10.1002/ppp.688>

854 Zhou XJ, Zhao P, Chen JM, Chen LX, Li WL (2009) Impacts of thermodynamic
855 processes over the Tibetan Plateau on the Northern Hemispheric climate. *Sci*

856 China Ser D Earth Sci 52: 1679-1693. <https://doi.org/10.1007/s11430-009-0194-9>

857 Zhou Y, Gao XQ, Zhang K, Li YJ, Yang LW (2020) Spatiotemporal variations
858 in 3.2 m soil temperature in China during 1980–2017. *Clim Dyn* 54: 1233-
859 1244. <https://doi.org/10.1007/s00382-019-05055-x>

860 Zhu FX, Cuo L, Zhang YX, Luo JJ, Lettenmaier DP, Lin YM, Liu Z (2018)
861 Spatiotemporal variations of annual shallow soil temperature on the Tibetan
862 Plateau during 1983–2013. *Clim Dyn* 51: 2209-2227.
863 <https://doi.org/10.1007/s00382-017-4008-z>

864

865