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Evaluation and Analysis of Soil Temperature Data over Poyang Lake Basin, China

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Abstract: Soil temperature reflects the impact of local factors，such as vegetation，soil and the atmosphere of a region. Therefore, it is important to understand the regional variation of soil temperature. However, lack of observations with adequate spatial and/or temporal coverage, it would be difficult to use the observation data to study the regional variation. Based on the observation data from Nanchang and Ganzhou stations and ERA-Interim/Land reanalysis data, this study analyzed the temporal-spatial distribution characteristics of soil temperature over Poyang Lake Basin. The results showed close correlations between observation data and reanalysis data at different depths. Reanalysis data could mainly reproduce the temporal-spatial distributions of soil temperature over the Poyang Lake Basin, but generally underestimate their magnitudes. Temporally, there is an obvious warming trend in the basin. Seasonally, the temperature raised fastest in spring and slowest in summer, except for the ST4, which rising fastest in spring and slowest in winter. In terms of depths, the temperature of ST1 rises fastest. For the other layers, the warming trend is almost similar. An abrupt change of annual soil temperature at all depths occurred in 1997, and annual soil temperatures at all depths were abnormally low in 1984. Spatially, annual soil temperature decreased with latitude, except for the summer ST1. Because of the high temperature and precipitation in summer, the ST1 are higher around the lake and the river. The climatic trend of soil temperature presents the general increase trend from south to north, opposite to the distribution of soil temperature. The findings provide a basis for understanding and assessing the variation of the soil temperature over the Poyang Lake Basin.

Keywords: Soil temperature; Data evaluation; Climatology; Interannual variation; Poyang Lake Basin

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1. Introduction

Soil temperature, an important parameter to characterize the thermal properties of soil, is the main factor affecting the atmosphere on the land surface. It can affect the climate change by affecting the energy distribution, exchange and water budget on the surface. It gradually acts on the upper atmosphere through the Surface Boundary Layer. Therefore, soil temperature plays an important role in the interaction of land and air [1, 2]. Soil temperature also plays an important role in climate change [3-5]. Changes in soil temperature associated with climate warming could result in variation of terrain and hydrologic conditions, alteration of the distribution and growth rate of vegetation, enhancement of soil organic carbon decomposition, and increased emission of CO2 from the soil to the atmosphere [6-11]. These effects could have significant consequences both locally and globally.

Under the influence of global warming, the mean surface temperature around the world has risen by 0.85 °C (0.65–1.06 °C) from 1880 to 2012[12]. In the past 50 years (1961–2011), the mean temperature of China has risen by 1.1 °C, which is greater than the global and the Northern Hemisphere [13]. Driven by the air temperature, the soil temperature in China has also shown a warming trend. Since 1990s, based on the monthly soil temperature data of 532 stations in China, the annual mean soil temperature has remarkably increased. Regionally, the soil temperatures in Northeast China increases most significantly; while in the eastern part of Southwest China, soil temperature shows an evident decreasing tend [14](Lu et al., 2006). In Lhasa (Tibet), from 1961 to 2005, the annual mean soil temperatures at shallow layers (0–40cm) have significant increasing trends, and the rising rates are (0.45–0.66°C)/10a, which is greater than the air temperature in the same period [15] (Du et al., 2008). In Alxa Left Banner (the Inner Mongolia Autonomous region, northwestern China), from 1961 to 2005, the rising rates of annual soil temperatures at 0–80 cm soil depths are (0.28–0.46°C)/10a, which is lower than air temperature (0.46°C/10a). Seasonally, the responses of summer, autumn and winter air temperature to climate change are more significant than soil temperatures, while the responses of soil temperatures to climate change are more significant than air temperature in spring[16]. Based on analysis of the long-term changes (1961–2018) in soil temperature at Nanchang (the middle–lower reaches of the Yangtze River, southern China), Zhan (2019) found that the annual variation of air temperature correlated very well with soil temperatures (0–320cm) [11]. The increase rates of soil temperature are reported as 0.074–0.186 °C/decade, lower than that of annual air temperature, 0.255 °C/decade.

Currently, many studies have investigated the variations of soil temperatures in stations, but examination of the spatial-temporal variations of soil temperature remains largely comparative. However, lack of observations with adequate spatial and/or temporal coverage, it would be difficult to use the observation data of stations to study the regional variation. Because of the continuity and adequate spatial and temporal coverage, reanalysis data plays an important role in soil temperature regional study. Yang and Zhang (2017) evaluate four reanalysis datasets of soil temperature, the land surface reanalysis of the European Centre for Medium-Range Weather Forecasts (ERA-Interim/Land), the second modern-era retrospective analysis for research and applications (MERRA-2), the National Center for Environmental Prediction Climate Forecast System Reanalysis (NCEP-CFSR), and version 2 of the Global Land Data Assimilation System (GLDAS-2.0) [17]. The results show that reanalysis data can mainly reproduce the spatial distributions of soil temperature in summer and winter, especially over the east of China, but generally underestimate their magnitudes. Four reanalysis products (the ERA-Interim re-analysis, ERA-Interim/Land, MERRA-Land, and NOAA-CIRES 20CR) are used to analysis the soil temperature variation over middle and high latitudes of East Asia [18]. ERA-Interim land surface temperature dataset is also used in mapping the permafrost distribution over the Tibetan Plateau [19].

In this study, the Poyang Lake Basin, located in subtropical monsoon region of China where is sensitive to climate change, is adopted as the research object. However, due to the lack of sufficient observation stations, it is not realistic to use observation data to study regional soil temperature variation. So, first, we evaluated the reanalysis data by the observation data. And then, we used the reanalysis data to study the temporal and spatial variation characteristics of soil temperature in Poyang Lake Basin. The research results will provide a scientific basis for improved understanding and assessment of the impact of climate change on terrestrial ecosystems.

2. Data

2.1 Study Area

The Poyang Lake Basin (28°22′–29°45′N, 115°47′–116°45′E, with an area of 1.62×105 km2) is located in the middle–lower reaches of the Yangtze River, within the sphere of the East Asian monsoon, has a typical monsoon climate characteristic (Figure 1). From 1961 to 2018, the annual temperature is 18.1°C and annual precipitation is approximately 1650mm. The region has four distinct seasons: spring (March–May), summer (June–August), autumn (September–November), and winter (December–February). It plays an important ecological and hydrological role for the middle and lower Yangtze River [20].

The main reason for choosing the Nanchang (28°36′N, 115°55′E; elevation: 46.9 m) and Ganzhou (28°52′N, 115°; elevation: 58.6 m) weather station as the research object is that the station have remained at the same location since 1960. Nanchang station is located in the northern part of the Basin and Ganzhou is located in the southern. Nanchang and Ganzhou can reflect the overall climate characteristics of the Basin. Moreover, the time series data of soil temperatures(at depths of 0, 20, 80, and 320 cm) at various depths recorded at the two stations are long and the data integrity is considered satisfactory (i.e., amount of missing data annually is <5%).

2.2 Observed data

The soil temperature dates (at depths of 0, 20, 80, and 320 cm) data from Nanchang and Ganzhou National Weather stations span from 1961 to present (black triangles in Fig. 1). Prior to further analysis, these data were tested for homogeneity. The missing data, less than 1%, have little or no effect on the research results.

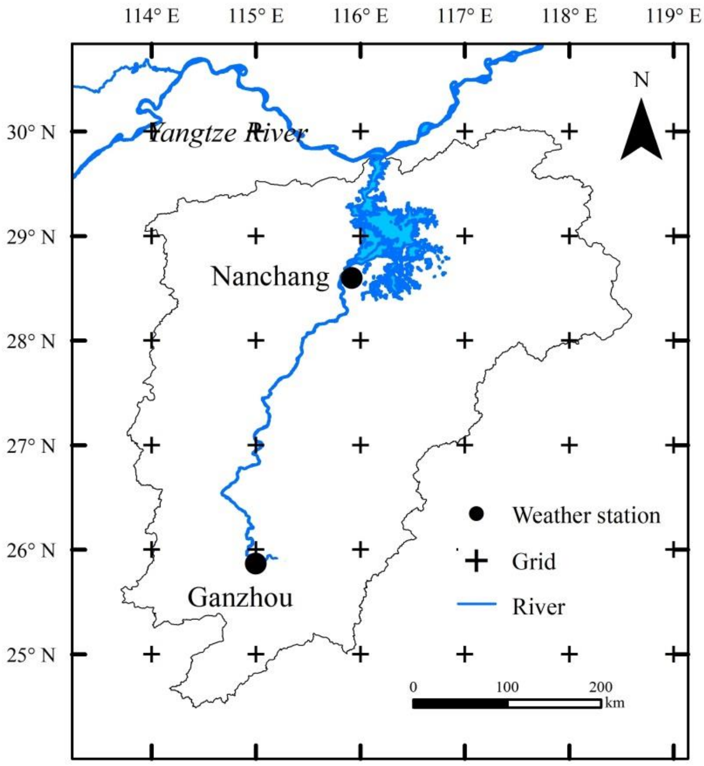


Figure 1. Location of the Nanchang and Ganzhou National Weather Station, China.

2.3. ERA-Interim/Land reanalysis data

ERA-Interim/Land is a global land surface reanalysis data set covering the period 1979 to present. It describes the evolution of soil moisture, soil temperature and snowpack. ERA-Interim/Land is the result of a single 32-year simulation with the latest ECMWF (European Centre for Medium-Range Weather Forecasts) land surface model driven by meteorological forcing from the ERA-Interim atmospheric reanalysis and precipitation adjustments based on monthly

GPCP v2.1 (Global Precipitation Climatology Project) [21,22]. There are four different soil depths 0-7cm，7-28cm，28-100cm，and 100-289cm, recording as ST1, ST2, ST3 and ST 4 respectively. The horizontal resolution is about 1°×1° and the time frequency is monthly (Grid in Fig.1). And the time spans from Jan.1979 to Dec. 2018.

2.4. Method

2.4.1 Applicability Evaluation of ERA-Interim/Land reanalysis data

The evaluation of the ERA-Interim/Land reanalysis data using observed data focuses on monthly variations. The correlation coefficients, mean error (ME), mean absolute error (MAE) and root mean square error (RMSE) between ERA soil temperature and observation soil temperature are calculated to investigate their agreements on monthly time-scales. The two observed time series are from Nanchang and Ganzhou stations. Their counterparts, the ERA-Interim/Land reanalysis data, are the average values of the two grid cells closest to the weather stations (red grid cells in Figure 1).

$$\mathrm{ME} = \sum_{i=1}^{n}(ST_{ERA} - ST_{obs.})/n \tag{1}$$

$$\mathrm{MAE} = \sum_{i=1}^{n}(\,|ST_{ERA} - ST_{obs.}|)/n \tag{2}$$

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(ST_{ERA} - ST_{obs.})^2} \tag{3}$$

2.4.2 Sen's slope estimator

Sen (1968) developed the non-parametric procedure for estimating the long-term trend [23]. Compared with the least squared linear regression, the Sen's slope estimator is insensitive to outliers and thus the estimated linear trend is significantly more accurate and robust for skewed data. The slope of N pairs of data points can be estimated by the following relation:

$$\beta = \mathrm{Median}\left(\frac{x_j - x_l}{j-l}\right) \qquad (j > l > 1) \tag{4}$$

where xl and xj are data values at time l and time j, respectively. Due to its robustness for estimating the magnitude of a trend, this method is widely applied to hydrological and climatic time series [24-28].

2.4.3 Test of abrupt change

The Mann-Kendall test is developed by Mann and Kendall [29,30] (Mann, 1945; Kendall, 1975). It is originally used to detect trend changes in the sequence. Goossens and Berger (1986) improved and developed the method. It enables this method to determine the year of the abrupt [31].

For time series X with n sample sizes, a rank series Sk is constructed.

$$S_k = \sum_{i=1}^{k} r_i \qquad r_i = \begin{cases} 1 & x_i > x_j \\ 0 & else \end{cases} \qquad \text{j=1, 2, ⋯, i} \tag{5}$$

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{Var(S_k)}} \qquad \text{k=1, 2, ⋯, n} \tag{6}$$

In Eq.(6), UF1=0, E(Sk) and Var(Sk) are the mean and variance of the Sk.

$$\mathrm{E}(S_k) = \frac{n(n+1)}{4} \qquad \mathrm{Var}(S_k) = \frac{n(n-1)(2n+5)}{72} \tag{7}$$

Arrange X in reverse chronological order, x_n, x_{n-1}, ⋯, x_1. Repeat the process again to get UB.

$$\mathrm{UB_k} = -\mathrm{UF_k} \qquad \text{k=n, n-1, ⋯, 1} \tag{8}$$

UF is a standard normal distribution, which is in the time series x order x1, x2, ····xn. Look up the normal distribution table at the given significance levelα. If$|UF_i| > U_\alpha$, it indicates that there is obvious trend change in the sequence. If α=0.05, $U_{0.05}=\pm1.96$.

If the UF and UB intersect and the$|UF_i| > 1.96$, X would abrupt at the intersection. The Mann-Kendall test has been frequently used to quantify the abrupt change in hydro-meteorological time series [32,33].

2.4.4 Anomaly and standard deviation

Climate anomalies are considered conditions in which anomalies of climatic elements reach a certain magnitude. The World Meteorological Organization believes that when an anomaly of a climatic element is more than double the standard deviation, the climatic element should be considered abnormal [11].

3. Results

3.1 Validation of ERA-Interim/Land reanalysis data for applicability

In this paper, the obs. soil temperature of Nanchang and Ganzhou stations are used to evaluate the ERA-Interim/Land reanalysis data at its nearby grid points (Figure 1). There are four different soil depths 0, 20, 80 and 320cm in observation data, recording as obs.ST1, obs.ST2, obs.ST3 and obs.ST 4 respectively.

Comparing the month-by-month average data from January 1979 to December 2018, we find a very strong correlation between ERA and obs. soil temperature data (Figure 2 and table 1). Take the Obs.ST1 of Nanchang and ST1 of ERA as example, the correlation coefficients is 0.99. And the average of Obs. and the ERA are 20.2 (3.2, 38.0) and 19.1(4.9, 32.1) respectively. The ME，MAE and RMSE are -1.1°C, 1.7°C and 2.2°C. It can be considered that there is a high degree of consistency between ERA and Obs. at the ST1. At the same depth the ERA soil temperature data to Obs. data in addition to individual data overall small, but overall the ERA-Interim/Land reanalysis data are in pretty good agreement with the observed data (Figure 2 and Table 1). The ERA-Interim/Land reanalysis data has been proved to be reliable for regional soil temperature research in the Poyang Lake basin.

Table 1. The monthly variations of ERA and Obs.

		Correlation Coefficients	ME(℃)	MAE(℃)	RMSE(℃)
ERA Vs Nanchang	ST1	0.99	-1.1	1.7	2.2
	ST2	0.99	-1.3	1.3	1.5
	ST3	0.99	-1.1	1.2	3.7
	ST4	0.94	-1.2	2.7	3.2
ERA Vs Ganzhou	ST1	0.99	-2.5	2.6	3.2
	ST2	0.99	-2.6	2.6	2.7
	ST3	0.99	-2.5	2.5	2.6
	ST4	0.87	-2.6	3.1	4

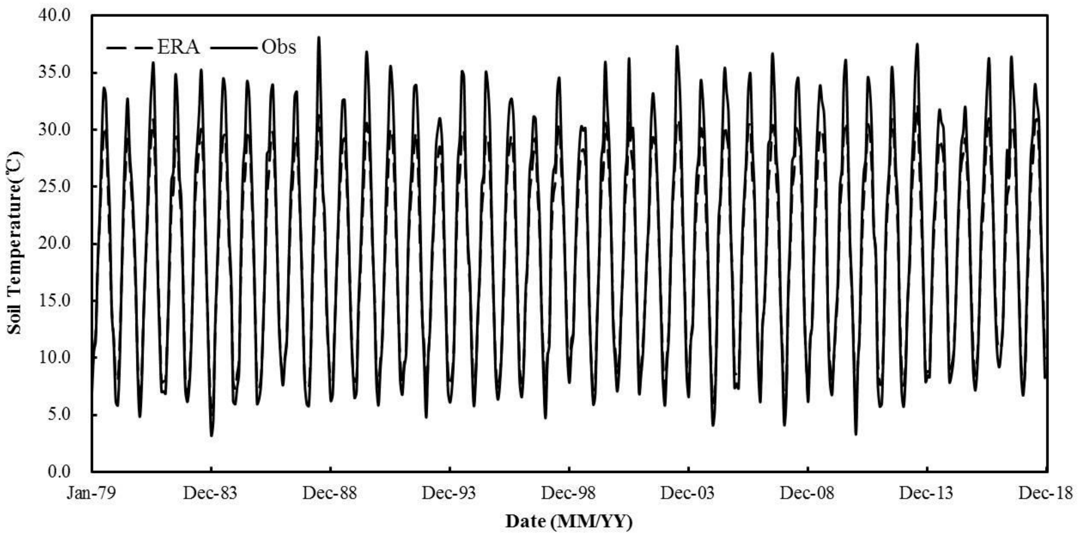


Figure 2. The monthly variations of ERA ST1 and Obs.ST1 of Nanchang

3.2. Monthly，seasonally and yearly changes of soil temperatures

The mean temperatures (from 1979 to 2018) of the four depths, in Poyang Lake Basin, are 19.8, 19.0, 19.1 and 19.1°C, respectively. In the ST1 (0-7cm), the temperature reaches a peak in July (28.8°C) and a minimum in January (9.6°C). The process of temperature rises from January, peaking in July, and then gradually decreasing. In ST2 (7-28cm) and ST3 (28-100cm), the changing process of temperature are very similar to ST1. Just the temperature peaks in August not in July. Different from other depths, in ST4 (100-289cm), the temperature start rising in March (12.6°C), peaking in September (25.4°C) and then declining to February next year (Figure 3). From March to September, the temperature of ST1 is higher than the temperature of ST4. So the heat would travel from the surface to the depth. The soil is in a state of absorbing energy. From October to February next year, the temperature of ST4 is higher than the temperature of ST1. The energy path would reverse, from the deep soil to the surface. Soil becomes a source of energy.

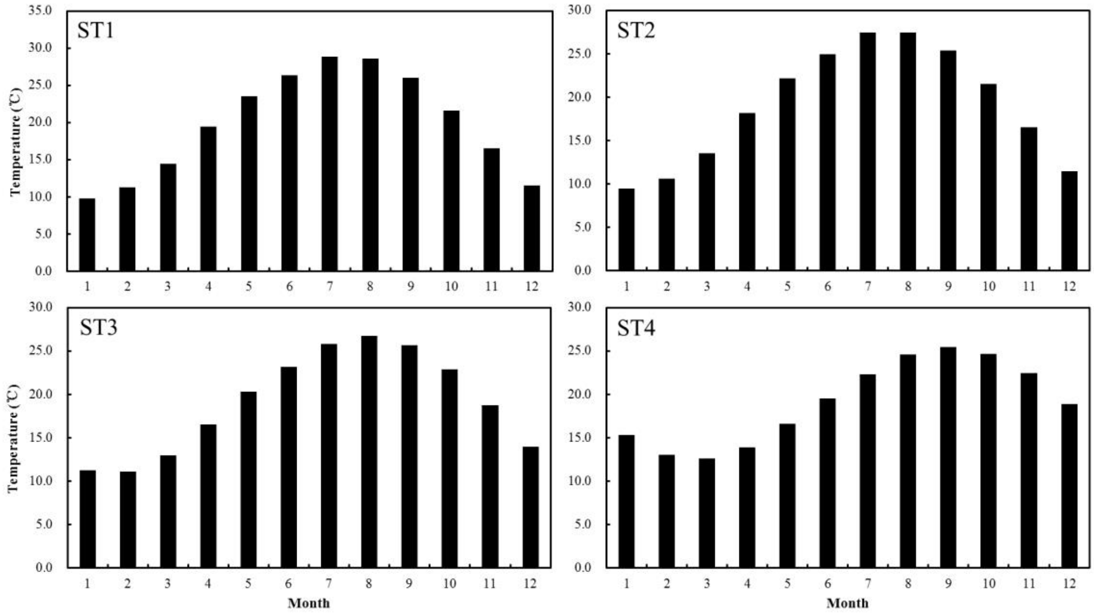
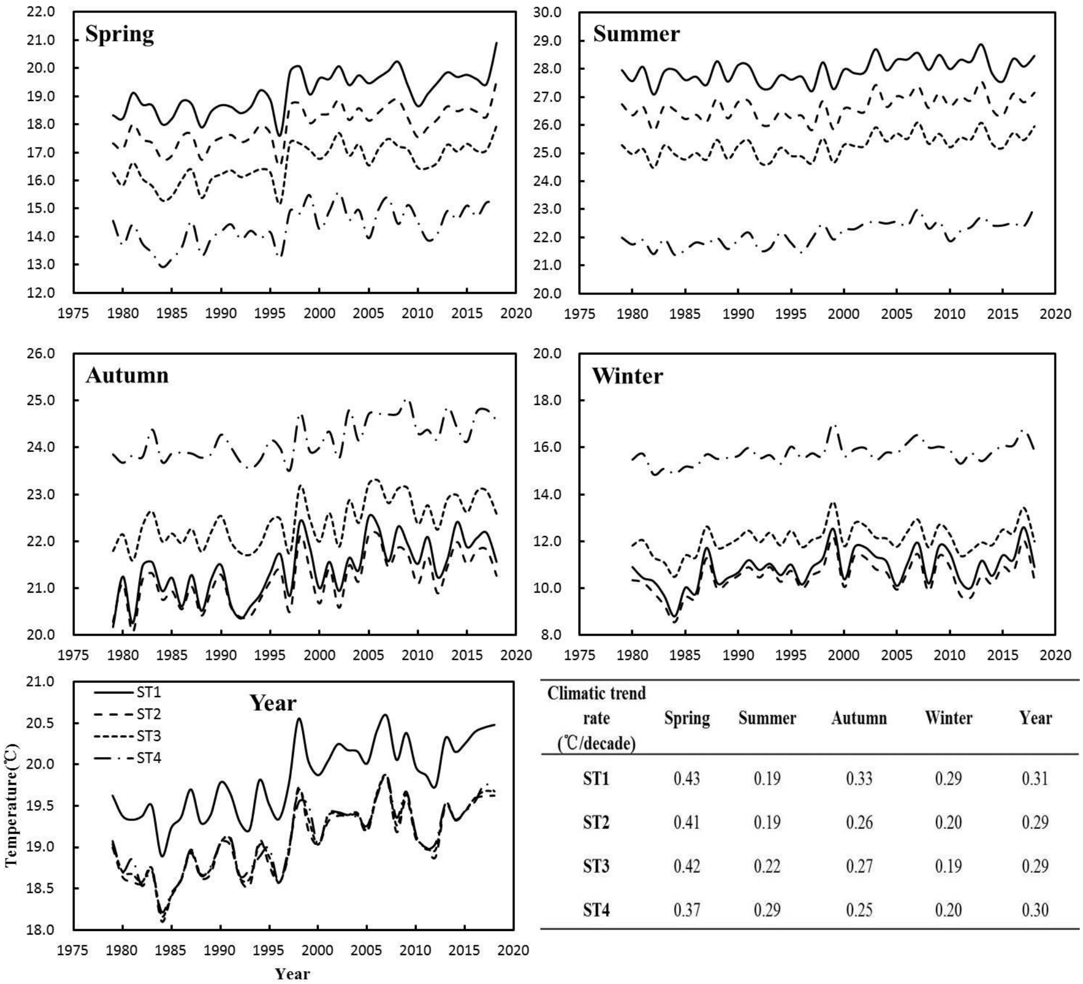


Figure 3. The monthly change of the soil temperature of four depths

Monthly values are averaged to obtain seasonal temperature. Seasons are defined as follows: winter = December, January, February; spring= March, April, May; summer= June, July, August and autumn=September, October, November. In general, the temperature at each depth and each season is rising year by year. In terms of seasons, the temperature raises fastest in spring and slowest in summer, except for the ST4, which rising fastest in spring and slowest in winter. In terms of depths, the temperature of ST1 rises fastest. For the other layers, the warming trend is almost similar (Figure 4).



Climatic trend rate (℃/decade)	Spring	Summer	Autumn	Winter	Year
ST1	0.43	0.19	0.33	0.29	0.31
ST2	0.41	0.19	0.26	0.20	0.29
ST3	0.42	0.22	0.27	0.19	0.29
ST4	0.37	0.29	0.25	0.20	0.30

Figure 4. Changes of seasonal and annual soil temperatures over the Poyang Lake Basin.

3.3. Abrupt change of soil temperatures

Based on Eqs. (5) to (8), the years of abrupt change in soil temperatures are calculated. Most annual and seasonal soil temperatures show abrupt changes; in general, the soil temperatures have changed from a relatively cold period to a comparatively warm period (Figure 5 and Table 2). An abrupt change of annual soil temperature at all depths occurred in 1997 (Figure 5), while the abrupt change of spring soil temperature occurred in 1996. Abrupt changes of summer soil temperatures of ST1, ST2 and ST3 occurred in 2002, except the summer soil temperature of ST4, which had abrupt change in 1999. In autumn, the abrupt changes of ST2, ST3 and ST4 occurred in 2000, while the ST1 had abrupt change in 1997. In winter, the ST2 and ST3 didn't show abrupt change. And the ST1 and ST4 had abrupt change in 1992.

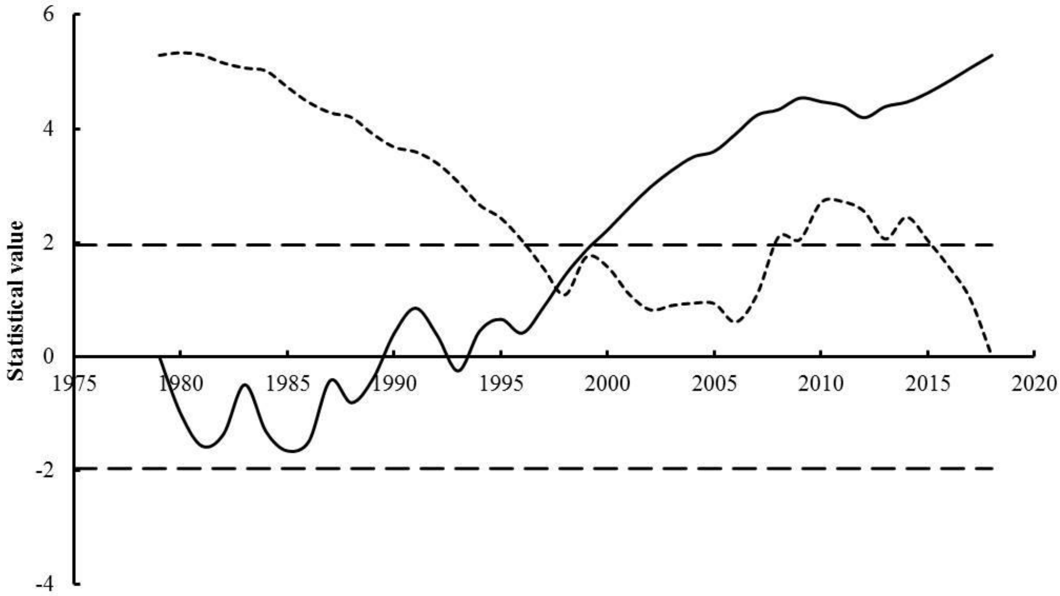


Figure 5. Abrupt change years of annual ST1

Table 2. Abrupt change years of annual and seasonal soil temperatures over Poyang Lake Basin

Index	Spring	Summer	Autumn	Winter	Annual
ST1	1996	2002	1997	1992	1997
ST2	1996	2002	2000	—	1997
ST3	1996	2002	2000	—	1997
ST4	1996	1999	2000	1992	1997

Note, "—" means no abrupt change

3.4. Anomalous characteristics of soil temperatures

In spring, the soil temperatures at depths of ST1, ST2 and ST3 were abnormally low in 1996 and abnormally high in 2018. In 1984, the soil temperature of ST4 was abnormally low. In summer, the soil temperature of ST1 was abnormally low in 1982. The soil temperatures at the depths of ST1, ST2, and ST3 were abnormally high in 2013, while the soil temperature of ST4 was abnormally high in both 2007 and 2018. In autumn, the soil temperature of ST1 was abnormally low in 1979; the soil temperature of ST2 was also abnormally low in 1981. The soil temperature of ST4 was abnormally high in 2009. In winter, soil temperatures at all depths were abnormally high (low) in 1999 and 2017 (1984). In terms of the annual mean, soil temperatures at all depths were abnormally low in 1984 (Table 3).

Table 3. Years of anomalous annual and seasonal mean soil temperatures over Poyang Lake Basin

Index	Spring	Summer	Autumn	Winter	Annual
ST1	1996(—), 2018(+)	1982(—), 2013(+)	1979(—)	1984 (—), 1999,2017(+)	1984 (—),
ST2	1996(—), 2018(+)	2013(+)	1981(—)	1984 (—), 1999,2017(+)	1984 (—),
ST3	1996(—), 2018(+)	2007,2013(+)		1984 (—), 1999,2017(+)	1984 (—),
ST4	1984(—)	2007,2018(+)	2009(+)	1984 (—)	1984 (—),

1999,2017(+)

Note, (+) abnormally high, (—) abnormally low

3.5. Spatial variations. of soil temperatures

In Poyang Lake Basin, annual mean st1 decrease with latitude. There are two low value areas in the northeast and northwest of Poyang Lake Basin (Figure 6a). The spatial distributions of almost all soil temperatures are very similar with the annual ST1 soil temperature, the spatial correlation coefficients are over 0.9, except for the summer soil temperatures of ST1 and ST2 (Table 4). The spatial correlation coefficient between summer soil temperature ST1 and ST2 is 0.860. Different from the annual soil temperature ST1, the summer soil temperature ST1 are higher around the lake and the river (Figure 6b).

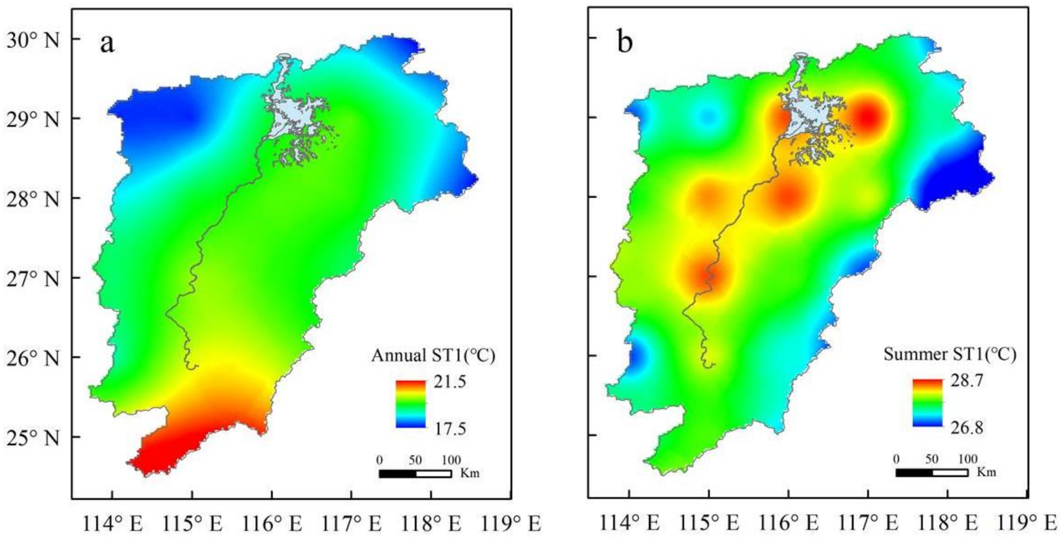


Figure 6. The spatial distribution of annual soil temperature (a) and summer soil temperature (b) of ST1 over the Poyang Lake Basin

Table 4. Spatial correlation coefficient between annual ST1 and other soil temperature

Correlation Coefficient		Annual ST1
ST1	Annual	—
	Spring	0.992
	Summer	0.497
	Autumn	0.997
	Winter	0.986
ST2	Annual	0.995
	Spring	0.996
	Summer	0.642
	Autumn	0.996
	Winter	0.984
ST3	Annual	0.995
	Spring	0.993
	Summer	0.872
	Autumn	0.991

	Winter	0.991
ST4	Annual	0.995
	Spring	0.992
	Summer	0.975
	Autumn	0.926
	Winter	0.978

Summer air temperature and summer precipitation may be the basic causes of spatial distribution of the summer ST1. The high temperature regions spatial distribution of summer air temperature and ST1 are basically the same, except for the northeast part of the basin. Heavy precipitation in the northeast part may cause the soil temperature to fail to rise (Figure 7).

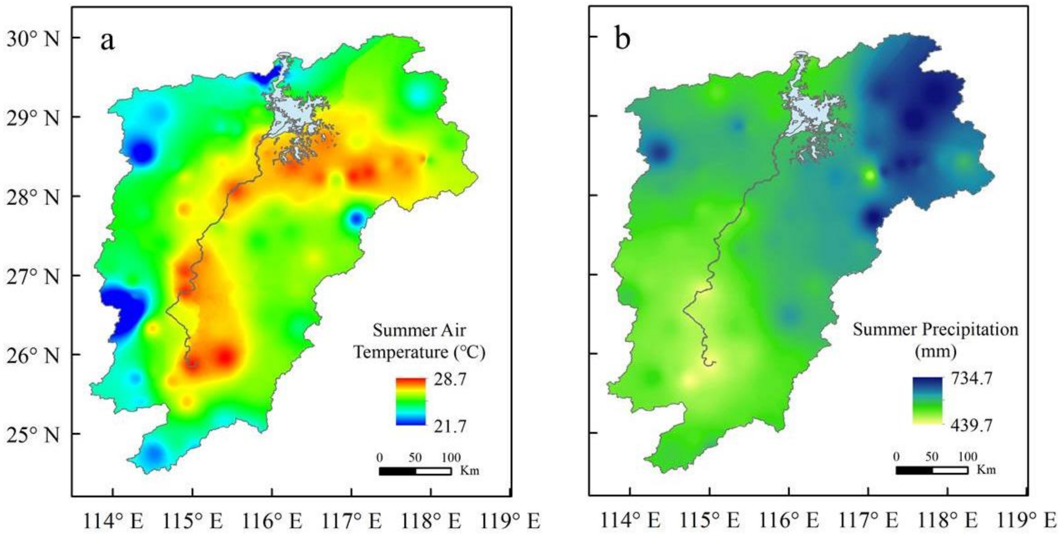


Figure 7. The spatial distribution of summer air temperature (a) and summer precipitation (b) over the Poyang Lake Basin

In general, the climatic trend of soil temperature presents the general increase trend from the south area to north in Poyang Lake Basin, opposite to the distribution of soil temperature. There are high value areas in the northeast region of Poyang Lake Basin (Figure 8). We plot distribution map of soil temperature at four depths in different scales(here not shown), most of whose correlation coefficients with annual ST1 are around 0.9, except for the trends of ST1 and ST2 in summer (Table 5). Only the low value area of the trend of summer ST1 is more northward. Annual ST1 shows an obvious upward trend, in most areas it can reach 0.3°C /decade (Figure 8a). Summer ST1 also shows upward trend in whole area, but less than Annual ST1.

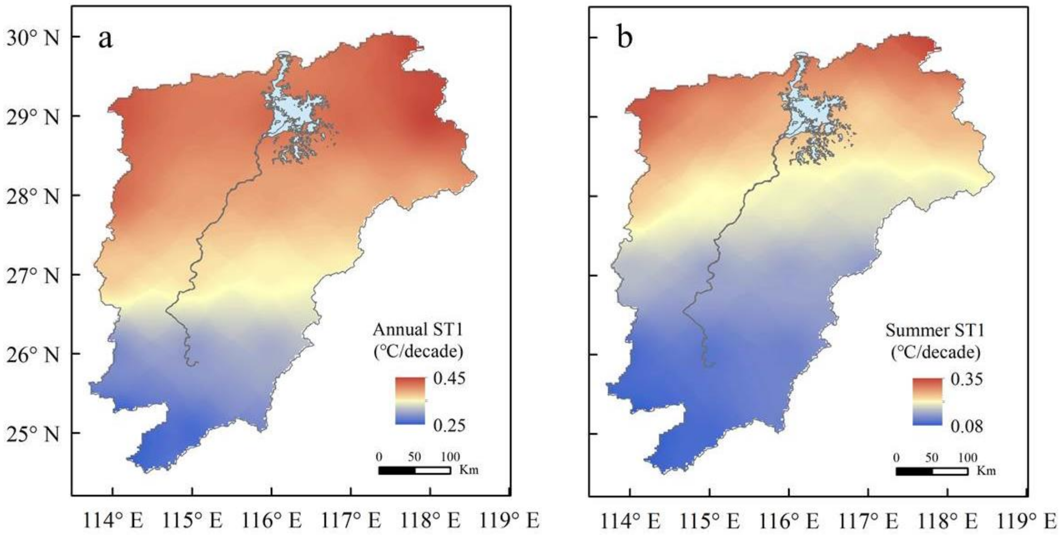


Figure 8. The spatial distribution of climatic trend of annual soil temperature (a) and summer soil temperature (b) of ST1 over the Poyang Lake Basin

Table 5. Spatial correlation coefficient between climatic trend of annual ST1 and other soil temperature

Correlation Coefficient		Annual ST1
ST1	Annual	—
	Spring	0.951
	Summer	0.768
	Autumn	0.933
	Winter	0.886
ST2	Annual	0.989
	Spring	0.933
	Summer	0.790
	Autumn	0.952
	Winter	0.900
ST3	Annual	0.989
	Spring	0.946
	Summer	0.862
	Autumn	0.943
	Winter	0.921
ST4	Annual	0.987
	Spring	0.946
	Summer	0.938
	Autumn	0.908
	Winter	0.946

4. Conclusions and Discussion

Over the past century, the effects of global warming affect not only air temperature but also precipitation patterns and soil temperature [34]. Soil temperature is one of the main factors affecting length of growing season, rates of mineralization and nutrient assimilation, as well as plant productivity[35-37]. So, it is very important to figure out the variation of soil temperature. Based on the observation and reanalysis data from 1979 to 2018, this study analyzed the variation of seasonal and annual soil temperature, abrupt changes and abnormal years, and the spatial distribution of the soil temperature and its trend. The main conclusions derived are as follows.

(1) The relationships between the observation data and reanalysis data at each of the studied depths over the past 40 years all showed good correlation (correlation coefficients≥0.87) and a significant upward trends. Compared with the observation data, the reanalysis data generally underestimates their magnitudes. Compared with Nanchang (Ganzhou), the ME is -1.1 to -1.2 (-2.5 to -2.6). The ERA-Interim/Land reanalysis data is reliable for regional soil temperature research in the Poyang Lake basin.

(2) Monthly, from March to September, the temperature of ST1 is higher than the temperature of ST4. So the heat would travel from the surface to the depth. From October to February next year, the temperature of ST4 is higher than the temperature of ST1. The energy path would reverse, from the deep soil to the surface.

Seasonally and yearly, the soil temperatures have mostly increased during the study period. In terms of seasons, the temperature raises fastest in spring (0.37-0.43 °C/decade) and slowest in summer (0.19-0.29 °C/decade), except for the ST4, which rising fastest in spring (0.37 °C/decade) and slowest in winter (0.20 °C/decade). Annually, the temperature of ST1 rises fastest (0.31 °C/decade). For the other layers, the warming trend is almost similar.

(3) Generally, the soil temperatures have changed from a relatively cold period to a comparatively warm period. Abrupt changes of the annual soil temperature at all depth occurred in 1997, while the abrupt change of spring soil temperature occurred in 1996. Abrupt changes of summer soil temperatures of ST1, ST2 and ST3 occurred in 2002, except the ST4, which had abrupt change in 1999. In autumn, the abrupt changes of ST2, ST3 and ST4 occurred in 2000, while the ST1 had abrupt change in 1997. In winter, the ST2 and ST3 didn’t show abrupt change. And the ST1 and ST4 had abrupt change in 1992.

(4) Annually, the years of anomalous soil temperatures at all depths were consistent, there were anomalously low in 1984. Seasonally, the years of anomalous soil temperatures of ST1, ST2, and ST3 cm were consistent, but they were inconsistent with soil temperature of ST4.

(5) Spatially, in Poyang Lake Basin, the soil temperature decrease with latitude, except the summer ST1. The high air temperature and heavy precipitation in summer may be the basic causes of spatial distribution of the summer ST1. Different from other soil temperatures, the summer soil temperature ST1 are higher around the lake and the river. The climatic trend of soil temperature presents the general increase trend from the south area to north in Poyang Lake Basin, opposite to the distribution of soil temperature.

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