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Persistent warming of the ground on the Earth's Third Pole

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Abstract

A continuously increasing ground temperature in the Tibetan Plateau (TP) can result in permafrost degradation and impact regional climate through land-atmosphere interactions. However, systematic knowledge of spatiotemporal dynamics and regulatory mechanisms of ground temperature changes in the region is limited. Here, we quantify the thermal status and trends of both soil temperatures measured at depth and typical permafrost profile temperatures. We show that, shallow soil layers (0-40 cm) in most TP regions experienced significant warming from 1981 to 2021, with lower rates at greater depths. Ground surface warming trends aligned with air temperature, but the timing of the maximum warming trend was progressively delayed with depth. Cold seasons exhibited the largest warming trends for air and ground surface, while warm seasons saw greater warming trends at 5-40 cm soil depths. Regionally, warming trends were larger at sites with lower mean annual temperature and higher elevation. Out of the factors tested in addition to air temperature, only snow-cover days and downward longwave radiation were significantly related to the soil warming rate trends. Further analysis reveals that the persistent shallow ground temperature increase over decades is linked to the Atlantic Multidecadal Oscillation's warm phase, impacting near-surface air temperature through teleconnections. Additionally, we present spatially heterogeneous observations of continuous warming in permafrost profiles, which show intense warming in the surface layers, and minimal warming at 40 m depth. Permafrost profile warming magnitude and depth-dependent variation are influenced by local climate and elevation. This study provides a comprehensive view of persistent warming in the Tibetan Plateau across surface and deep layers.

Keywords: Persistent warming, surface soil temperature, frozen ground region, Tibetan Plateau

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1. Introduction

The thermal regime of the ground is a critical factor regulating interactions and feedbacks among multi-sphere systems in cold regions (Biskaborn et al., 2019; Smith et al., 2022). One of the fundamental parameters of the land's thermal regime is soil temperature which plays an essential role in land-atmosphere interactions and has significant effects on the climate (Zhang et al., 2021). Increased greenhouse gas emissions caused by human activities have resulted in continuous and rapid global atmospheric warming, leading to near-surface air warming and persistent warming of both the active layer and the deeper permafrost layer through downward heat transfer (IPCC, 2021). Changes in soil temperature involve both above-ground and below-ground processes, meaning that soil warming influences for example, energy and water cycles, biogeochemical processes, infrastructure stability (Chen et al., 2021c; Hjort et al., 2022; Wang et al., 2023). However, understanding the spatiotemporal dynamics and regulatory mechanisms of soil temperature changes is challenging for many reasons, including limited and unevenly distributed observation sites, high levels of spatial heterogeneity, and an oversimplified representation of complicated soil thermal transfer processes in current models (Chen et al., 2021a; Etzelmüller et al., 2020; Qian et al., 2011).

Previous studies have demonstrated that air temperature largely controls variations in the ground temperature at shallow depths (Melo-Aguilar et al., 2022; Petersen, 2021; Qian et al., 2011; Wang et al., 2018). However, the coupling between air and shallow ground temperatures is strongly influenced by buffer zones, such as vegetation, snow cover, and organic layers (Smith et al., 2022). Ground temperature fluctuations decrease with depth and respond with a lag to surface air temperature due to the filtering effect of the ground on high-frequency variations (Chen et al., 2021a; Smith et al., 2022). Ground- warming drivers and air-ground temperature coupling exhibit complex spatial, temporal, and

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vertical variability, with different factors dominating in different regions. For example, Qian et al (2011) attributed soil warming in Canada from 1958 to 2008 mainly to trends in air temperature and snow-cover depth, while Chen et al (2021b) suggested that snow-cover thickness was the primary factor controlling trends in the difference between air and soil temperatures over Northern Eurasia, followed by snow-cover duration and solar radiation. Studies of the thermal regime deep underground (several dozen meters) have mainly been conducted in the permafrost region of the circumpolar Arctic and the Tibetan Plateau (Biskaborn et al., 2019; Cao et al., 2018; Etzelmüller et al., 2020; Zhao et al., 2010). Etzelmüller et al (2020) analyzed permafrost dynamics in European mountains and found that, during the past 20 years, deep permafrost had warmed at all the sites studied, with warming rates tending to be smaller in warm permafrost, due to latent heat effects. Additionally, various factors such as regional climate, elevation, topography, soil water and ice content, lithology, and geological structure may also affect changes in ground temperature. An integrated analysis of these complex factors is required to understand the spatiotemporal dynamics and regulatory mechanisms of ground temperature changes. Such understanding is crucial for predicting the impact of climate change on ecosystems and human activities.

The Tibetan Plateau (TP), known as the Earth's Third Pole, has the world's largest permafrost zone outside of the polar regions (Zou et al., 2017). It has been suggested that this Tibetan permafrost is distinct from circumarctic permafrost in that it is more vulnerable to climate change due to higher temperatures, lower ice content, thicker active layers, and thinner permafrost layers (Wang et al., 2022). The plateau's frigid climate has led to a significant organic carbon buildup in the soil (Ding et al., 2016). Observations have revealed that over the past 50 years the plateau has experienced significant warming, twice as fast as the global average, with a corresponding rise in the frequency of extreme temperatures

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including heatwaves. This amplified warming has resulted in a substantial increase in ground temperature and an accelerated release of soil organic carbon from the TP, exacerbating the positive feedback between carbon release and climate warming (Taihua et al., 2020; Yang et al., 2019; Zhao et al., 2020). Additionally, continual increases in surface temperature may have a significant impact on regional (and larger-scale) climate change through land-atmosphere interactions (Yao et al., 2019). To gain better insight into the thermal status of the ground and regional changes across the Earth's Third Pole, it is crucial to understand the spatio-temporal dynamics and regulatory mechanisms of layered soil and deep ground warming.

This study aims to provide a comprehensive understanding of the implications of recent variations in ground temperature across the Tibetan permafrost regions. We analyzed ground temperature measurements made at various depths over the past several decades. These data were obtained from both meteorological observation sites and permafrost borehole sites. Specifically, our analysis focuses on temporal trends and the spatial distribution characteristics of layered ground temperature changes, including the active layer and the permafrost layer, at annual and interannual scales from 1981 to 2021. Additionally, we investigate the driving mechanisms behind ground temperature variations on the TP.

2. Data and methods

2.1. Data compilation

The ground temperature observation networks primarily cover the central and eastern regions of the TP, where there is considerable variation in climate due to altitude and geographic position (Fig. 1). The daily soil temperature data were collected from meteorological observation stations operated by the China Meteorological Administration (http://www.nmic.gov.cn). These data consist of mean soil temperatures measured at the ground surface (0cm) and at seven depths below the surface: the shallow measurements at 5, 10, 20 and 40 cm, and the deeper ones at 80, 160 and 320 cm. To monitor ground surface (0 cm) temperature, surface geothermometers were placed on bare ground (Wang et al., 2018). Prior to 2005, during the winter snowfall, the snow surface temperature was used as the 0 cm soil temperature measurement, while after 2005, the ground surface temperature beneath the snow was used. Shallow soil temperatures (5-20 cm) were measured with curved tube thermometers, while deep soil temperatures (40-320 cm) were measured with straight tube thermometers (Shi et al., 2021). Due to the harsh environment of the TP, there were frequent instrument failures during the early years of soil temperature observations, and so we selected a time series for analysis from January 1st 1981 to February 28th 2022 which had relatively little missing data. However, because of a restriction imposed by data sharing policies, the 80 to 320 cm soil temperature time series began in 2007. Some missing data are inevitable for most long-term soil temperature monitoring sites due to harsh conditions or instrument malfunctions, and we therefore conducted strict quality control assessments of the soil temperature observations from all the available sites and selected data from high-quality and long-term sites for this analysis (Wang et al., 2018). The number of sites with shallow soil data (0-40 cm) available for analysis decreases with increasing measurement depth, however.

We also extracted daily air temperature, precipitation and snow depth data from the meteorological observation station records to investigate the potential influence of environmental factors on soil temperature variations. These daily observations were averaged or summed into monthly or annual values: mean annual air temperature (MAAT), mean annual soil temperature (MAST), annual rainfall (PPT), snow-cover days (SCD, the total number of days with snow cover) and the annual mean of daily snow depth. In addition to these *in-situ* observations, ERA5-Land monthly averaged products from 1981-2021, including volumetric water content (SWC), surface net solar radiation and surface downwards thermal radiation (DLR), were accessed at https://cds.climate.copernicus.eu/. Additionally, AVHRR-V6 *NDVI* products with a 0.05° × 0.05° spatial resolution and daily temporal resolution were also used (https://www.ncei.noaa.gov/products/climate-data-records/normalized-difference-vegetation-index). To minimize atmospheric and cloud pollution effects, the monthly maximum synthesis method (MVC) was adopted to calculate monthly-timescale *NDVI* datasets, which were then aggregated to the annual scale (Yao et al., 2018). Soil property data, including soil bulk density and soil texture, were extracted from the basic soil property dataset of the high-resolution China Soil Information Grids (https://data.tpdc.ac.cn/zh-hans/data/e1ccd22c-348f-41a2-ab46-dd1a8ac0c955). To explore the potential effect of soil organic matter on surface soil warming, soil organic carbon density (SOCD) data was used (Ding et al., 2016). The corresponding values for remote sensing data, reanalysis data, and upscaling results from literature, were extracted according to the latitude and longitude of the soil temperature observation sites and used to carry out the driving-factor attribution analysis.

Our study also involved consideration of the background atmospheric circulation of the TP. We selected nine atmospheric circulation indices comprising seven large-scale atmospheric and oceanic circulation patterns, namely the North Atlantic Oscillation (NAO), Arctic Oscillation (AO), Atlantic Multidecadal Oscillation (AMO), Pacific Decadal Oscillation (PDO) and El Niño Southern Oscillation (ENSO) (including the Nino3.4 sea surface temperature and multivariate ENSO index (MEI)). These were all accessed at https://psl.noaa.gov/data/climateindices/list/. Additionally, two summer monsoon indices were used: the South Asian summer monsoon index (SASMI) and the East Asian Summer Monsoon Index (EASMI) (Li and Zeng, 2002, 2003).

In addition, ground temperatures from depths of 3 m to 40 m at the permafrost borehole sites and

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the mean annual ground temperature profile dataset at typical permafrost sites across the TP were obtained from the National Tibetan Plateau Data center (https://data.tpdc.ac.cn/) and the National Cryosphere Desert Data Center (http://www.ncdc.ac.cn/portal/).

2.2. Trend analysis

To examine temperature trends, we adopted the Mann-Kendall (M-K) nonparametric trend test (Mann, 1945; Kendall 1975). The Theil–Sen method was utilized to estimate the magnitude of the trend, while the nonparametric M–K method was employed to determine the significance of interannual trends in the temperature variables. The level of significance of trend alterations was expressed by a Z value, where $Z < 0$ indicated a decrease and $Z > 0$ an increase. In particular, these trends were considered statistically significant at the 99% confidence level ($P < 0.01$) if $|Z| \geq 2.58$ and at the 95% confidence level ($P < 0.05$) if $|Z| \geq 1.96$. This nonparametric test is less sensitive to outliers and more accurate than the linear regression method, and thus is widely used to analyze hydrometeorological time-series data (Ding et al., 2018; Jiao et al., 2021). The regional averages of temperature indices were calculated as the arithmetic mean of the values at all the selected observation sites.

2.3. Statistical analysis

The Pearson correlation analysis method was used to identify the driving factors of TP ground warming. This method quantifies the degree of compactness by analyzing the magnitude of the linear relationship between two variables (Ding et al., 2019). A two-tailed version of Student's t-test was used to determine the statistical significance of the correlation coefficients at the significance levels $P<0.05$ and $P<0.01$. The annual maximum and minimum mean daily soil temperatures were calculated as

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annual maximum temperature (T_{max}, ◦C), and annual minimum temperature (T_{min}, ◦C), respectively. Here, spring, summer, autumn and winter are defined as extending from March to May (MAM), June to August (JJA) September to November (SON) and December to the following February (DJF), respectively.

3. Results

3.1. Regional annual tendencies and spatial patterns of soil temperature in multiple layers

Figure 2 and Table 1 depict the regional annual trends and statistical analyses of multi-layer soil temperatures in the Tibetan Plateau between 1981 and 2021. During this period, a statistically significant (P<0.05) warming trend was observed at depths ranging from 0 to 40 cm at the majority of sites (>80%) (Tab. 1). However, due to the limited time span of the observations at depths between 80 and 160 cm, a higher percentage of sites exhibited non-significant warming trends at these depths. The linear tendencies of soil temperature at 0 cm depth (T_{s_0cm}) in the TP region ranged from −0.24 to 1.29 ℃/decade, with an average regional warming rate of 0.51 ℃/decade (P< 0.01) (Fig. 2a and Tab. 1). The warming rates gradually decreased with increasing soil depth; the regional warming trends declined from 0.47 °C/decade at a depth of 5 cm to 0.40°C/decade at 40 cm. The regional average warming rates of shallow soil between 0 and 20 cm were greater than that of air temperature (Fig. 2a). Additionally, the annual maximum soil temperature (T_{max}) warming rate generally increased with soil depth from the ground surface to a depth of 40 cm (Fig. 2d), whereas the warming rate of the minimum soil temperature (T_{min}) exhibited a decrease at greater depth (Fig. 2f). Notably, the T_{max} warming rate exceeded that of T_{min} between the depths of 5 and 40 cm, leading to an increase in the intra-annual variation of surface soil temperature across the whole region. The difference in annual mean

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temperature between different soil depths was much smaller than the variation in annual maximum and minimum temperatures. These results indicate that the variation of the gradient of soil temperature with depth was greater during the coldest and warmest months.

Figure 3 and Figure S1 display the spatial distributions of the annual mean air temperature and layered soil temperature warming trends. Although there are some variations in the magnitudes of the trend changes in air temperature and soil temperature at depths of 0-40 cm, the spatial patterns of the warming trends remain largely consistent. Regionally, the relationships between trends in surface air temperature and soil temperature at depths between 0 and 40 cm are significant (P<0.05). However, the correlation efficiencies between air temperature and soil temperature warming rates gradually decrease with increasing soil depth, ranging from 0.72 at the ground surface to 0.42 at a depth of 40 cm (Fig. 4a). For T_{s_0cm}, the central and northeastern parts of the TP have experienced a higher increase in soil temperature than other areas. In contrast, the stations with relatively small warming rates are mainly located in the southern and southeastern regions of the TP, and almost all of the stations with insignificant positive trends are also situated in these areas (Fig. 3a). From the ground surface to 40 cm below ground, the number of effective observation sites decreased, and the temperature rising at the same site declined simultaneously. Due to the closely spaced measurement depths, the distribution patterns and magnitudes of the change trends of T_{s_5cm}, T_{s_10cm} and T_{s_20cm} are very similar (Fig. S1 and Fig. 3b-c). However, the spatial distributions of the trends at 80-160cm differed substantially from the surface soil temperature because of the short observation time periods. Generally, in terms of individual station trends for depths between 80-160cm, upward trends were detected at approximately 60% of stations, while 20.9%-31.1% of stations passed the significance test at the 0.05 level (Table. 1). The few stations with lower significance negative tendencies were mainly in the southern TP. Pearson

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correlation coefficients were calculated for the multi-year mean values and the related temperature trends during the observation period to clarify the spatial patterns between the air temperature and the layered soil temperature increase rates. The results show that the warming trends tend to be stronger at sites with lower multi-year mean temperatures, but the relationship was not significant (P>0.05) for deeper soils (Fig. S2).

3.2. Monthly and seasonal trend variability of layered soil temperature

In the preceding sections, we examined the temporal and spatial variations of layered soil temperatures at an interannual scale, and found that the spatiotemporal change patterns exhibited both regularity and variability with soil depth. To elucidate the trend differences of monthly and seasonal variations in layered soil temperature, further exploration is required. To this end, we analyzed the regional average monthly trends for layered soil temperature for the period of 1981–2021. Our results demonstrate a significant warming trend in air temperature and layered soil temperature in all months on the TP (Fig. 5). Notably, the warming trend in soil temperature varies with month at different depths, but follows a regular pattern. Specifically, the monthly average warming trend of the ground surface (i.e., T_s_0cm) was consistent with that of air temperature, with both reaching their maximum in February (Fig. 5a and b). However, the month with the maximum warming trend was gradually delayed to a later date, with increasing soil depth. More specifically, the months with the greatest average warming trend at 5 cm, 10 cm, 20 cm, and 40 cm soil depth were March, April, April, and June, respectively (Fig. 5c-f). These findings suggest that the warming of the surface soil is driven by the increasing temperature of the air near the surface, with the warming of the deeper soil lagging behind the surface soil.

In addition to analyzing the monthly results, we further examined the long-term variations in seasonal soil temperatures. The results show a clear regularity between soil temperature in different layers and seasonal variation (Fig. 6). Specifically, during spring and summer, the temperature decreased with increasing soil depth, while during autumn and winter, the opposite trend was observed, with deeper soil layers exhibiting higher temperatures. These findings can be attributed to the storage and release of soil heat resulting from seasonal changes in land-atmosphere interactions. Furthermore, the temperature difference between the ground surface and the deepest soil layer was largest in summer and winter, and smallest in spring and autumn. With regards to seasonal trends, it appears that air temperature and soil temperature at shallow depths (between 0 and 40cm) significantly (P<0.05) increased in all seasons over the past four decades. The seasonal warming trend of the ground surface (i.e., *T*s_0cm) remained consistent with the air temperature and was larger in the cold season, i.e., autumn and winter, while the warming trend of the 5-40 cm soil layer was greater in the warm season, i.e., spring and summer. For the surface soil (between 5 and 40 cm) the warming trend gradually increased with increasing depth in spring and summer, whereas in autumn and winter, it showed a decreasing trend. However, the soil at depths between 80 and 160 cm showed a warming trend in almost all seasons, but the warming rates were small and insignificant (P>0.05), probably due to the shorter period of observations for these depths.

3.3. The impact of geographic location and altitude on layered soil temperatures

The preceding analysis indicates a discernible spatial pattern in the warming rates of surface soils on the TP. For instance, stations with greater warming magnitudes at 0 cm are predominantly situated in the northeastern and central regions of the TP, as depicted in Figure 3a. Consequently, to comprehensively determine the potential impact of geographical location and topographic environment on the variation trends in air temperature and layered soil temperature, a correlation analysis was conducted to examine the relationships between longitude, latitude, altitude, and temperature trends. As shown in Table 2, we observed a significant correlation between the trends of air temperature and layered soil temperatures with altitude in the TP region, indicating that the warming amplitude tends to be higher at higher altitudes. However, almost all the correlation coefficients between temperature increasing rates and longitude and latitude are not statistically significant at the 0.05 level, suggesting that longitude and latitude have minimal effects on the regional warming rates of surface soil in the TP area.

3.4. Impacts of environmental drivers and soil properties on surface soil warming

The spatial variability of soil temperature increases is influenced by a range of environmental factors, including climate variables, snow depth and cover, vegetation, and soil properties. Owing to the highly consistent and similar soil temperature trends in the surface layer (0-40 cm) of the TP on both temporal and spatial scales, we chose to use the 20 cm soil depth (the middle of the surface soil layer) for our examination of the impact of environmental drivers and soil properties on surface soil warming. Our findings reveal a weak but non-significant (P>0.05) positive correlation between soil warming and trend changes in precipitation and surface soil water content, indicating that the warming rate tends to be higher at sites with increased precipitation and soil water content (Fig. 7a and b). In contrast, the changing trends in snow depth and snow-cover days had negative associations with surface soil warming; that is, soil warming trends were greater at sites with decreasing snow depth or snow-cover days. However, the trend between changes in snow-cover days and soil warming was the only statistically significant one (P<0.05). Vegetation changes can impact surface albedo and therefore surface heat gain. However, in this study, there was practically no discernible correlation between vegetation index trend changes and soil temperature increases, likely due to the locations of the

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observation stations, which are primarily in eastern alpine meadow regions (Fig 7e). Further, downward long-wave radiation plays a crucial role in ground energy acquisition. Our analysis demonstrates a relatively weak, yet significant, positive correlation between downward long-wave radiation and soil temperature increase, suggesting that the rise in downward long-wave radiation could drive soil warming (Fig 7f). However, our results for soil properties showed that soil organic carbon content, soil bulk density, and soil texture had almost no association with soil temperature increases (Fig 7g-i).

3.5. Association between atmospheric circulations and shallow soil warming

Shallow soil warming reflects the overall regional ground energy balance and is closely related to regional atmospheric circulation patterns and changes in the climate system. To clarify the relationships between the variability of layered soil temperatures and large-scale climate systems, we analyzed the correlations between regional average annual change trends of layered soil temperatures and the AMO, AO, NAO, PDO, ENSO (MEI and Nino3.4), and summer monsoon indices (including SASMI and EASMI) (Table 3).

Table 3 shows that the shallow-soil warming trends have significant positive correlations with the AMO (P<0.01), weak significant negative correlations with PDO and MEI (P< 0.05), and insignificant negative correlations with most of the remaining atmospheric circulation indices. These findings indicate that AMO has a strong impact on shallow soil warming on the TP at the annual scale. Additionally, we analyzed the long-term trends of T_{s_20cm} and AMO indices to further explore the possible mechanism by which the atmospheric circulation index influences surface soil warming. The results show that the annual variations of T_{s_20cm} have an almost perfect matching relationship with the phase change of AMO.

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3.6. Ground temperature variations of the permafrost borehole site

The soil temperature observation sites analyzed above are primarily located in the seasonally frozen ground of the TP. The soil temperature results presented above only represent variations in near-surface ground temperature. However, the TP hosts the world's largest alpine permafrost zone outside of the polar regions, and therefore, we further integrated observation sites in the typical permafrost zone of the TP, analyzing changes in ground temperature from the surface to much deeper layers (i.e., 30-60m) to gain a more comprehensive understanding of ground temperature changes in the permafrost region of the TP.

Ground temperature at depths ranging from 3 m to 40 m showed greater warming trends at the lower temperature sites (Fig. 8). For instance, at a depth of 3 m, the warming rate was 1.2 ℃/decade at the coldest site (QTB09), and 0.20 ℃/decade at the warmest site (QTB11) (Fig. 8a). Moreover, the warming rate at the lowest and highest temperature sites at a depth of 30 m were 0.21 and 0.10 ℃/decade, respectively. The warming trends of ground temperatures at most sites gradually decreased with increasing depth, and the warming rate was minimal at the greatest measured depth of 40 m (Fig. 8f). For example, at the WD4 site, the warming rate gradually decreased from 0.27 ℃/decade at a depth of 10 m to 0.06 ℃/decade at a depth of 40 m. However, several sites exhibited anomalous warming trends with depth, which may be due to various local factors influencing soil temperature changes.

We conducted an additional analysis of the annual temporal variation of ground temperature profiles at several typical permafrost observation sites on the TP. Due to data sharing constraints, we only analyzed observations from between 2001 and 2010, but this short period should still basically reflect changes in permafrost ground temperature on the TP. We found that ground temperatures have

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risen notably at all permafrost profiles since 2001 down to depths of 30m, 40m, or 60m in different sites (Fig. 9a-e). For most sites, record high ground temperatures were observed in 2010. The exceptions were QTB02 and QTB05 which might have been influenced by snow cover, resulting in a corresponding cooling change. The variation of ground temperature with depth and the trend of warming at different depths varied due to the influence of regional topography, climate, lithology, ice content, snow depth, and snow-cover duration. Based on the profiles of ground temperature variation, we found that 10 m was the approximate demarcation depth for QTB05, QTB06, and QTB15 (the depth above which the temperature sharply decreased and below which it gradually increased). For QTB01, the ground temperature increased continuously from the surface to the deep layer, while for QTB02, the temperature underwent a phase of warming, cooling, and re-warming. The surface ground temperature (at approximately 5 m depth) varied significantly with depth for all sites, whereas the deeper layers exhibited relatively weak variations. Furthermore, the warming trend decreased with increasing depth at all sites, and the low-temperature sites, such as QTB02 and QTB15, exhibited the most pronounced temperature increase at all depths (Fig. 9b and e). However, the site where the surface temperature was close to 0 ◦C, QTB06, was significantly different to the other sites, in that it was difficult to observe an obvious warming trend below 5 m depth (Fig. 9d).

4. Discussion

4.1 A warmer climate has led to persistent and enhanced soil warming

Our study shows a significant increase in soil temperatures in shallow ground on the TP from 1981 to 2021, with most sites exhibiting statistically significant (P<0.05) warming trends. The trend of soil warming gradually decreases with depth, with regional increasing trends ranging from

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0.47 °C/decade at a depth of 5 cm to 0.40 °C/decade at 40 cm. We also found that warming trends tend to be stronger at sites with lower mean temperatures or higher elevations. Overall, our study provides a comprehensive evaluation of the evolution of soil temperature on the TP by quantifying spatial and temporal trends in multi-layer shallow ground temperatures.

The continuous warming of shallow soils on the TP over the past few decades is noteworthy, and, taken together with similar warming trends observed in various regions across the globe (Chen et al., 2021c; Dorau et al., 2022; Gao et al., 2022; Qian et al., 2011; Wang et al., 2018), is a clear indication of global warming. The spatial warming trend of the ground surface is strongly correlated with air temperature and gradually decreases with depth (Fig. 4a). This indicates that soil warming is driven by air temperature, with heat transfer and decay progressing downwards into the soil following surface warming (Chen et al., 2021a; Wang et al., 2021). As a result, the temperature of the deep soil lags behind the surface warming, and the magnitude of warming becomes progressively smaller with depth due to the filtering effect of the soil layers above (Smith et al., 2022). Monthly and seasonal trend variability of multi-layered soil temperature provide a better indication of the transmission and decline of soil warming trends from the surface to the deeper layers. For example, the fluctuations in the monthly average warming trend of the ground surface were almost wholly consistent with those of air temperature (Fig. 5). However, the month in which the maximum warming trend occurred was regularly delayed to a later date at deeper soil depths. Seasonal variation in soil temperature in different layers is due to the superposition and transfer effect of monthly trends. As a result of this lag-effect of heat transfer, although the maximum warming trends of the ground surface occurred in winter, the seasonal warming rate of the soil at a depth of 40 cm reached its maximum in summer.

Although air temperature is the main controlling factor of soil warming, the heat transfer process

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from atmospheric conditions to shallow ground will be affected by the insulating effects of vegetation, snow cover and other factors (Smith et al., 2022). The deepest soil layers respond less to atmospheric warming due to environmental factors like soil texture, soil organic matter, and soil water content. This leads to a gradual weakening of the correlation between surface air and soil warming rates with increasing depth (Fig. 4a). However, in this study, only snow-cover days and downward long-wave radiation were significantly correlated with surface soil temperature trends (Fig. 7). Snow-cover limits heat loss from the ground surface, affecting the response of shallow ground thermal conditions to surface air warming (Chen et al., 2021b). However, the snow cover on the TP has had a significant downward trend in recent decades under the background of intense climate warming, with reduced depth and shortened duration (Xu et al., 2017). The snow cover on the TP is mainly concentrated in winter and spring. The delay in the start of the snow-covered period and the associated decrease in the number of snow-cover days in winter weakens the ground thermal insulation effect, slowing down the trend of increasing temperature of the shallow soil. In contrast, the advance of the end of the snow-cover period in spring allows the ground to receive more solar radiation and absorb more heat, intensifying the warming trend of the shallow soil layers (Qian et al., 2011). This asynchronous response of soil temperature to snow-cover changes in different seasons leads to a weak negative correlation between the number of days with snow cover and the rate of surface soil temperature increase on an interannual scale (Fig. 7d).

Atmospheric downward longwave radiation (DLR) is an essential part of the surface energy balance and a basic indicator of the effect of atmospheric greenhouse gases on climate warming (Tang et al., 2021). The increase in DLR, seen here, allows the ground surface layer to absorb more heat, driving a sustained warming of the shallow soil layer. In recent decades, the *NDVI* of the TP has shown

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a continuous increasing trend under the warming and wetting climate (Shen et al., 2022). This improvement of the vegetation increases solar radiation absorption by reducing albedo, accelerating surface warming. However, at the same time, evaporative cooling induced by vegetation growth weakens surface warming, and so, overall, vegetation growth generally has little influence on shallow soil warming (Shen et al., 2015). As the largest region of permafrost in the mid-latitudes, the TP has a huge store of soil organic carbon (Taihua et al., 2020). Soil organic matter has a low thermal diffusivity, leading to a weakening of the warming rate of shallow soil (Zhu et al., 2019). However, we found no obvious relationship between the warming rate of shallow soil and soil organic carbon content. This may be due to the limited accuracy of the soil organic carbon data extracted from other up-scale studies and the fact that the ground temperature observation stations were mainly located in the central and eastern regions of the plateau.

In addition to the environmental driving factors discussed above, the heterogeneity of topography and atmospheric circulations may also impact the changing trends in soil temperatures. Our results show a positive correlation between shallow soil warming and altitude, indicating that warming trends tend to be greater at higher altitudes (Table 2). The increase in soil warming rates with elevation is primarily due to elevation-dependent surface air warming, which may be related to snow/ice-albedo feedback, aerosol feedback, and cloud feedback (You et al., 2020). Furthermore, the number of snow-covered days tends to decrease significantly with increasing altitude (Fig. S3), resulting in a lower ground albedo and increased solar radiation absorption at the surface, exacerbating soil warming in regions of high elevation (Zhang et al., 2022). However, in this study, the observation sites were of limited number with an uneven distribution: a full analysis of the mechanisms of soil temperature increasing with altitude would require an increase in in-situ measurements and corresponding theoretical support.

Large-scale atmospheric circulations may modulate the rate of shallow ground warming on the TP through their effects on near-surface air temperature and the ground-surface radiation balance. Our results demonstrate strong positive correlations between long-term trends of T_{s_20cm} and the AMO indices (Table 3). The AMO index describes quasi-periodic warm and cold anomalies of sea surface temperatures in the North Atlantic, which can cause prominent climate changes globally through atmosphere–ocean–sea ice interactions (Hao et al., 2015; Schlesinger and Ramankutty, 1994). Previous research has shown that sea surface temperature anomalies in the North Atlantic can cause anticyclonic circulation anomalies and have a crucial impact on the variability in surface air temperature in many places around the world through teleconnection (Ding et al., 2020; Li et al., 2020; Zhang et al., 2020a). Furthermore, weak, significant negative correlations between shallow soil warming rates and the Pacific Decadal Oscillation (PDO), North Atlantic Oscillation (NAO), and Multivariate ENSO Index (MEI) suggest that large-scale atmospheric circulations in other regions may also influence shallow ground warming over the TP through teleconnection. The physical mechanisms of atmospheric circulations regulating ground warming are complex; they may affect surface warming rates by influencing regional changes in solar radiation, aerosols, air pressure, precipitation, and particularly air temperature, thereby causing changes in the ground surface energy balance.

4.2 Potential mechanisms of permafrost-profile warming dynamics

Consistent with shallow soil warming in the seasonal permafrost zone, permafrost temperatures and dynamics at typical sites have increased steadily over the past two decades (Fig. 8 and 9), in alignment with observed warming in permafrost regions globally (Biskaborn et al., 2019; Etzelmüller

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et al., 2020). However, the magnitudes of warming at different permafrost sites vary due to the regulating effects of regional environmental attributes, such as snow cover, ice, content, vegetation and organic-layer thickness. Maximum temperature increases at various depths from 3 m to 40 m typically occur at the colder sites (Fig. 8), mainly due to a faster warming rate of surface air temperature at colder sites. In addition, due to the filtering and "memory" functions of the ground, the interannual temperature fluctuations are greater at shallower ground levels and decrease progressively with depth (Smith et al., 2022). Similarly, the warming trend gradually decreases with depth, becoming quite weak at depths such as 40 m for example (Fig. 8f). The ground thermal regime and its variability across the typical permafrost sites on the TP can be explained more clearly by considering the temperature variation of the ground profiles. Our findings reveal that the warming trend gradually decreases with depth and is most prominent at sites with lower surface temperatures, such as QTB02 and QTB15, followed by sites with higher surface temperatures, such as QTB05. However, sites with surface temperatures close to 0 ℃, such as QTB06, showed a negligible increase in temperature down the profile (Fig. 9). The primary mechanism behind this phenomenon is the latent heat effect that occurs during permafrost thawing. This effect consumes a significant amount of the energy used for warming, making it difficult to detect changes in the ground temperature signal across the profile at sites with surface temperatures close to 0 ℃ (Etzelmüller et al., 2020).

Our observations show significant variations in ground temperature changes with depth across the different sites (Fig. 9). This variability can be attributed to differences in permafrost properties such as ice and organic matter content, and rock composition, which lead to variations in thermal conductivity and thus the regulation of vertical heat transfer within the permafrost (Etzelmüller et al., 2020; Zhu et al., 2019). The combined effects of surface buffer zones and differences in subsurface thermal

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conductivity determine the vertical variation in ground temperature in different permafrost regions. However, since current permafrost ground temperature monitoring is sporadically distributed across the TP, the conclusions derived from this analysis may not fully explain the potential mechanisms of permafrost ground warming dynamics.

4.3 Implications of persistent increases in ground temperature

According to our study, multi-layered soil temperature and ground temperatures in typical permafrost zones on the Tibetan Plateau (TP) have experienced continuous warming in recent decades, with the warming being more pronounced in low temperature and high elevation areas. This sustained increase in ground temperature has resulted in significant environmental changes that have profound impacts on multi-sphere coupling and changes in the TP (Yang et al., 2019; Yao et al., 2022; Yao et al., 2019). Notably, low temperature and high altitude areas are also the most concentrated regions of permafrost and glacier distribution on the TP. Persistent ground warming in these areas will aggravate permafrost degradation by accelerating the melting of ice, thickening the active layer and expanding the distribution of thermokarst landforms, etc. (Mu et al., 2020). For instance, the lower altitudinal limit of permafrost distribution has been continuously rising, and the total area of permafrost on the TP has shrunk by about 30% in the last 50 years due to persistent ground warming (Cheng et al., 2012; Zou et al., 2017). In the permafrost region of the TP, the cold environment sequesters a large amount of soil organic carbon (Ding et al., 2016). The degradation of permafrost caused by rising ground temperature accelerates the exposure, decomposition and lateral transport of this organic carbon to rivers, which leads to the acceleration of greenhouse gas emissions possibly enhancing climate warming in a positive feedback effect (Liu et al., 2022; Zhang et al., 2020b). Further, the sustained increase in ground temperature in the glacier areas of the TP will accelerate glacier melting and

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collapse, which will promote lake expansion and increase runoff in the basin in the short term. In the long term, however, ice avalanche debris flow and severe geological disasters will also increase, leading to an imbalance of the Asian water tower (Zheng et al., 2021). The continuous rise of ground temperature will accelerate water evaporation and the decline of groundwater levels in this globally important area of alpine wetland, resulting in a gradual drying and degradation of the wetlands, and the loss of ecohydrological functions (Shen et al., 2019).

In summary, persistent ground warming accelerates the instability of the TP cryosphere. Understanding the ground temperature changes on the TP is critical to accurately assess the regional carbon and water cycles and their feedbacks to climate change. Currently, however, ground temperature observations are inadequate, model simulation mechanisms are insufficient, and result evaluations have large uncertainties. Specifically, the monitoring of soil temperature on the TP mainly relies on meteorological stations in the central and eastern parts of the plateau, while observation of deep permafrost ground temperature is only sporadically distributed in the permafrost area (Fig. 1). Due to the harsh environmental conditions and limitations on accessibility, *in-situ* observations of ground temperature in the western permafrost region are extraordinarily scarce. Additionally, the complex subsurface structure introduces numerous factors affecting internal heat transfer, and models often cannot account for the heterogeneity of these factors when simulating regional ground heat transfer. Therefore, there are often large errors in simulations of regional soil warming. To remove these limitations on the progress of research in this area, it is necessary to intensify monitoring networks of ground temperature in the central and western plateau regions. Observational results should be continuously used to evaluate and optimize model outputs to improve their accuracy, and satellite remote sensing technology should be strengthened to improve the accuracy of regional estimates.

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5. Conclusions

We investigated multi-layered soil warming trends, permafrost ground temperature profiles, and their driving factors on the Tibetan Plateau. Our study demonstrates that shallow soil layers on the TP warmed significantly from 1981 to 2021, with trends decreasing with depth. Areas with lower annual mean temperatures and higher elevations had more pronounced warming trends. The change in the monthly average warming trend of the ground surface was consistent with changes in air temperature, but with increasing soil depth, the month in which the maximum warming trend occurred was delayed to a later date. The seasonal warming trends of the ground surface and air temperature were larger in the cold season, i.e., autumn and winter, while the warming trend of the soil in the 5-40 cm layer was greater in the warm season, i.e., spring and summer. Out of the multiple factors, in addition to air temperature, that may affect sustained soil warming, we only found significant positive correlations with soil warming rates for snow-cover days and downward longwave radiation. The Atlantic Multi-decadal Oscillation (AMO) strongly influenced shallow soil warming at annual scales. Our analysis also suggests persistent warming in typical permafrost profiles although there is spatial heterogeneity in these results. Consistent with the warming pattern of the surface soil, the permafrost profile warming rate was intense in the surface layer and decreased with increasing depth, becoming quite minimal at the deepest observed depth of 40 m. The extent and variation of profile warming with depth are influenced by multiple factors, including local climate, lithology, and elevation. Given the numerous adverse effects of continued ground temperature rise on the TP cryosphere, we strongly urge intensified field monitoring of ground temperature in the permafrost region, combined with satellite remote sensing technology, and the development of accurate subsurface heat transport models, suitable for the plateau, to improve our understanding of the implications of rapidly warming ground.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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Figures

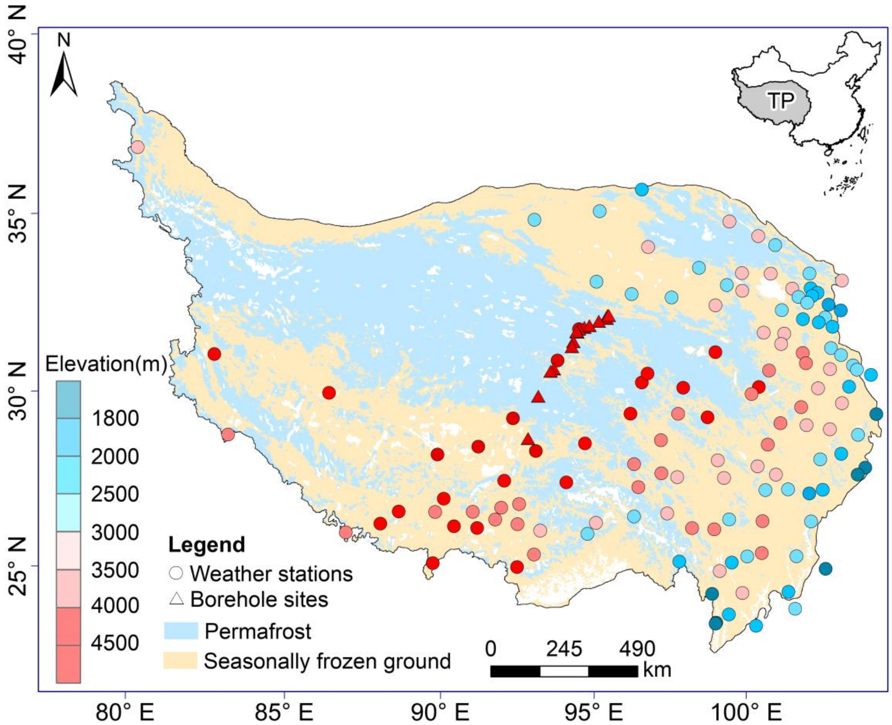

Fig. 1. Distribution of ground temperature observation sites in the permafrost regions of the Tibetan Plateau.

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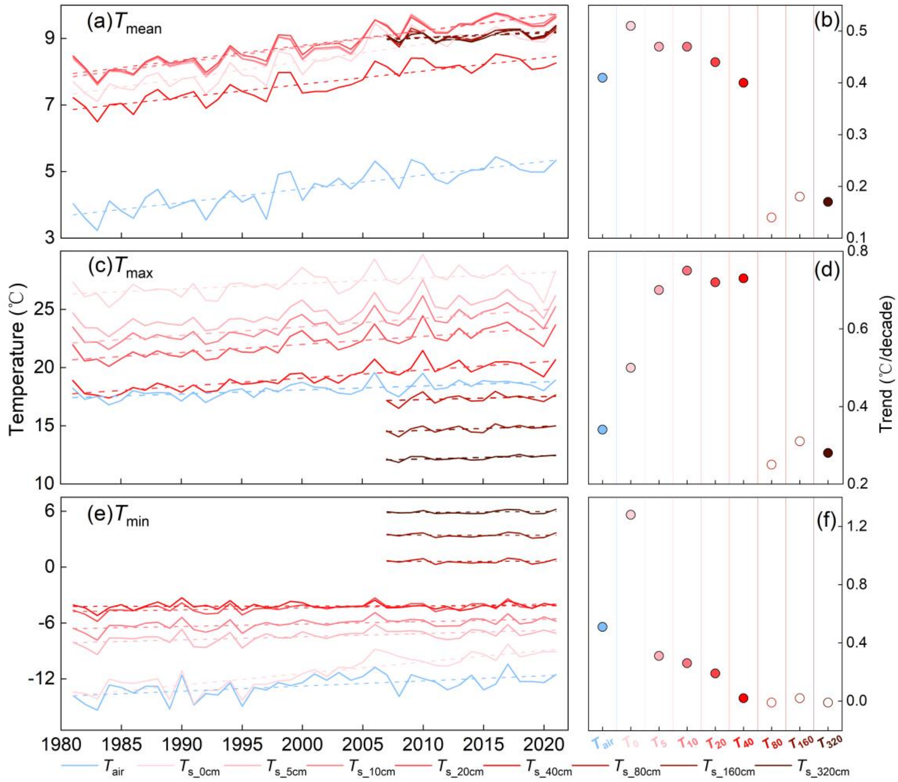

Fig. 2. Regional average, maximum, and minimum annual air temperature (T_{mean}, T_{max}, T_{min}) and layered soil temperature series from 1981 to 2021.

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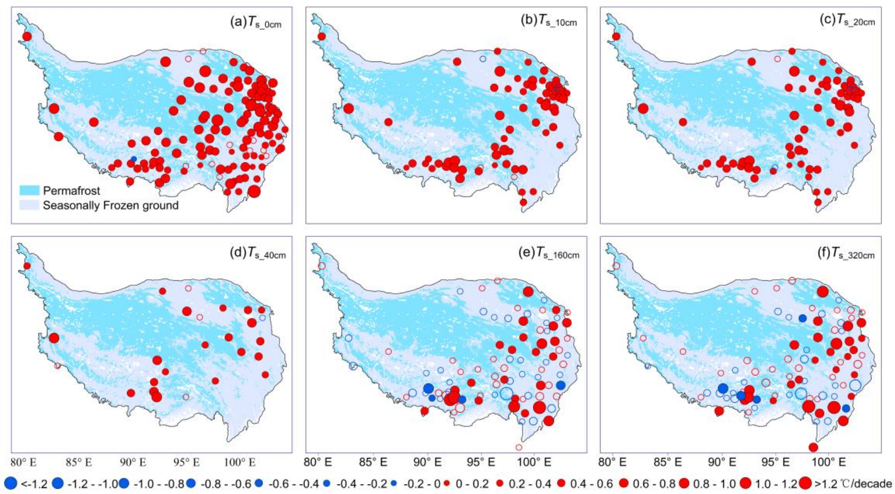

Fig. 3. Spatial patterns of trends in layered soil temperatures from 1981 to 2021. The hollow blue circles and red circles in the figure represent the decrease and increase trend, respectively.

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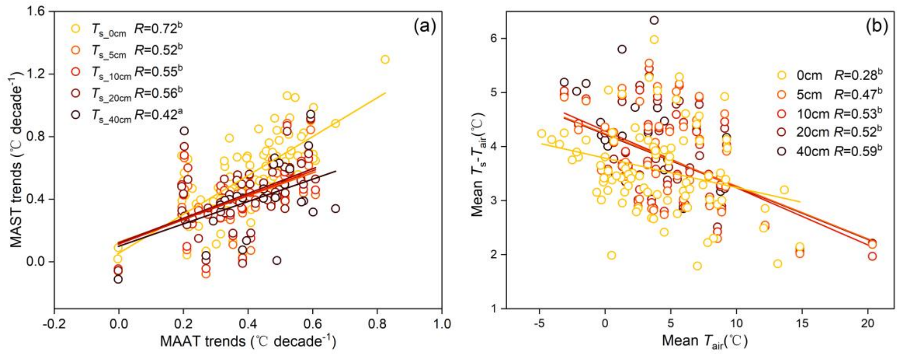

Fig. 4. Linear relationships between (a) trends in mean annual air temperature (MAAT) and mean annual soil temperatures (MASTs), and (b) the regional average MAAT and annual difference between MAST and MAAT, at depths of 0-40 cm.

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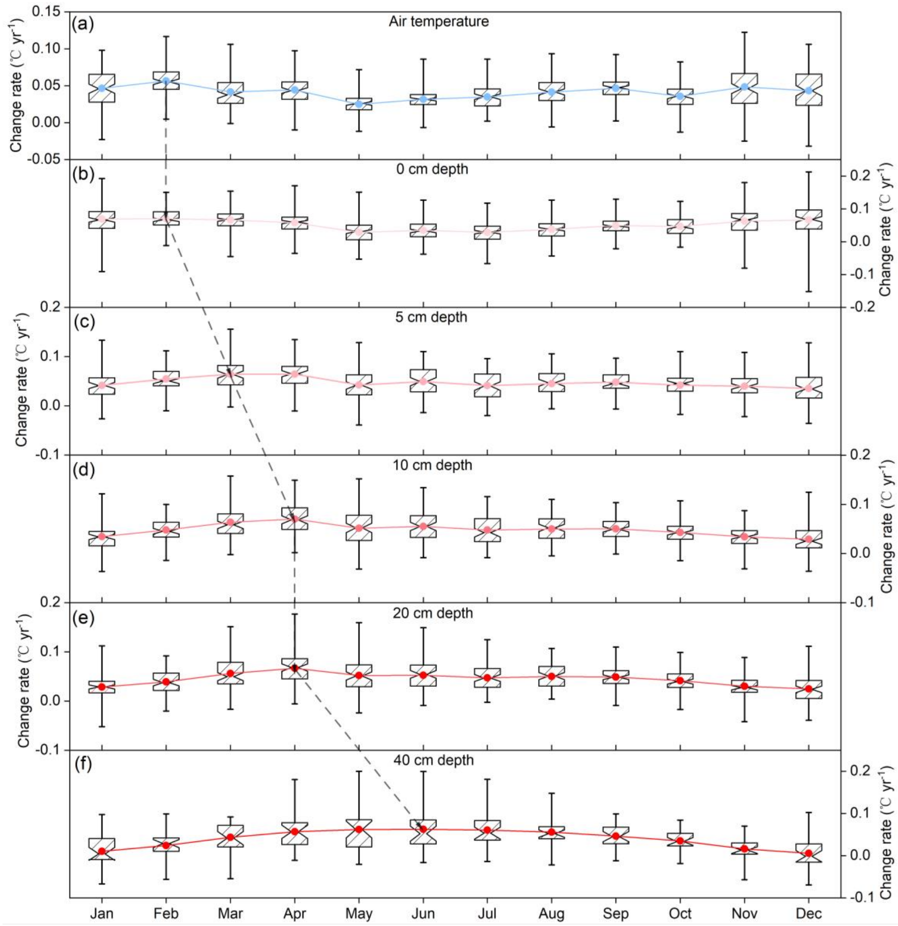

Fig. 5. Regional average monthly trends for air temperature and layered soil temperatures for 1981–2021. The dashed line with arrows connects the months with the highest temperature trend each year.

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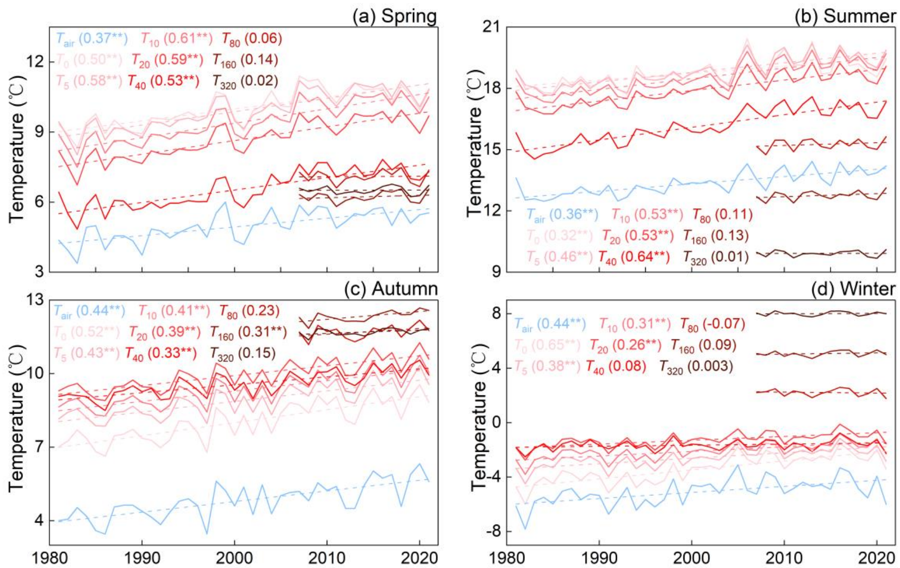

Fig. 6. Regional average of seasonal series for air temperature and layered soil temperatures over the period 1981–2021.

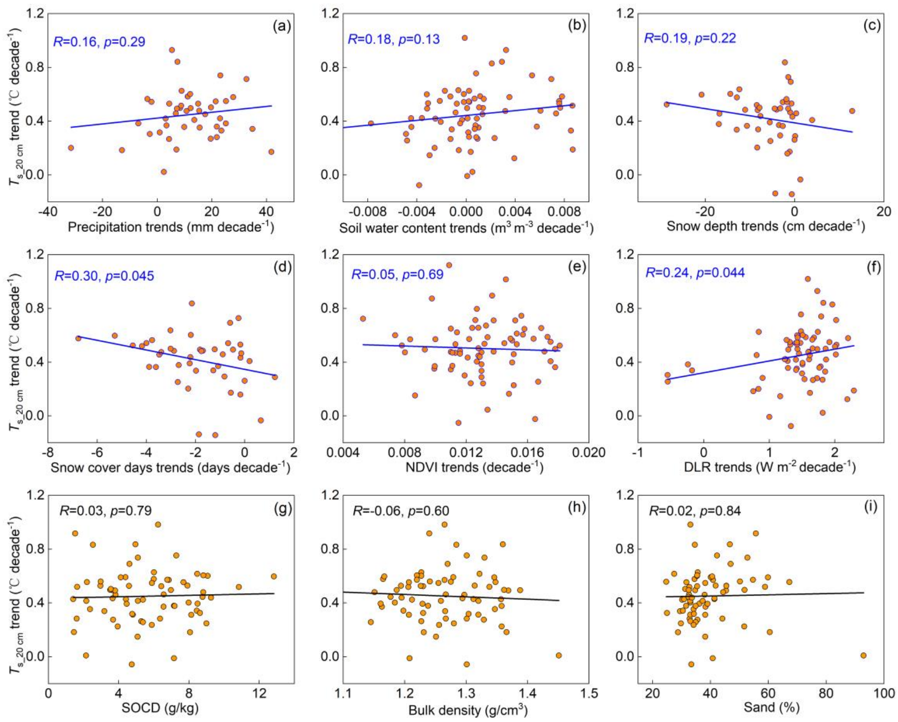

Fig. 7. Impacts of environmental drivers and soil properties on surface soil warming at a depth of 20 cm. The abbreviations *NDVI*, *DLR*, and *SOCD* refer to Normalized Difference Vegetation Index, Downward Longwave Radiation, and Soil Organic Carbon Density, respectively.

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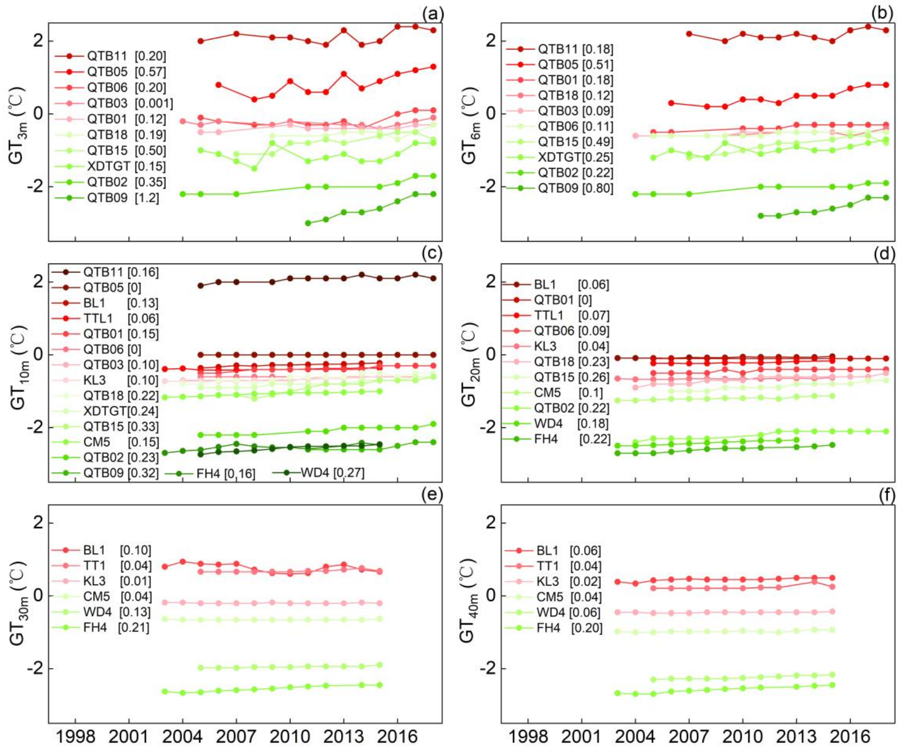

Fig. 8. Changes in annual ground temperature (GT) from shallow ground (3m) to the deep layer (40m) at compiled permafrost borehole sites. The values in brackets represent the increase/decrease trend during the observed period.

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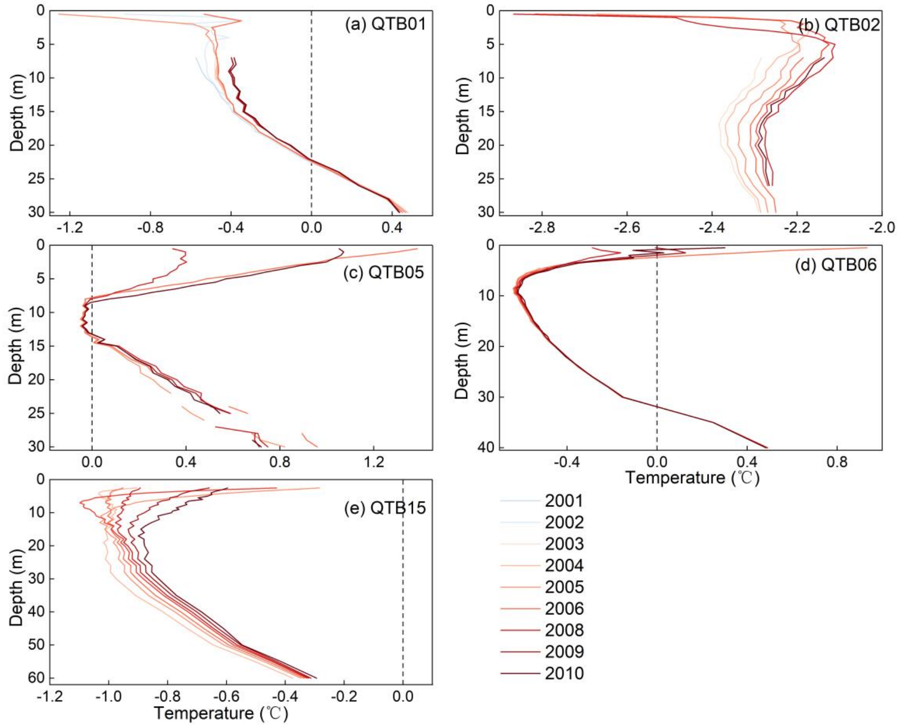

Fig. 9. Mean annual ground temperature profiles at typical permafrost sites on the Tibetan Plateau from 2000 to 2010. The dash lines are the longitudinal 0 °C line.

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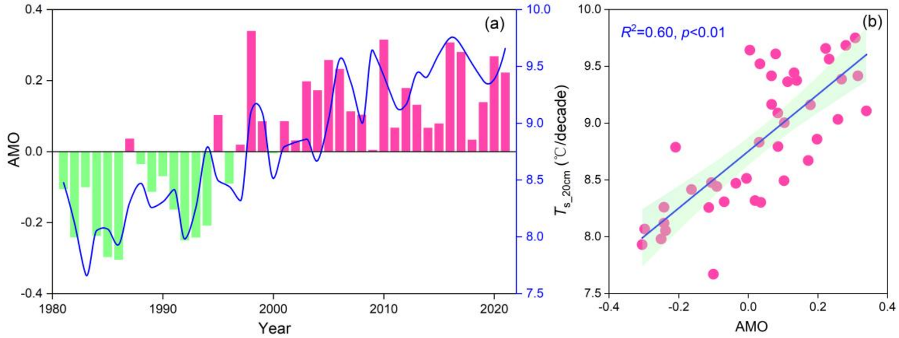

Fig. 10. Long-term trends of the Atlantic Multi-decadal Oscillation (AMO) indices and the 20 cm deep soil temperature (T_{s_20} cm) over the period 1981–2021.

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Tables

Table 1. Regional decade-scale changes and the number of stations showing statistically significant (S) trends (significant at the 0.05 level) in air temperature and layered soil temperatures.

			Percentage of stations with S trends (%)	
Indices	Unit	Range of regional trends (mean) ($decade^{-1}$)	Increasing trend (S)	Decreasing trend (S)
T_{air}	°C	-0.003 ~ 0.82 (0.41)	97.8 (97.8)	2.2 (2.2)
T_{s_0cm}	°C	-0.24 ~ 1.29 (0.51)	98.4 (89.8)	1.6 (0.8)
T_{s_5cm}	°C	-0.08 ~ 0.91 (0.47)	97.2 (93.1)	2.8 (0)
T_{s_10cm}	°C	-0.05 ~ 0.95 (0.47)	97.2 (93.1)	2.8 (0)
T_{s_20cm}	°C	-0.06 ~ 0.98 (0.44)	97.2 (93.1)	2.8 (0)
T_{s_40cm}	°C	-0.11 ~ 0.94 (0.40)	96.2 (80.8)	3.8(0)
T_{s_80cm}	°C	-1.53 ~ 1.79 (0.14)	57.1 (20.9)	42.9 (7.7)
T_{s_160cm}	°C	-1.43 ~ 1.57 (0.18)	60.4 (27.5)	39.6 (4)
T_{s_320cm}	°C	-1.19 ~ 1.50 (0.17)	65.6 (31.1)	34.4 (5.6)

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Table. 2. Correlations between latitude, longitude, altitude and temperature trends on the Tibetan Plateau.

Indices	Longitude	Latitude	Altitude
T_{air}	-0.10	0.19	0.35[b]
T_{s_0cm}	-0.11	0.23[b]	0.31[b]
T_{s_5cm}	-0.005	0.05	0.16
T_{s_10cm}	-0.04	0.07	0.24[a]
T_{s_20cm}	-0.13	0.01	0.36[b]
T_{s_40cm}	-0.19	-0.24	0.44[b]

[a] Significant at the 0.05 level (t-test)

[b] Significant at the 0.01 level (t-test)

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Table. 3. Correlations between regionally averaged temperature indices and atmospheric circulation indices over the Tibetan Plateau from 1981 to 2021.

Indices	T_{air}	T_{s_0cm}	T_{s_5cm}	T_{s_10cm}	T_{s_20cm}	T_{s_40cm}
AMO	0.77[b]	0.78[b]	0.76[b]	0.76[b]	0.78[b]	0.77[b]
AO	-0.10	-0.05	-0.04	-0.02	-0.02	-0.04
NAO	-0.31[a]	-0.31[a]	-0.29	-0.27	-0.27	-0.28
PDO	-0.33[a]	-0.36[a]	-0.35[a]	-0.34[a]	-0.35[a]	-0.40[b]
MEI	-0.40[b]	-0.37[a]	-0.35[a]	-0.34[a]	-0.35[a]	-0.40[a]
Nino 3.4	-0.16	-0.10	-0.09	-0.08	-0.08	-0.14
WPI	0.04	-0.03	-0.04	-0.04	-0.03	0.01
SASMI	-0.20	-0.22	-0.27	-0.28	-0.25	-0.23
EASMI	-0.10	-0.07	-0.06	-0.06	-0.05	-0.06

[a] Significant at the 0.05 level (t-test)
[b] Significant at the 0.01 level (t-test)