Future trends of seasonal frozen ground changes in the northeastern Qinghai-Tibet Plateau

Authors: Feng Xiaoli, Liu ZhenleiThe, Yan Jiyun, Li Hongmei, Huang Yun

Date: 2026-01-30T16:53:16+00:00

Abstract

Based on 22 high-resolution multi-model datasets (NEX-GDDP-CMIP6) that have undergone bias correction and downscaling, the changes in annual maximum freezing depth, freezing onset date, thawing termination date, and the areal extent of seasonally frozen ground on the northeastern Tibetan Plateau under different emission scenarios in the mid-21st century (2025–2000) and late 21st century (2061–2100) are projected. The results indicate that, in the mid-21st century, the annual maximum freezing depth will decrease significantly under all emission scenarios, by 9.8–14.9 cm relative to the historical reference period. Meanwhile, under the three emission scenarios, the onset date of seasonal freezing will be delayed at a rate of 1-3 d·$(10a)^{-1}$, whereas the thawing termination date will advance at a rate of -2 to -4 d·$(10a)^{-1}$. The advancement rate of the thawing termination date is approximately twice the delay rate of the freezing onset date, and the higher the emission scenario, the more pronounced the shortening of the freezing period. Under the low-emission scenario, changes in seasonally frozen ground are relatively moderate in the late 21st century; under the medium-emission scenario in the late 21st century, the change rates of maximum freezing depth and freeze–thaw period are close to those projected for the mid-21st century under the low-emission scenario; under the high-emission scenario, however, the maximum freezing depth will continue to decrease markedly, and the freezing period will be substantially shortened. From the perspective of different eco-functional zones, in the mid- and late 21st century, the annual maximum freezing depth of seasonal frozen ground in the eastern agricultural region decreases the fastest under the low- and medium-emission scenarios, whereas under the high-emission scenario, the Three-River Source region exhibits the highest rate of decrease in annual maximum freezing depth of seasonal frozen ground; the shortening of the freezing period is also most pronounced in the Three-River Source region. In the mid-21st century, the area of seasonal frozen ground increases by 14.4–19.8\$$\times 10^4 km^2 relativetothereferenceperiodunderdifferentemissionscenarios; bythelate21stcentury, theare$

km^2 under the low-, medium-, and high-emission scenarios, respectively. Overall, seasonally frozen ground in the northeastern Tibetan Plateau is projected to respond strongly to future climate change, with the reduction in maximum freezing depth and shortening of the freezing period being most pronounced under the high-emission scenario, and the transition from permafrost to seasonally frozen ground becoming more intense, whereas energy conservation and emission reduction will help to mitigate the future degradation trend of frozen ground.

Full Text

Projected Changes of Seasonally Frozen Ground over the Northeastern Qinghai-Xizang Plateau

FENG Xiaoli[1], **LIU Zhenlei**[2], **YAN Jiyun**[3], **LI Hongmei**[4], **HUANG Yun**[5] [1] Qinghai Climate Centre, Xining 810001, Qinghai, China
[2] Information and Technology Support Center of Xiaogan Meteorological Bureau, Xiaogan 432000, Hubei, China
[3] Huangnan Tibetan Autonomous Prefecture Meteorological Observatory, Tongren 811300, Qinghai, China
[4] China Atmospheric Background Observatory, Xining 810001, Qinghai, China
[5] China Three Gorges Corporation Qinghai Branch, Xining 810000, Qinghai, China

Abstract

Based on 22 bias-corrected and downscaled high-resolution simulations from NEX-GDDP-CMIP6, this study projects changes in the annual maximum freezing depth, freezing start date, thawing end date, and areal extent of seasonally frozen ground over the northeastern Qinghai-Xizang Plateau under SSP1-2.6, SSP2-4.5, and SSP5-8.5 scenarios for the mid-21st century (2025–2060) and late 21st century (2061–2100). The results show that, across all three scenarios, the annual maximum freezing depth is projected to decrease significantly by 9.8–14.9 cm during the mid-21st century relative to the historical reference period (1995–2014). Concurrently, the freezing start date is projected to delay at a rate of 1–3 days per decade, while the thawing end date is projected to advance at a rate of 2–4 days per decade, with the advance occurring nearly twice as rapidly as the delay. The shortening of the frozen period becomes more pronounced under higher emission scenarios. Under the SSP1-2.6 scenario, changes in seasonally frozen ground remain relatively stable in the late 21st century. Under SSP2-4.5, the rates of change in maximum freezing depth and freeze-thaw timing resemble those projected for the mid-21st century under SSP1-2.6. Under SSP5-8.5, the maximum freezing depth continues to decrease substantially, accompanied by a significant shortening of the frozen period. Across different ecological functional zones, the annual maximum freezing depth of seasonally frozen ground decreases most rapidly in the eastern agricultural area during the mid- and late 21st century under SSP1-2.6 and SSP2-4.5 scenarios, whereas the Three River Source Region experiences the fastest rate of decline under SSP5-8.5. Moreover, the frozen period shortens most significantly in the Three River Source region across all scenarios. The area of seasonally frozen ground is projected to expand by 14.4\$×10$^{\{4\}-19.8\times10}$\{4\}\$ km^2 in the mid-21st century across all scenarios relative to the historical reference period. This expansion continues into the late 21st century, with further increases of 2.2\$×10ˆ{4}\$ km^2, 8.6\$×10ˆ{4}\$ km^2, and 12.4\$×10ˆ{4}\$ km^2 under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. Overall, seasonally frozen ground in the northeastern Qinghai-Xizang Plateau will be profoundly affected by future climate change, with the most pronounced reductions in maximum freezing depth and frozen period duration under SSP5-8.5 alongside accelerated permafrost-to-seasonally-frozen-ground conversion, and energy conservation and emission reduction measures can effectively mitigate this degradation trend.

Keywords: Qinghai-Xizang Plateau; seasonal frozen ground; climate change; NEX-GDDP-CMIP6

1. Introduction

The Qinghai-Xizang Plateau, with its unique underlying surface characteristics and distinctive atmospheric processes, represents a sensitive and vulnerable region of global climate and environmental change, as well as a key area experiencing the most significant warming worldwide. Under a warming climate, the plateau’ s cryosphere, water resources, and ecosystems are undergoing rapid and profound changes, with climate risks exhibiting increasing aggregation effects, chain reactions, and amplification impacts. Natural systems and human society face multiple challenges and severe threats from climate warming. When a component of the climate system reaches a state where it can self-sustain without external forcing, it signifies that a tipping point has been reached. Tipping points in the Earth system represent one of the greatest risks in our changing world, as they may trigger abrupt or irreversible severe damage, or both. The 2023 Global Tipping Points Report identified 26 critical elements, of which 10 belong to the cryosphere. Since the 21st century, abrupt cryospheric events have been observed on the plateau, likely related to regionally high warming rates and frequent extreme precipitation. These cryospheric mutations pose destructive threats to local and downstream climate, water resources, ecosystems, and socio-economics, representing a significant factor endangering China’ s climate security that requires adequate attention and effective risk reduction measures.

Frozen ground constitutes an important component of the Qinghai-Xizang Plateau cryosphere. Near-surface soil freeze-thaw processes directly affect soil hydrothermal conditions, triggering changes in physical and chemical properties that significantly impact regional landscape patterns, ecosystem functions, hydrological processes, and major engineering projects. Freeze-thaw cycles enhance energy exchange between soil and atmosphere, thereby influencing East Asian regional climate through atmospheric circulation. Meanwhile, soil carbon stored in frozen ground may be released into the atmosphere through freeze-thaw cycles. Additionally, regional hydrological processes on the plateau, including runoff generation, groundwater-surface water interactions, and soil moisture conditions, are all affected by frozen ground.

Numerous observational and modeling studies have demonstrated that over past decades, significant changes have occurred in frozen ground start/end dates, duration, and depth, exhibiting clear regional differences. With rising air temperatures, soil freeze-thaw processes have generally shown delayed freezing onset, earlier thawing, shortened frozen periods, and shallower freezing depths, particularly pronounced in high-latitude and high-altitude regions. Climate warming has been confirmed as the primary cause of seasonal frozen ground degradation. Under the SSP5-8.5 scenario, the retreat rate of frozen ground area in the Northern Hemisphere is 2–3 times that under SSP1-2.6, and effective greenhouse gas emission control can significantly slow permafrost degradation and reduce rapid thawing risks. By the end of this century, all emission scenarios project significant shortening of frozen periods and prolonged thawing periods in Northern Hemisphere permafrost, with continuously rising soil temperatures weakening freezing capacity. Under future warming, permafrost loss on the Qinghai-Xizang Plateau may exceed that in the Arctic, facing more severe degradation risks. By the end of this century under different emission scenarios, the maximum freezing depth of seasonal frozen ground on the plateau is projected to decrease by 47.71 cm (SSP1-2.6), 39.5 cm (SSP2-4.5), and 24.6 cm (SSP5-8.5), with the reduction showing clear elevation dependency—higher elevations exhibit greater reduction rates. From a basin perspective, the Qinghai Lake basin shows the fastest reduction rate. Under the medium emission scenario (RCP45/SSP245), permafrost area on the plateau is projected to decrease by 65\$×10^{4}\$ km^{2} and 61\$×10^{4}\$ km^{2} by 2100 relative to current conditions. Facing the dual pressures of climate warming and cryosphere shrinkage, systematic projection and analysis of future evolution trends of seasonal frozen ground in the northeastern plateau are necessary.

This study employs 22 bias-corrected and downscaled high-resolution multi-model datasets (NEX-GDDP-CMIP6) to project future freeze-thaw periods, annual maximum freezing depth, and area of seasonal frozen ground in the northeastern Qinghai-Xizang Plateau, analyzing mid- and late-21st century degradation trends under different emission scenarios to provide references for climate change adaptation and mitigation in the cryosphere domain.

2. Data and Methods

2.1 Data Sources

Daily frozen soil depth, mean temperature, maximum temperature, minimum temperature, and precipitation data from 1961–2020 were obtained from surface meteorological observation stations in the northeastern Qinghai-Xizang Plateau. This data originates from manually quality-controlled surface meteorological observations to ensure accuracy and reliability. Except for Tuotuohe (where no frozen soil instrument was installed due to terrain or geological conditions) and unattended stations at Tuole, Qingshuihe, Wudaoliang, Yeniugou, Chaka, Lenghu, and Xiaozaohuo, all national surface meteorological observation stations have complete frozen soil records. The selected 45 stations are mainly distributed in seasonal frozen ground regions [Figure 1: see original paper].

The model data used in this study are derived from NASA' s NEX-GDDP-CMIP6, which generated daily mean, maximum, and minimum temperature and precipitation data for the historical period and three emission scenarios (SSP1-2.6, SSP2-4.5, SSP5-8.5) using bias correction and spatial disaggregation (BCSD) methods based on 22 CMIP6 climate model outputs. The horizontal spatial resolution is 25 km .

2.2 Research Methods

According to the China Meteorological Administration' s *Code of Practice for Surface Meteorological Observation*, the date when frozen soil depth stabilizes at a non-zero value is defined as the freezing start date, and the last day before October 31 when frozen soil depth stabilizes at zero is defined as the thawing end date. The period from the previous July 1 to June 30 of the following year is designated as a freezing year, with freezing start and thawing end dates converted to day numbers for statistical analysis [43].

To comprehensively assess the impacts of temperature, precipitation, maximum temperature, and minimum temperature on seasonal frozen ground indices, integrated impact assessment models were established between climate factors and frozen ground indicators. Due to large magnitude differences between frozen ground indices and climate variables, normalization was applied to freezing start date, thawing end date, annual maximum freezing depth, precipitation, mean temperature, maximum temperature, and minimum temperature. Regression equations were constructed between major frozen ground indices and climate factors, with coefficients determining the weight of different meteorological elements (Table 2). The fitted equations show that seasonal frozen ground freezing start date decreases (delays) with increasing November mean temperature, consistent with physical mechanisms and objective facts. The thawing end date advances with increased spring precipitation and rising spring mean and minimum temperatures. Annual maximum freezing depth decreases with increased precipitation during soil freezing months, rising winter mean temperature, and rising winter minimum temperature.

Using the established integrated impact assessment models, seasonal frozen ground annual maximum freezing depth, freezing start date, and thawing end date in the northeastern plateau were simulated. Results show correlation coefficients of 0.81, 0.78, and 0.85 between simulated and observed values for annual maximum freezing depth, freezing start date, and thawing end date, respectively, all passing the 0.001 significance level. These high correlations indicate strong model credibility in estimating frozen ground freeze-thaw periods and maximum freezing depth, confirming climate change as the main driver of regional frozen ground index variations. Based on these models and climate variables under different emission scenarios, possible future trends in seasonal frozen ground indices were projected.

Frozen ground area was estimated using the Surface Frost Index (SFI) model proposed by Nelson and Outcalt [44]:

$$\mathrm{SFI} = \frac{\mathrm{FI}}{\mathrm{FI} + \mathrm{TI}}$$

where FI and TI are freezing and thawing indices, respectively, representing cumulative values of daily air temperature below 0°C (cold season) and above 0°C (warm season). The freezing index calculation spans the complete winter period from July 1 to June 30 of the following year, while the thawing index covers June 1–August 31. In permafrost regions, $\mathrm{SFI} \geq 0.5$; in seasonal frozen ground regions, $\mathrm{SFI} < 0.5$. Therefore, $\mathrm{SFI} = 0.5$ was selected as the boundary between seasonal and permafrost [45]. Using ArcGIS spatial analysis techniques and a digital elevation model, different frozen ground types in the northeastern plateau were calculated [46].

3. Results

3.1 Future Changes in Maximum Freezing Depth

Figure 3 shows the multi-model ensemble mean annual maximum freezing depth of seasonal frozen ground under the three scenarios. Across all scenarios, the annual maximum freezing depth exhibits significant decreasing trends during the mid-21st century, with climate tendency rates of -1.9 cm/decade (SSP1-2.6), -3.8 cm/decade (SSP2-4.5), and -5.3 cm/decade (SSP5-8.5), all passing the 0.001 significance level. Under the low emission scenario, the decreasing trend becomes insignificant in the late 21st century, while under medium and high emission scenarios, significant decreasing trends persist at rates of -2.3 cm/decade and -5.1 cm/decade, respectively.

Figure 4 shows climate tendency rates for different ecological functional zones. Under SSP1-2.6, the eastern agricultural area shows the fastest decrease in annual maximum freezing depth, while the Three River Source Region shows the slowest. Under SSP2-4.5, the eastern agricultural area again shows the fastest decrease. Under SSP5-8.5, the Three River Source Region exhibits the most pronounced decrease in annual maximum freezing depth. In the late 21st century under SSP1-2.6, all regions show weak increasing trends in mean annual maximum freezing depth. Under SSP2-4.5, the decreasing rate slows overall. Under SSP5-8.5, all regions show continued decreasing trends, with the Three River Source Region remaining the area with fastest depth reduction. Thus, high emission scenarios make the Three River Source Region the core area for frozen depth reduction in the mid-21st century, while degradation trends slow significantly across all regions under low and medium emission scenarios in the late 21st century.

Based on multi-model ensemble projections, the change rate of annual maximum freezing depth shows regional heterogeneity (Figure 4), with consistently positive skewness in distribution. Without effective emission reductions (SSP5-8.5), change rates in the mid-21st century are predominantly negative, ranging from -4 to -8 cm/decade. Under low and medium emission scenarios, the decreasing rate of maximum freezing depth slows in the late 21st century compared to the mid-21st century. Notably, the frequency distribution of change rates under medium emission in the late 21st century resembles that under low emission in the mid-21st century.

Compared with the historical reference period (1995–2014), annual maximum freezing depth decreases by 9.8 cm, 11.2 cm, and 14.9 cm in the mid-21st century under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively. In the late 21st century, decreases are 12.1 cm, 21.0 cm, and 39.5 cm, respectively. The reduction rate under SSP2-4.5 in the late 21st century is similar to that under SSP1-2.6 in the mid-21st century. Under SSP5-8.5, the reduction continues to accelerate, reaching 24.6 cm in the late 21st century.

3.2 Future Changes in Freeze-Thaw Period

Figure 5 shows projected changes in freezing start and thawing end dates. Under SSP1-2.6, the freezing start date shows a delayed trend of 1.0 day/decade in the mid-21st century, while under SSP2-4.5 and SSP5-8.5, delays are 2.0 and 3.0 days/decade, respectively, all significant at the 0.001 level. The delay trend becomes insignificant under SSP1-2.6 in the late 21st century but remains significant under medium and high emission scenarios at 1.0 and 3.0 days/decade, respectively.

Correspondingly, the thawing end date shows consistent advancing trends across all scenarios in the mid-21st century, with rates of -2.0 days/decade (SSP1-2.6), -3.0 days/decade (SSP2-4.5), and -4.0 days/decade (SSP5-8.5). The advance rate is approximately twice the delay rate of the freezing start date. In the late 21st century, the advancing trend becomes insignificant under SSP1-2.6 but remains significant under medium and high emission scenarios at -2.0 and -4.0 days/decade, respectively, though the rate slows compared to the mid-21st century.

Compared with the historical reference period, freezing start dates are delayed by 1–3 days and thawing end dates advanced by 2–4 days in the mid-21st century. By the late 21st century, delays reach 1–3 days and advances reach 2–4 days under respective scenarios. The advance rate of thawing end date is about twice the delay rate of freezing start date, with higher emission scenarios showing more pronounced frozen period shortening.

Across ecological functional zones (Figure 5), under SSP1-2.6 in the mid-21st century, all zones show delayed freezing start dates, with the Three River Source Region showing the most significant delay. Under SSP2-4.5, the eastern agricultural area shows the fastest delay rate. Under SSP5-8.5, the Three River Source Region shows the most pronounced delay. In the late 21st century under SSP1-2.6, the delay trend weakens, with some zones showing slight advancement. Under SSP2-4.5, the delay trend continues but weakens. Under SSP5-8.5, the delay persists across both periods, with the Three River Source Region maintaining significant delays.

For thawing end dates across zones (Figure 5), under SSP1-2.6 in the mid-21st century, all zones show advancing trends, most pronounced in the Three River Source Region. In the late 21st century, the advancement continues but slows. Under medium and high emission scenarios, thawing end dates advance significantly in both periods, with the Three River Source Region showing the most pronounced advancement. Under SSP5-8.5, thawing end dates continue to advance significantly in both periods.

The frequency distributions of change rates for freezing start and thawing end dates remain positively skewed (Figure 6). In the mid-21st century, freezing start dates show delayed trends under all scenarios, but in the late 21st century, the change rate shifts from positive to negative under SSP1-2.6. For thawing end dates, change rates are negative in the mid-21st century across all scenarios. In the late 21st century, rates adjust: under high emission scenarios, thawing end dates continue advancing, but under medium and low emission scenarios, the advancement rate slows significantly.

3.3 Future Area Projections of Seasonally Frozen Ground

Based on multi-model ensemble projections, the distribution of seasonal and permafrost in the northeastern plateau is shown in Figure 7. In the mid-21st century, projected seasonal frozen ground areas are 50.7$×10^{4}$ km^2 (SSP1-2.6), 52.6$×10^{4}$ km^2 (SSP2-4.5), and 56.1$×10^{4}$ km^2 (SSP5-8.5), accounting for 72.8%, 75.5%, and 80.7% of the study area, respectively. Compared with the historical reference period, seasonal frozen ground area increases by 14.4$×10^{4}$ km^2, 16.2$×10^{4}$ km^2, and 19.8$×10^{4}$ km^2, respectively, while permafrost area decreases by 14.4$×10^{4}$ km^2, 16.2$×10^{4}$ km^2, and 19.8$×10^{4}$ km^2, representing 23.3%, 20.6%, and 28.5% of the study area.

In the late 21st century, seasonal frozen ground area further expands to 52.9$×10^{4}$ km^2, 61.1$×10^{4}$ km^2, and 68.5$×10^{4}$ km^2 under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively, with increases of 2.2$×10^{4}$ km^2, 8.6$×10^{4}$ km^2, and 12.4$×10^{4}$ km^2 compared to the mid-21st century, accounting for 76.2%, 87.8%, and 98.5% of the study area. Permafrost area decreases by 2.2$×10^{4}$ km^2, 8.6$×10^{4}$ km^2, and 12.4$×10^{4}$ km^2, representing 16.3%, 22.1%, and 35.7% of the study area. Under SSP5-8.5, most permafrost areas transition to seasonal frozen ground, leaving only 24.8$\times10^{4}$ km^2 of permafrost (35.7% of the study area) by the late 21st century.

Overall, under SSP1-2.6, seasonal frozen ground area remains stable at 73–76% of the study area in both periods, with stable thawing rates. Under SSP2-4.5, seasonal frozen ground area expands to 75–88% of the study area, with rapid initial expansion that slows later. Under SSP5-8.5, seasonal frozen ground area reaches 76–98%, with the frozen period shortening most significantly and permafrost-to-seasonal-frozen-ground conversion accelerating. Energy conservation and emission reduction help slow future frozen ground degradation. The central-western Three River Source Region is the core key area for permafrost degradation under all scenarios.

Currently, large uncertainties exist in frozen ground simulation, particularly regarding insufficient understanding of controlling effects from vegetation, snow cover, and environmental factors, which increases simulation and projection uncertainties. Future work should introduce more climate and frozen ground models for multi-model comparative analysis to reduce uncertainty.

4. Conclusions

Based on 22 high-resolution multi-model ensemble projections, this study projects changes in annual maximum freezing depth, freezing start date, and thawing end date of seasonal frozen ground in the northeastern Qinghai-Xizang Plateau, yielding the following conclusions:

1. During the mid-21st century, the mean annual maximum freezing depth shows significant decreasing trends across all scenarios, with reductions of 9.8–14.9 cm relative to the reference period. In the late 21st century, the decreasing trend becomes insignificant under SSP1-2.6, while under SSP2-4.5 the reduction rate resembles that under SSP1-2.6 in the mid-21st century. Under SSP5-8.5, the maximum freezing depth continues to decrease substantially as anthropogenic radiative forcing increases.

2. During the mid- and late 21st century under low and medium emission scenarios, the eastern region shows the fastest decrease in seasonal frozen ground depth. However, under SSP5-8.5, the Three River Source Region shows the fastest decrease in annual maximum freezing depth.

3. During the mid-21st century, freezing start dates are projected to delay significantly at 1–3 days/decade across all scenarios, while thawing end dates advance at 2–4 days/decade. Higher emission scenarios lead to more pronounced frozen period shortening. During the late 21st century, changes remain stable under SSP1-2.6, while under SSP2-4.5 the rates resemble those under SSP1-2.6 in the mid-21st century. Under SSP5-8.5, the trends continue significantly.

4. During the mid-21st century, seasonal frozen ground area remains at 73–

81% of the study area, increasing by 14.4\$×10$^{\{4\}-19.8\times10}${4}\$ km^2 relative to the reference period. In the late 21st century, seasonal frozen ground area increases further by 2.2\$×10^{4}\$ km^2, 8.6\$×10^{4}\$ km^2, and 12.4\$×10^{4}\$ km^2 under SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively, accounting for 16.3%, 22.1%, and 35.7% of the study area. Permafrost degradation area increases multiplicatively with emission scenario severity.

5. With energy conservation and emission reduction measures, changes in seasonal frozen ground maximum depth and freeze-thaw timing remain relatively stable in the late 21st century under SSP1-2.6, while under SSP2-4.5 they resemble SSP1-2.6 mid-21st century conditions. Future permafrost in the northeastern Qinghai-Xizang Plateau will be significantly impacted by climate change, particularly under high emission scenarios where maximum freezing depth continues to decrease, freeze-thaw dates show significant trends, and frozen ground degradation is most severe.

References

[1] Li F, Gao Y Q, Wan X, et al. Earth three poles climate change under global warming[J]. Transactions of Atmospheric Sciences, 2021, 44(1): 1-11.

[2] Su B, Gao X J, Xiao C D. Interpretation of IPCC SR1.5 on cryosphere change and its impacts[J]. Climate Change Research, 2019, 15(4): 395-404.

[3] Kang S C, Guo W Q, Wu T H, et al. Cryospheric changes and their impacts on water resources in the Belt and Road regions[J]. Advances in Earth Science, 2020, 35(1): 1-17.

[4] Bao W, Duan A M, You Q L, et al. Research progress on climate change and its impact on water resources over the Tibetan Plateau[J]. Climate Change Research, 2024, 20(2): 158-169.

[5] Dai L C, Ke X, Zhang F W, et al. Characteristics of hydrothermal coupling during soil freezing-thawing process in seasonally frozen soil regions on the Tibetan Plateau[J]. Journal of Glaciology and Geocryology, 2020, 42(2): 390-398.

[6] Lenton T M, Armstrong M D I, Loriani S, et al. The Global Tipping Points Report 2023[R]. UK: University of Exeter, 2023.

[7] Ma L J, Yuan J S, Xu Y. Climate tipping points and its potential challenges to climate security in China[J]. Climate Change Research, 2025, 21(2): 273-287.

[8] Ma L J, Yuan J S, Huang L. Prospect of climate risks management in China under the framework of UN early warning for all initiative[J]. Climate Change Research, 2024, 20(1): 48-61.

[9] Wang C H, Dong W J, Wei Z G. Study on relationship between the frozen-thaw process in Qinghai-Xizang Plateau and circulation in East Asia[J]. Chinese Journal of Geophysics, 2003, 46(3): 309-316.

[10] Li Q, Chen H S. Variation of seasonal frozen soil in East China and their association with monsoon activity under the background of global warming[J]. Climate Change Research Letters, 2013, 2(2): 47-53.

[11] Steffen W, Rockström J, Richardson K, et al. Trajectories of the earth system in the anthropocene[J]. Proceedings of the National Academy of Sciences, 2018, 115(33): 8252-8259.

[12] Lenton T M, Johan R, Owen G, et al. Climate tipping points—too risky to bet against[J]. Nature, 2019, 575(7784): 592-595.

[13] Yu R, Zhai P M. Ocean and cryosphere change related extreme events, abrupt change and its impact and risk[J]. Climate Change Research, 2020, 16(2): 194-202.

[14] Wang K, Zhang T J, Mou C C, et al. From the Third Pole to the Arctic: Changes and impacts of the climate and cryosphere[J]. Journal of Glaciology and Geocryology, 2020, 42(1): 104-123.

[15] Xu P K, Zhu H L, Li B F, et al. Effects of freeze-thaw cycles on shear characteristics and microstructure of alpine meadow soil in riparian zone[J]. Arid Zone Research, 2025, 42(10): 1841-1850.

[16] Wei X, Huang C H, Wei N, et al. The impact of freeze-thaw cycles and soil moisture content at freezing on runoff and soil loss[J]. Land Degradation and Development, 2019, 30(5): 515-523.

[17] Luo S Q, Wang J Y, Pomeroy J W, et al. Freeze-thaw changes of seasonally frozen ground on the Tibetan Plateau from 1960 to 2014[J]. Journal of Climate, 2020, 33(21): 9427-9446.

[18] Li N, Lan C, Zhang Y X. On the freeze-thaw cycles of shallow soil and connections with environmental factors over the Tibetan Plateau[J]. Climate Dynamics, 2021, 57(11): 3183-3206.

[19] Lan C, Zhang Y X, Bohn T J, et al. Frozen soil degradation and its effects on surface hydrology in the northern Tibetan Plateau[J]. Journal of Geophysical Research, 2015, 120(16): 8276-8298.

[20] Zheng D H, Rogier V D V, Su Z B, et al. Impact of soil freeze-thaw mechanism on the runoff dynamics of two Tibetan rivers[J]. Journal of Hydrology, 2018, 563: 382-394.

[21] Yang X L, Wang J S. The change characteristics of maximum frozen soil depth of seasonal frozen soil in Northwest China[J]. Chinese Journal of Soil Science, 2008, 39(2): 32-37.

[22] Chen R, Yang M X, Wan G N, et al. Soil freezing-thawing processes on the Tibetan Plateau: A review based on hydrothermal dynamics[J]. Progress in Geography, 2020, 39(11): 1944-1958.

[23] Wang X Q, Chen R S, Liu G H, et al. Spatial distributions and temporal variations of the near-surface soil freeze state across China under climate change[J]. Global and Planetary Change, 2019, 172: 258-273.

[24] Li T, Chen Y Z, Han L J, et al. Shortened duration and reduced area of frozen soil in the Northern Hemisphere[J]. The Innovation, 2021, 2(3): 100146.

[25] Wang J Y, Luo S Q, Lv Z B, et al. Improving ground heat flux estimation: Considering the effect of freeze/thaw process on the seasonally frozen ground[J]. Journal of Geophysical Research: Atmospheres, 2021, 126(24): e2021JD035445.

[26] Jin H D. Future Changes and Potential Hazard of Permafrost in the Northern Hemisphere[D]. Lanzhou: Lanzhou University, 2023.

[27] Wang C H, Zhao W, Cui Y. Changes in the seasonally frozen ground over the eastern Qinghai-Xizang Plateau in the past 60 years[J]. Frontiers in Earth Science, 2020, 8: 270.

[28] Zhang T, Barry R, Knowles K, et al. Distribution of seasonally and perenially frozen ground in the Northern Hemisphere[C]//Proceedings of the 8th International Conference on Permafrost, 2003, 2: 1289-1294.

[29] Chen B, Li J. Characteristics of spatial and temporal variation of seasonal and short-term frozen soil in China in recent 50 years[J]. Chinese Journal of Atmospheric Sciences, 2008, 32(3): 432-443.

[30] Peng X Q, Zhang T J, Frauenfeld O W, et al. Active layer thickness and permafrost area projections for the 21st century[J]. Earth’ s Future, 2023, 11: e2023EF003573.

[31] Wei J J. Permafrost Loss on Tibetan Plateau under Future Warming[D]. Lanzhou: Lanzhou University, 2023.

[32] Peng X Q, Tian W W, Li X J, et al. Research progress on changes in frozen ground on the Qinghai-Xizang Plateau and in the circum-Arctic region[J]. Journal of Glaciology and Geocryology, 2023, 45(2): 521-534.

[33] Chang Y, Lyu S H, Luo S Q, et al. Evaluation and projections of permafrost on the Qinghai-Xizang Plateau by CMIP5 coupled climate models[J]. Plateau Meteorology, 2016, 35(5): 1157-1168.

[34] Peng X Q, Frauenfeld O W, Cao B, et al. Response of changes in seasonal soil freeze/thaw state to climate change from 1950 to 2010 across China[J]. Journal of Geophysical Research: Earth Surface, 2016, 121(11): 1984-2000.

[35] Peng X, Zhang T, Cao B, et al. Changes in freezing-thawing index and soil freeze depth over the Heihe River Basin, Western China[J]. Arctic, Antarctic, and Alpine Research, 2017, 48(1): 161-176.

[36] Feng X L, Li H M, Luo S Q, et al. Freeze-thaw characteristics of seasonally frozen ground in the Three River Source Region from 1961 to 2020[J]. Plateau Meteorology, 2022, 41(2): 295-305.

[37] Li L, Wang Z Y, Wang Q C, et al. Cause of seasonal tjale degeneration and its response to climate change in Qinghai[J]. Geographical Research, 2008, 27(1): 162-170.

[38] Nan Z T, Li S X, Cheng G D, et al. Surface frost number model and its application to the Tibetan Plateau[J]. Journal of Glaciology and Geocryology, 2012, 34(1): 89-95.

[39] Ran Y H, Li X. Challenges and opportunities of permafrost mapping in China[J]. Advances in Earth Science, 2019, 34(10): 1015-1027.

[40] Wang T H, Yang D W, Fang B J, et al. Data-driven mapping of the spatial distribution and potential changes of frozen ground over the Tibetan Plateau[J]. Science of the Total Environment, 2019, 649: 515-525.

[41] Wang B Q, Ran Y H. Machine learning based forecasting of future maximum frost depth over the Third Pole[J]. Journal of Glaciology and Geocryology, 2023, 45(2): 798-807.

[42] Zou D F, Zhao L, Sheng Y, et al. A new map of permafrost distribution on the Tibetan Plateau[J]. The Cryosphere, 2017, 11(6): 2527-2542.

[43] China Meteorological Administration. Code of Practice for Surface Meteorological Observation[M]. Beijing: Meteorological Press, 2003: 1-151.

[44] Nelson F E, Outcalt S I. A computational method for prediction and regionalization of permafrost[J]. Arctic and Alpine Research, 1987, 19(3): 279-288.

[45] Tian Q X, Liu J C, Zeng F C, et al. Permafrost dynamics in the Northern Hemisphere under future climate scenarios based on CMIP6[J]. Chinese Journal of Applied Ecology, 2025, 36(5): 1496-1506.

Note: Figure translations are in progress. See original paper for figures.