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

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Abstract

Based on 22 bias-corrected, high-resolution multi-model datasets (NEX-GDDP-CMIP6), this study projects the trends in annual maximum freezing depth, freezing onset date, thawing end date, and the areal extent of seasonally frozen ground in the northeastern Tibetan Plateau under different emission scenarios for the mid- (2025–2000) and late (2061–2100) 21st century. The results show 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annual maximum freezing depth will decrease significantly under all emission scenarios, by 9.8–14.9 cm relative to the historical reference period. At the same time, the freezing onset date of seasonally frozen ground will be delayed at a rate of 1–3 d · (10 a)^-1 under the three emission scenarios, whereas the thawing end date will advance at a rate of −2 to −4 d · (10 a)^-1; the advance rate of the thawing end 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 frozen period. Under the low-emission scenario, changes in seasonally frozen ground are relatively stable in the late 21st century; under the medium-emission scenario in the late 21st century, the rates of change in maximum freezing depth and freeze–thaw period are close to the projected results for the mid-21st century under the low-emission scenario; under the high-emission scenario, however, the maximum freezing depth will continue to decrease substantially and the frozen period will shorten markedly. From the perspective

Full Text

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

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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freezing depth is projected to decrease significantly by 9.8–14.9 cm during the mid-21st century relative to the historical reference period. 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 SSP1-2.6 scenario, changes in seasonally frozen ground remain relatively stable in the late 21st century. Under SSP2-4.5 scenario, 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 scenario, 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\$×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. 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; seasonally frozen ground; climate change; NEX-GDDP-CMIP6

1. Data and Methods

1.1 Data Sources

We utilized daily observations of frozen soil depth, mean temperature, maximum temperature, minimum temperature, and precipitation from meteorological stations across the northeastern Qinghai-Xizang Plateau for the period 1961–2020. These data were obtained from quality-controlled surface meteorological observations. With the exception of Tuotuohe (where no frozen soil instrument was installed due to terrain or geological conditions) and several unattended stations (Tuole, Qingshuihe, Wudaoliang, Yeniugou, Chaka, Lenghu, and Xiazaohuo), all national surface meteorological stations maintained complete frozen soil records. The 45 selected stations are primarily located in seasonally frozen ground regions [Figure 1: see original paper].

The model data were sourced from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) for CMIP6, which provides bias-corrected and spatially disaggregated (BCSD) daily outputs from global climate models. This dataset includes historical simulations and three emission scenarios (SSP1-2.6, SSP2-4.5, and SSP5-8.5) for mean, maximum, and minimum temperature and precipitation, with a horizontal spatial resolution of 25 km .

1.2 Research Methods

According to the China Meteorological Administration' s *Code of Practice for Surface Meteorological Observation*, the freezing start date is defined as the first day when frozen soil depth remains consistently above zero, while the thawing end date is defined as the last day before July 31st when frozen soil depth remains consistently at zero. The period between these dates constitutes the frozen period. For statistical analysis, dates were converted to ordinal day numbers [43].

To comprehensively evaluate the influence of climatic factors on seasonally frozen ground indices, we developed integrated assessment models linking climate variables to frozen ground parameters. Given the substantial magnitude differences among variables, we normalized the freezing start date, thawing end date, annual maximum freezing depth, precipitation, mean temperature, maximum temperature, and minimum temperature. Regression equations were then constructed between frozen ground indices and key climatic factors, with coefficients used to determine the weight of each meteorological element (Table 2). The resulting models show that the freezing start date increases (delays) with rising November temperatures and decreases (advances) with increasing spring precipitation—a pattern consistent with physical processes. The thawing end date advances with increased spring precipitation and rising spring mean and minimum temperatures. Annual maximum freezing depth decreases with greater precipitation during soil freezing months and increases with lower winter mean temperatures.

Using these models, we simulated seasonally frozen ground indices for the northeastern Qinghai-Xizang Plateau. The correlation coefficient between simulated and observed annual maximum freezing depth is 0.91, with correlations of 0.86 for freezing start date and 0.88 for thawing end date—all statistically significant at the 95% confidence level. Mean relative errors are 1.9 days, 2.9 days, and 3.4 cm, respectively, demonstrating high model reliability [Figure 2: see original paper].

For area estimation, we employed the Surface Frost Index (SFI) model [44]:

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

where FI and TI represent freezing and thawing indices, respectively—the cumulative sums of daily temperatures below and above 0°C. The freezing index calculation spans the complete winter period (July 1–June 30), while the thawing index covers the warm season (January 1-December 31). SFI values indicate frozen ground types: $\mathrm{SFI} < 0.5$ denotes seasonally frozen ground, while $\mathrm{SFI} > 0.5$ indicates permafrost. Using this approach with elevation models, we calculated the distribution of different frozen ground types across the study region [Figure 2: see original paper].

2. Results

2.1 Future Changes in Maximum Freezing Depth

Under all three emission scenarios, the multi-model ensemble mean indicates a significant decreasing trend in annual maximum freezing depth across the northeastern Qinghai-Xizang Plateau during the mid-21st century, with climate tendency rates of -1.9, -3.8, and -5.3 cm per decade for SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively (all significant at the 95% confidence level). Under SSP1-2.6, the trend becomes insignificant in the late 21st century, whereas under SSP2-4.5, the decreasing trend persists. Under SSP5-8.5, the maximum freezing depth continues to decline substantially [Figure 3: see original paper].

Spatial variations across ecological functional zones show that under SSP1-2.6 and SSP2-4.5, the eastern agricultural area experiences the fastest decrease in maximum freezing depth during both periods, while the Three River Source Region shows the slowest decline. Under SSP5-8.5, the Three River Source Region exhibits the most rapid decrease [Figure 3: see original paper].

Frequency distributions reveal that under SSP5-8.5, the change rates for maximum freezing depth are consistently negative. Under lower emission scenarios, the distribution shifts toward less negative values in the late 21st century, with SSP2-4.5 showing a pattern similar to SSP1-2.6 in the mid-21st century [Figure 4: see original paper].

2.2 Future Changes in Freeze-Thaw Period

The multi-model ensemble projects significant delays in freezing start date across all scenarios, with rates of 1.0, 2.3, and 3.0 days per decade for SSP1-2.6, SSP2-4.5, and SSP5-8.5, respectively, during the mid-21st century. Concurrently, thawing end dates advance at rates of 2.0, 3.5, and 4.0 days per decade. The advance of thawing end date is approximately twice as rapid as the delay in freezing start date. Under SSP1-2.6, these trends stabilize in the late 21st century, whereas under higher emission scenarios, they persist [Figure 5: see original paper].

Relative to the historical reference period (1995–2014), freezing start dates are projected to delay by 1–3 days while thawing end dates advance by 2–4 days during the mid-21st century. By the late 21st century, these changes intensify under SSP5-8.5 but moderate under lower emission scenarios.

Across ecological zones, the Three River Source Region shows the most pronounced advancement of thawing end date under all scenarios. The frequency distributions of change rates indicate that under SSP1-2.6, the trend in freezing start date shifts from positive to negative between the mid- and late 21st century, while under SSP5-8.5, both freezing start delay and thawing end advance accelerate continuously [Figure 6: see original paper].

2.3 Projected Changes in Seasonally Frozen Ground Area

Under the three emission scenarios, the area of seasonally frozen ground in the mid-21st century is projected to be 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), representing 72.8%, 75.5%, and 80.7% of the study region, respectively. This represents increases of 14.4$×10^{4}$ km^2, 16.2$×10^{4}$ km^2, and 19.8$×10^{4}$ km^2 compared to the reference period, accounting for 20.6%, 23.3%, and 28.5% of the total area [FIGURE:7, Table 3].

In the late 21st century, seasonally frozen ground area expands further to 52.9$×10^{4}$ km^2, 61.1$×10^{4}$ km^2, and 68.5$×10^{4}$ km^2 under the three scenarios, representing 76.2%, 87.8%, and 98.5% of the region. These correspond to additional increases of 2.2$×10^{4}$ km^2, 8.6$×10^{4}$ km^2, and 12.4$×10^{4}$ km^2, respectively. Under SSP5-8.5, most permafrost areas transition to seasonally frozen ground, with permafrost area decreasing by 24.8$×10^{4}$ km^2 (35.7% of the region) [FIGURE:7, Table 3].

3. Conclusions

Based on 22 high-resolution, bias-corrected CMIP6 model simulations, we project changes in seasonally frozen ground indices over the northeastern Qinghai-Xizang Plateau and draw the following conclusions:

1. During the mid-21st century, annual maximum freezing depth shows significant decreasing trends under all emission scenarios, with reductions of 9.8–14.9 cm relative to the reference period. Under SSP1-2.6, the trend stabilizes in the late 21st century. Under SSP2-4.5, the reduction rate in the late 21st century resembles that under SSP1-2.6 in the mid-21st century. Under SSP5-8.5, the decreasing trend intensifies with increasing radiative forcing.
2. Across ecological functional zones, the eastern agricultural area shows the fastest decrease in maximum freezing depth under SSP1-2.6 and SSP2-4.5, whereas the Three River Source Region experiences the most rapid decline under SSP5-8.5.
3. During the mid-21st century, freezing start dates delay at 1–3 days per decade while thawing end dates advance at 2–4 days per decade across all scenarios. The rate of change increases with emission scenario severity, with the thawing end date advancing approximately twice as fast as the freezing start date delays. The Three River Source Region shows the most significant shortening of the frozen period.
4. Seasonally frozen ground area increases across all scenarios, reaching 73-81% of the study region in the mid-21st century (14.4\$$\times10^{\{4\}-19.8\times10}$\{4\}\$ km^2 increase). By the late 21st century, area expansion continues, particularly under SSP5-8.5 where seasonally frozen ground occupies 98.5% of the region. Permafrost degradation area increases multiplicatively with emission scenario severity.
5. Energy conservation and emission reduction measures effectively mitigate frozen ground degradation. Under SSP1-2.6, changes in maximum freezing depth and freeze-thaw timing stabilize in the late 21st century, while under SSP2-4.5, late-21st-century conditions resemble those under SSP1-2.6 in the mid-21st century. Under SSP5-8.5, frozen ground degradation remains severe throughout both periods.

Current frozen ground simulations still involve considerable uncertainty, particularly regarding the controlling effects of vegetation, snow cover, and environmental factors. Future research should incorporate additional climate and frozen ground models to reduce projection uncertainties through multi-model intercomparison.

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