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Weakening warming on spring freeze–thaw cycle caused greening Earth's third pole

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The Tibetan Plateau, recognized as Earth's third pole and among the most responsive regions to climate shifts, profoundly influences regional and even global hydrological processes. Here, we discerned a significant weakening in the influence of temperature on the initiation of surface freeze–thaw cycle (the Start of Thawing, SOT), which can be ascribed to a multitude of climatic variables, with radiation emerging as the most pivotal factor. Additionally, we showed that the diminishing impact of warming on SOT yields amplified soil moisture within the root zone. This, in turn, fosters a greening third pole with increased leaf area index and solar-induced chlorophyll fluorescence. We further showed that current Earth system models failed to reproduce the linkage between weakened sensitivity and productivity under various shared socioeconomic pathways. Our findings highlight the dynamic shifts characterizing the influence of climate warming on spring freeze–thaw process and underscore the profound ecological implications of these changes in the context of future climate scenarios.

permafrost thawing | climate change | third pole

As the most expansive domain within middle and low latitudes experiencing frequent land surface freeze–thaw cycles, the Tibetan Plateau is highly sensitive to global warming (1–4). While prevailing research underscores that escalating global temperatures trigger the freeze–thaw cycle and augmenting carbon emissions (5, 6), scant attention has been directed toward comprehending the temporal evolution of warming's influence on freeze–thaw cycle across an extensive temporal scale. Equally underexplored are the potential hydrological and ecological consequences tied to these evolving impacts.

In this context, we have employed the earth system data record encompassing daily landscape freeze/thaw states (referred to as FT-ESDR) to ascertain the start of surface freeze–thaw cycle [SOT (Start of Thawing)] over the period spanning 1980 to 2018. This comprehensive approach is coupled with the incorporation of regional meteorological parameters encompassing temperature, precipitation, snow depth and radiation, CO_2 concentration, and nitrogen deposition, along with root zone soil moisture (SM_{root}) (10 to 100 cm), leaf area index (LAI), and solar-induced chlorophyll fluorescence (SIF). Our study is guided by three primary objectives: first, to dissect the temporal oscillation in temperature's role in governing SOT; second, to explore the contributory factors influencing the way of warming on SOT; and finally, to elucidate the cascading and ecological effects resultant from these evolving dynamics.

Results

Our investigation has revealed a widespread decline in the temporal responsiveness of SOT to warming. Remarkably, approximately 40.8% of regions exhibited diminished warming-induced control (referred to as T_{sen}^-) over SOT, contrasting with 14.7% that displayed an intensified (T_{sen}^+) influence of warming on SOT (Fig. 1*A*). Temporal patterns using the moving-window approach showed similar results that the trend of SOT sensitivity to temperature was significantly weakened ($R^2 = 0.66$, $P < 0.001$, Fig. 1*B*). Employing advanced Random Forest (RF) and Shapley Additive exPlanations (SHAP) techniques, we delved into the determinants of these alterations and identified mean radiation as the most influential factor (Fig. 1*C*). Additionally, a comprehensive comparison of meteorological variables between regions with weakened and enhanced control (Fig. 1*D*) indicated that T_{sen}^- regions exhibited significantly higher levels of radiation and temperature, coupled with more snow but less precipitation.

Turning our attention to the ecological implications stemming from the attenuated temperature control on SOT, we employed spring (March–May) root-zone soil moisture (SM_{root}) as an intermediary connection. In exploring the associations between Sen_T and LAI and SIF, we uncovered a robustly positive relationship between Sen_T and

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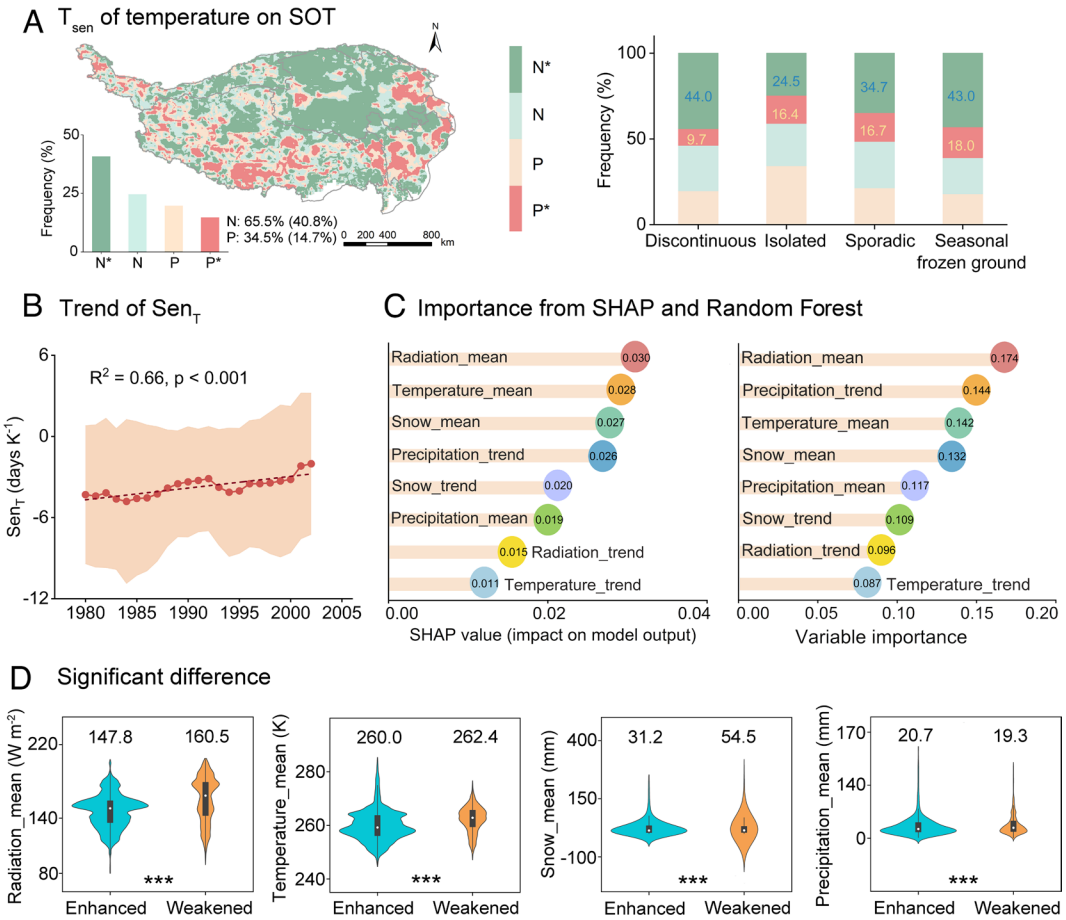

Fig. 1. Changes in the control of temperature on the start of freeze–thaw cycle (SOT, day of year, DOY) and the underlying mechanisms. (*A*) illustrates the trend in the absolute temperature sensitivity of SOT (T_{sen}). (*B*) represents annual variations of SOT sensitivity to temperature (Sen_T), and the shaded area indicates 1 SD (*SI Appendix*). (*C*) presents the relative importance of various factors determined through the application of the RF and SHAP techniques. (*D*) showcases the statistically significant disparities in mean radiation, temperature, snow, and precipitation between regions characterized by enhanced and weakened temperature control. N and P represent negative and positive correlations, respectively. *** represents significance at $P < 0.001$.

SM_{root}, with a significance of 48.3% ($P < 0.05$) (Fig. 2*A*). Remarkably, we also observed a statistically significant and positive alignment between SM_{root} and both LAI (47.2%, $P < 0.05$) and SIF (54.5%, $P < 0.05$) with effects from CO_2 and nitrogen being removed (Fig. 2 *B* and *C*). The observational data revealed that the temporal shifts in the temperature-SOT relationship culminated in elevated SM_{root} levels, thereby causing greening over the third pole. To investigate whether the state-of-the-art models (CMIP6 models over 2015 to 2100) can reproduce the observed greening, we analyzed the partial correlation between Sen_T and gross primary productivity (GPP) based on ten CMIP6 models (*SI Appendix*) and found that the CMIP6 models failed to reproduce the positive correlation between Sen_T and GPP (Fig. 2*D*). We found that there were only two scenarios (SSP125 and SSP370) in which five models (out of 10) showed larger positive correlations. In scenario SSP245, four models showed significant positive correlations, while in scenario SSP585, this number decreased to 3.

Discussion

Our current study unveils a nonlinear trajectory of SOT advancement over the preceding four decades, showcasing a substantial attenuation in the potency of climate warming on SOT across Earth's third pole. This phenomenon is ascribed predominantly to the influence of radiation. Explanations are also provided for these important correlations. We suggest that the interactions between climate change and freeze–thaw cycles could explain the contribution of radiation in controlling the weakening warming on SOT. Solar radiation is the main input energy that drives land surface processes, and the importance of radiation will strengthen, given that the pronounced role of albedo often becomes stronger in winter-spring transition and therefore greatly controls the surface energy balance (3, 7). This energy balance can affect the surface melting process, e.g., slow down the melting of snow and warming of the soil (8). The importance of radiation also agrees with previous studies showing that the solar radiation variations drive the heat under the snow and conduct heat to the ground, further determining the melting process (9). We also observed increased SM_{root} with the diminishing impact of warming on SOT, and the reason could be the increased top-layer soil that favors water infiltration into deep soil layers (10). Therefore, the sufficient water supply contributed to the better growth of vegetation, as evidenced in the larger LAI and SIF consequently (11).

The attenuation of temperature control potentially implies a shift in the dominant driving forces behind premature freeze–thaw cycle across Earth's third pole, potentially diverting emphasis from warming towards factors such as soil physical and chemical attributes or climate variables linked to water (12). To succinctly conclude, a more nuanced delineation of the interrelations among climate, permafrost, and land surface stands to enhance the accuracy of projections concerning cryospheric and biospheric dynamics. Moreover, it augments our comprehension of freeze–thaw cycles within the context of a warming planet, thereby enriching our prospective insights into the future.

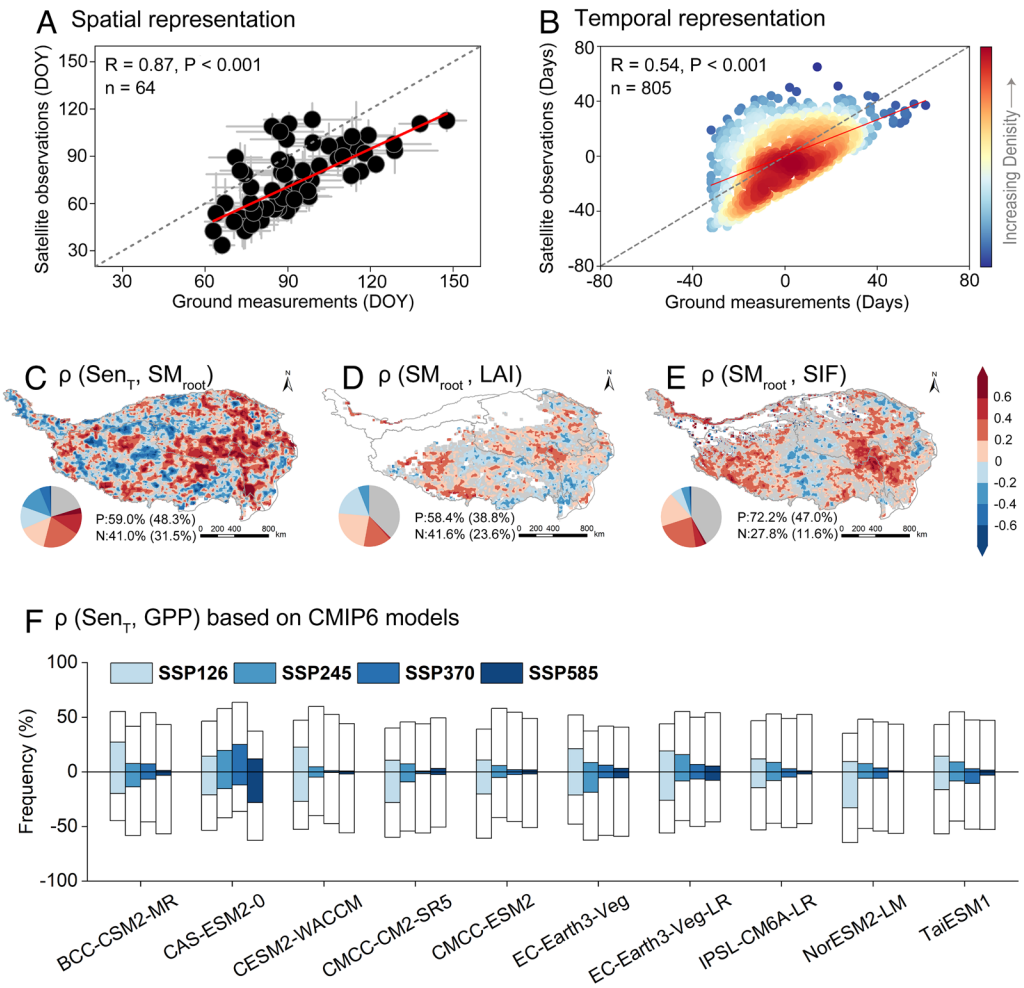

Fig. 2. Unpacking the ecohydrological implications stemming from the shifts in the temperature sensitivity of the start of freeze–thaw cycle (SOT, day of year, DOY). (*A* and *B*) show the spatial and temporal validation of satellite-observed SOT using 64 ground sites (*Methods*). (*C*–*E*) unravel the connections between Sen_T and SM_{root}, SM_{root} and LAI, and SM_{root} and SIF, respectively. (*F*) represents the connection between Sen_T and GPP for ten Earth system models (CMIP6) under different shared socioeconomic pathways (SSP126, SSP245, SSP370, and SSP585). The effects from CO_2 and nitrogen deposition were removed with partial correlations. P and N represent positive and negative correlations, respectively. All connections outlined are statistically significant at $P < 0.05$.

Materials and Methods

We used multiple datasets, including the ground monitoring sites, satellite observations, meteorological data, and future projections of Earth system models on surface freeze–thaw cycles. We harnessed partial correlation, the SHAP method and the significant difference approach to elucidate the transformations in temperature control over SOT in tandem with shifts across these influencing factors. See *SI Appendix* for extended methods.

Data, Materials, and Software Availability. All codes for the study are available at https://doi.org/10.5281/zenodo.10583382 (13). All data used in this study are available online. All study data are included in the main text and *SI Appendix*.

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