Geographical Sciences REPORT

Thaw subsidence accelerates permafrost degradation

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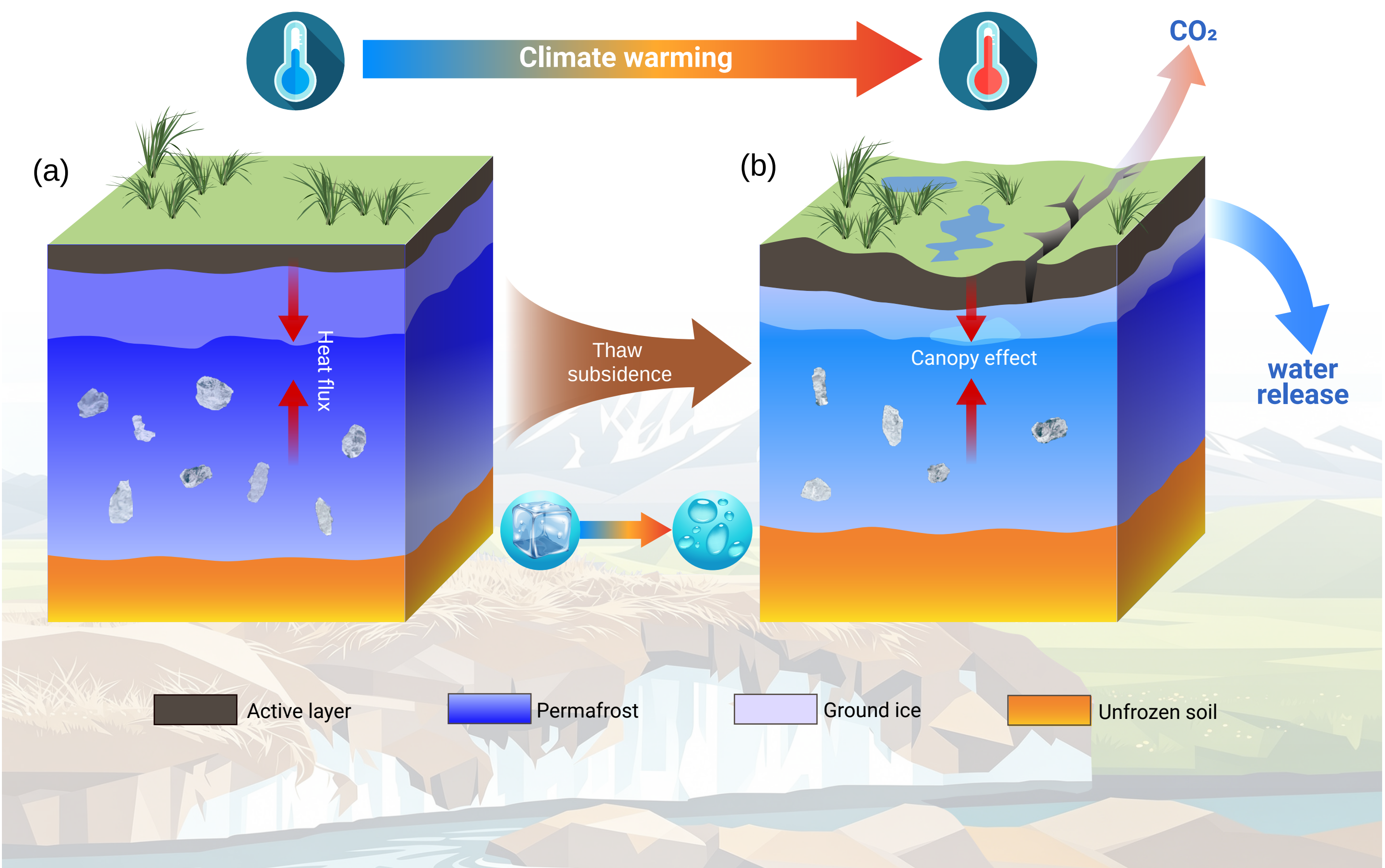
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Melting ground ice leads to thaw subsidence, accelerating permafrost loss under warming.
- Thaw subsidence can make complete permafrost loss occur decades earlier than expected.
- More than 88% of absorbed energy is used to melt ground ice, not simply warm the soil.
- Earth system models should include thaw subsidence to improve permafrost-related water and carbon simulations.

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One of the major issues associated with degrading permafrost is thaw subsidence caused by the melting of ground ice. This process has great impacts on engineered structures, hydrological cycles, the carbon cycle, and energy processes under climate change. However, accurately representing thaw subsidence in permafrost dynamics still poses a significant challenge for Earth system models (ESMs). In this study, we used a moving-grid permafrost model (MGPM) incorporating heat transfer processes, the ground ice melting process, and thaw subsidence processes to project that the rates of increase in cumulative thaw subsidence will be 0.43 m/decade, 0.58 m/decade, and 0.77 m/decade under the SSP1-2.6, SSP4-6.0, and SSP5-8.5 scenarios, respectively. On average, accounting for thaw subsidence accelerates the complete degradation of permafrost by over 17 years across future scenarios with varying ground ice conditions. This mainly manifests in the marked acceleration of upward degradation of permafrost due to the warming of the upper boundary, which obstructs the upward transfer of geothermal energy from the lower boundary, creating a canopy effect. When thaw subsidence is accounted for, the initial energy consumed by ground ice melting increases substantially—absorbing 7% more energy on average—thereby accelerating permafrost thinning. Moreover, incorporating thaw subsidence leads to faster release of meltwater from ground ice and accelerated thawing of permafrost-stored carbon. By quantifying its effects, this study enhances understanding of permafrost degradation and its consequences. These findings underscore the need to integrate thaw subsidence into Earth System Models (ESMs) to improve permafrost simulations.

INTRODUCTION

With climate warming, significant and widespread permafrost degradation has occurred globally.[1-5] Permafrost degradation is mainly characterized by an increase in the active layer thickness, an increase in ground temperature, and a contraction in the distribution of permafrost.[1,2,6,7] Another prominent feature of degradation is the melting of ground ice, which can lead to thaw subsidence and subsequently affect hydrological processes and landscapes, altering the carbon cycle, and threatening the stability of infrastructure.[8-11] Over the years, many studies have focused on improving permafrost modeling to better assess the climate implications of future permafrost thaw.[12,13] However, these efforts are complicated by the limitations of current models, which still do not incorporate important factors such as ground ice and thaw subsidence.[12,14,15] Ice-rich permafrost exhibits amplified subsidence toward the end of an exceptionally warm summer,[16] and the exclusion of key permafrost processes from ESMs introduces substantial uncertainty in quantifying thaw-induced carbon emissions.[14,17-19]

Among permafrost thaw consequences, ground subsidence emerges as a key process driving landscape reorganization and carbon mobilization. Incorporating this process into ESMs would facilitate a better understanding of rapidly changing permafrost environments and any resulting climate feedback.[15,17,20] Indeed, some studies have tried to improve models of permafrost systems by considering the effects of melting ground ice and thaw subsidence.[21-23] These models have generally indicated that permafrost tables will move closer to the ground surface, resulting in more intense permafrost thawing.[22,24,25] These developments constitute significant progress in the simulation of thaw subsidence,[21,23,25,26] with the inclusion of thaw subsidence allowing for a more realistic evaluation of permafrost thaw dynamics. Despite the importance of this feedback, its specifics remain poorly constrained because permafrost dynamics still pose a significant challenge for ESMs.[14] Thaw subsidence and its effects are nonlinear processes, and due to limited monitoring data, it is difficult for current ESMs to accurately simulate these processes, making it impossible to fully anticipate the effects of permafrost degradation, not to mention the related energy, hydrological, and carbon cycling processes.[15,17,20,22] Furthermore, numerical models used for permafrost change projections do not consider the water release and thaw of permafrost carbon caused by thaw subsidence.[21,25] Therefore, accurate simulation of thaw subsidence dynamics requires mechanistic understanding of permafrost degradation processes and their cascading impacts.[17,20]

Previous study has observed widespread thaw subsidence across permafrost regions with rates of up to 2 $cm \cdot yr^{-1}$ in the areas with low ice content and more than 3 $cm \cdot yr^{-1}$ in regions with ice-rich permafrost.[20] This clearly indicates that thaw subsidence will play an increasingly important role under warming climatic conditions.[20,27] However, there is still no consensus on the long-term effects, with one study has revealed that the positive feedbacks between subsidence and thaw is self-limiting over decadal time scales due to drier tundra with weaker surface/atmosphere coupling.[28] Therefore, how thaw subsidence affects energy transfer processes, ground ice-water release processes, and carbon release processes during permafrost degradation remains unclear. The absence of a detailed and accurate representation of this process introduces systematic biases in models of permafrost dynamics and compromises the reliability of future permafrost carbon emission assessments.[15,17,20] To address this, ESMs should incorporate the thaw subsidence in permafrost modeling to quantitatively reveal the influence of thaw subsidence on permafrost-related processes due to the melting of ground ice during permafrost degradation. This will help improve simulations of permafrost change processes and reduce the uncertainties in permafrost carbon emissions estimates in future climate projections.[14,15,17]

In this study, we use a moving-grid permafrost model (MGPM), which has been validated and shown good performance in permafrost regions on the Qinghai-Tibet Plateau.[6,22,29,30] The model couples the moving-grid method with simulations of heat transfer processes, ground ice melting processes, and thaw subsidence processes. This allows for further quantification thaw subsidence effects on permafrost degradation processes, including energy transfer, ground ice meltwater fluxes, and carbon release dynamics. Our objective was to assess the impact of thaw subsidence on permafrost degradation and related processes. The model incorporates standard climate projections to simulate ground temperature down to 100 m below the surface and focuses on the effects of thaw subsidence with different ground ice contents on permafrost degradation and its impact (Text S1). Specifically, we (1) examine the effects of thaw subsidence on the thermal state and degradation of permafrost, and (2) quantitatively estimate the effects of thaw

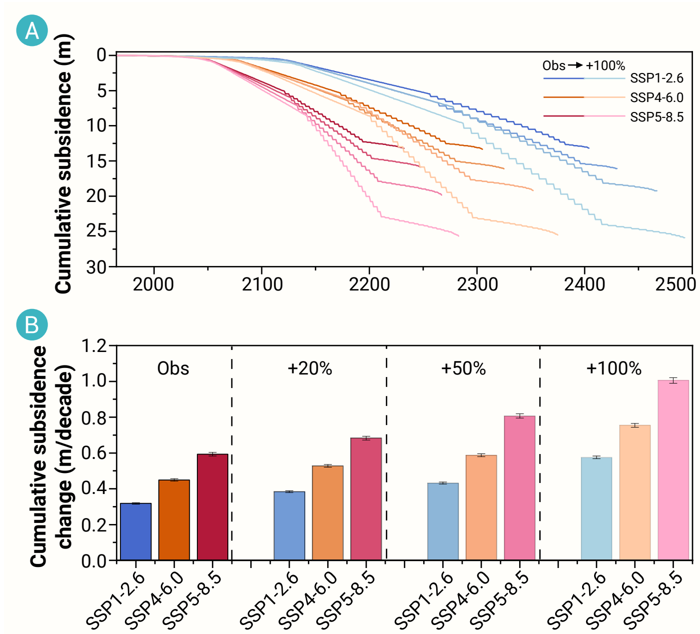

Figure 1. Cumulative thaw subsidence (A) and rate of change in cumulative thaw subsidence; (B) under different climate scenarios at the Wudaoliang site The labels "Obs", "+20%", "+50%", and "+100%" denote the observed ground ice content and the respective increases above this level.

subsidence on energy consumption and the release of water and carbon under different ground ice content scenarios.

MATERIALS AND METHODS

Study area

In this study, boreholes at the Wudaoliang site (35.22°N, 93.08°E; altitude 4,783 m) with long-term ground temperature observations at different depths above the permafrost base were selected for analysis. This data spanned from 2012 to 2022. The Wudaoliang sites with permafrost thicknesses greater than 65 meters are located in the hinterland of the Qinghai-Tibet Plateau in the continuous permafrost region (Figure S1). Ground temperatures in boreholes were measured using thermistors (an accuracy of ± 0.1°C; produced by the State Key Laboratory of Frozen Soil Engineering, Cold and Arid Regions Environmental and Engineering Research Institute of the Chinese Academy of Sciences (SKLFSE, CAREERI, CAS)), which automatically recorded data each hour using loggers CR10X/CR1000/CR3000 (Campbell Company, USA).[6] The volumetric ice content in this paper was obtained through lithological analysis of drill cuttings collected during drilling operations, using the liquid displacement method. Extensive ground ice deposits (volumetric ice content > 30%) occur near the active layer-permafrost interface at Wudaoliang, exhibiting pronounced cryostratigraphic heterogeneity with depth (Figure S2).[22]

Moving-grid permafrost model (MGPM)

The MGPM model is designed to study permafrost changes with thaw subsidence.[22] This model can simulate soil columns tens to hundreds of meters in height, with a centimeter-scale vertical resolution. The detailed output of this model facilitates direct verification through field measurements at the site level, allowing the annual dynamics in active layer thickening and permafrost temperature field variations under climate warming to be discerned. Notably, the model features a flexible thaw subsidence computation module that can be activated or deactivated to accommodate permafrost simulations with and without the inclusion of thaw subsidence.[22,31] Detailed information regarding the forcing data, associated parameters, and model validation has been thoroughly described in previous articles.[19,22,25,30] The lower boundary is set at a depth of 100 m, with the observed mean annual geothermal heat flux—0.08 W/m^2 at Wudaoliang—applied as the lower boundary condition.[25]

Tracking ground surface displacement due to thaw subsidence is also a classic moving boundary problem, which can be addressed using the Lagrangian method. This variable space-step moving-grid technique dynamically adjusts spatial grid nodes over time to accommodate changes in the computational domain's shape, enabling the precise and explicit calculation of moving boundary evolution. The calculation method is as follows:

$$S = \alpha(H_t - H_0) \tag{1}$$

$$\alpha = A(\theta - \theta_0) \tag{2}$$

where S represents the thaw subsidence caused by permafrost thawing; α is the thawing subsidence coefficient depending on the soil texture parameter A; H_0 and H_t are the calculated thickness of the frozen soil layers before and after ground ice melting; and θ and θ_0 are the volumetric ice content and critical volumetric ice contents for thaw subsidence. A and θ_0, which cannot be directly measured, are selected from the previous references.[22,25]

In the thaw subsidence computation module, the soil column is divided into finite variable spatial meshes following Hooke's law, just like an elastomer. The ground surface is defined as a dynamic boundary.[22] At each time step, the governing equation for thaw subsidence is solved to determine the displacement of each grid node, while preserving the original topology and count of the deformed grid cells. The total thaw settlement is then calculated by summing the deformations of all spatial grid cells during the model's execution. The displacement equation used to calculate the domain nodes in a unit time step is as follows:

$$\begin{cases} \Delta z_i = z_i^{new} - z_i^{old} = \Delta S_{ij}, h_{table}^{old} < z_i < h_{table}^{new} \\ \Delta z_i = \Delta S = \sum S_{ij}, \qquad 0 < z_i \le h_{table}^{old} \\ \Delta z_i = 0, z_i \ge h_{table}^{new} \end{cases} \tag{3}$$

where Δz_i is the displacement of node i; z_i^{new} and z_i^{old} are the spatial positions of node i before and after displacement; h_{table}^{old} and h_{table}^{new} are the permafrost table depths before and after ground ice melting; ΔS_{ij} is the amount of subsidence and compression caused by the melting of ground ice in the spatial mesh composed of node i and adjacent node j in this unit time step, as calculated by control Equations (1) and (2); and ΔS is the thaw subsidence amount, which is the sum of the melting settlement compression amount generated by all the spatial meshes where ground ice melting occurs.

Estimated water release from melted ground ice

The calculation of water released from melting ground ice is based on the latent heat required to convert ice to water, the equation is as follows:

$$q = \sum_{i}^{n} Q_i / L \tag{4}$$

where q is the cumulative water release from melted ground ice (m^3/m^2); Q_i is the latent heat required to convert ice to water (MJ/m^2); and L is the volumetric latent heat from the ice–water phase transition (334.54 MJ/m^3).

Estimated thawed permafrost carbon

Because observation data on permafrost carbon stocks are only available from 2 to 18 m deep,[32] the carbon stock data from 18 to 40 m are estimated based on the functional relationship between depth and the observed data established in Figure S3; the data from 40 m to the permafrost base are estimated based on the functional relationship for deep permafrost carbon stocks established by Mu et al (2015).[32] It is also assumed that, in the process of permafrost degradation, the carbon of each layer of permafrost is released once the permafrost thaws. The cumulative soil organic carbon released due to permafrost thaw at all depths is the cumulative thawed permafrost carbon.

RESULTS

Thaw subsidence cannot be ignored under climate change

Climate-driven permafrost degradation induces ground ice melt, generating thaw subsidence that exhibits a positive correlation with ice content. This trend intensifies across emission scenarios, with progressively greater subsidence from SSP1-2.6 to SSP5-8.5 scenario (Figure 1A). It can be seen that,

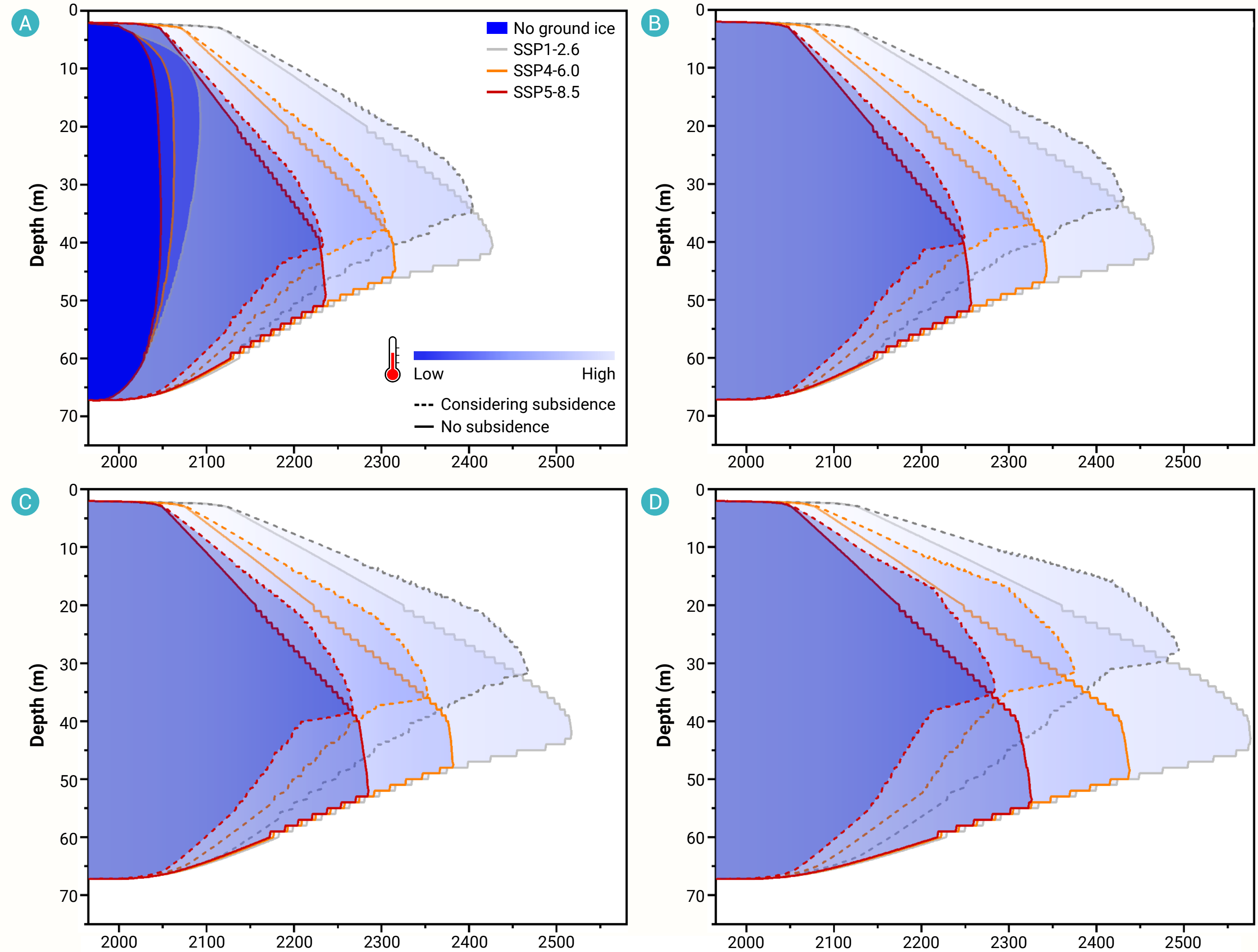

Figure 2. Permafrost degradation process under different climatic scenarios with different ground ice conditions at the Wudaoliang site (A) Observed ground ice; (B) +20% ground ice; (C) +50% ground ice; and (D) +100% ground ice. The labels (+20%, +50%, +100%) correspond to those in Figure 1. The blue shading represents permafrost regions.

with actual ground ice contents, thaw subsidence upon the complete degradation of permafrost is expected to exceed 13 m, but if the ground ice content is doubled, thaw subsidence due to the complete melting of ground ice would exceed 25 m (Figure 1A). Initially, thaw subsidence is a slow process, but it accelerates significantly when more ground ice melts. The degree of thaw subsidence upon the complete melting of ground ice, given the same ground ice content, is essentially consistent. However, thaw subsidence occurs at different rates under different climate scenarios (Figure 1A). The rate of cumulative thaw subsidence increases gradually from scenario SSP1-2.6 to SSP5-8.5; it also increases progressively with increasing ground ice content (Figure 1B). The maximum cumulative thaw subsidence rate exceeds 1.00 m/decade under the SSP5-8.5 scenario with doubled ground ice content, whereas the cumulative thaw subsidence rate is relatively slow across a range of different ground ice contents in the SSP1-2.6 scenario (Figure 1B). On average, the rates of increase in cumulative thaw subsidence were 0.43 m/decade, 0.58 m/decade, and 0.77 m/decade for scenarios SSP1-2.6, SSP4-6.0, and SSP5-8.5, respectively.

Thaw subsidence accelerates permafrost degradation

The results showed that permafrost degradation significantly accelerates when thaw subsidence is incorporated, mainly manifesting in the marked acceleration of upward degradation of permafrost (Figures 2A-D). The time taken until the complete degradation of permafrost with and without accounting for thaw subsidence decreases gradually from the low to high emission scenarios (Figures 2A-D). The time to complete degradation of permafrost is also shortened with increasing ground ice content after accounting for thaw subsidence, especially in the SSP1-2.6 scenario, where the time at which complete degradation of permafrost occurs advances by more than 80 years with a 100% increase in ground ice content (Figure 2D). On average, the time at which complete degradation of permafrost occurs with different ground ice content under scenarios SSP1-2.6, SSP4-6.0, and SSP5-8.5 is advanced by 47, 29, and 17 years, respectively, when thaw subsidence is considered. Furthermore, the permafrost table is significantly shallower, and the thawing of the permafrost base accelerates upwards when thaw subsidence is accounted for, indicating that thaw subsidence will lead to increasing rates of permafrost thinning (Figures 2A-D).

Accounting for thaw subsidence reveals contrasting dynamics in permafrost boundary evolution, while permafrost table thickening slows considerably, permafrost base thawing accelerates markedly. This divergence amplifies with ground ice content - doubling ice content reduces the average permafrost table decline rate from 0.95 to 0.65 m/decade while increasing the average base thaw rate from 0.41 to 1.07 m/decade, when thaw subsidence is considered (Figure 3D). Accounting for thaw subsidence, the average permafrost table decline rate decreases from1.09 to 0.85 m/decade, while the average permafrost base thaw rate increases from 0.55 to 1.04 m/decade across climate scenarios and ground ice conditions (Figures 3A-D).

Thaw subsidence causes more energy to enter the permafrost layer

The energy that enters the permafrost layer during permafrost simulations

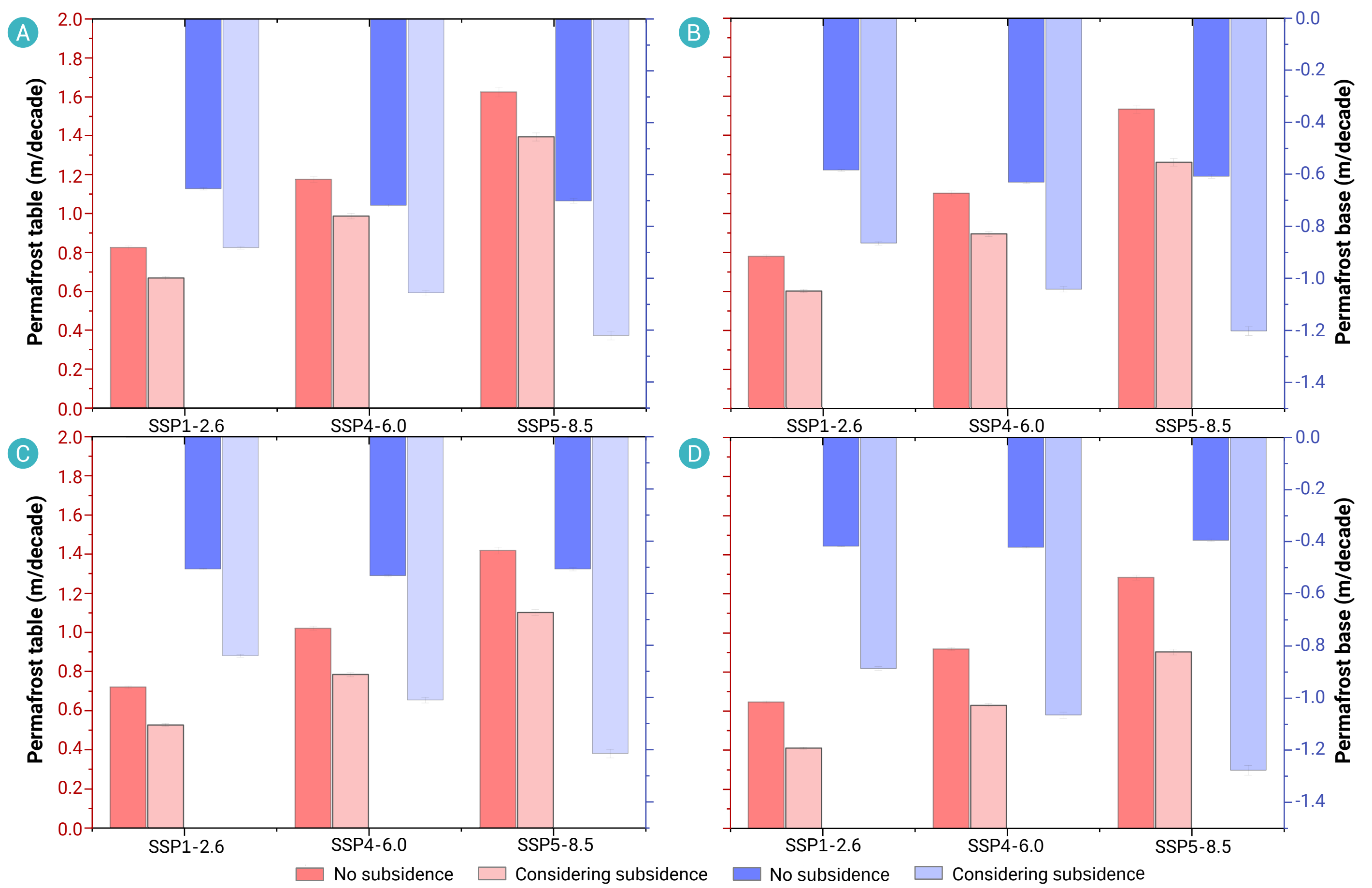

Figure 3. Changes in the permafrost table and base under different climate scenarios with and without thaw subsidence at the Wudaoliang site (A) Observed ground ice; (B) +20% ground ice; (C) +50% ground ice; and (D) +100% ground ice. The labels (+20%, +50%, +100%) correspond to those in Figure 1.

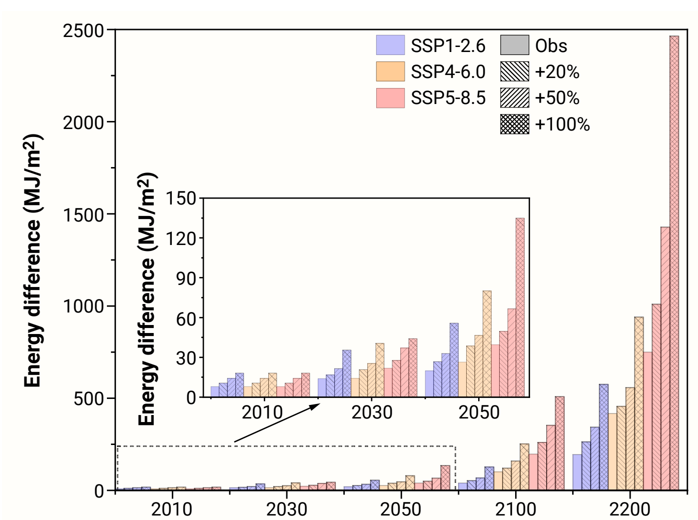

Figure 4. Difference in energy absorption considering thaw subsidence and not considering thaw subsidence at the Wudaoliang site The labels (Obs, +20%, +50%, +100%) correspond to those in Figure 1.

is also underestimated if ground subsidence is not considered. The difference between the cumulative energy with and without considering thaw subsidence becomes much larger as ground ice increases (Figure 4). More energy is absorbed when considering thaw subsidence than when it is not considered, and this difference in cumulative energy increases gradually from scenario SSP1-2.6 to scenario SSP5-8.5. The difference in energy absorption reaches 194.16 MJ/m^2, 417.46 MJ/m^2, and 750.54 MJ/m^2 under actual ground ice content conditions by 2200 under the SSP1-2.6 scenario, and exceeds 2,400 MJ/m^2 by 2200 under the SSP5-8.5 scenario when ground ice is doubled (Figure 4). On average, the difference in cumulative energy under different ground ice content conditions by 2200 reach 343.56 MJ/m^2, 593.07 MJ/m^2, and 1,413.41 MJ/m^2 for the SSP1-2.6, SSP4-6.0, and SSP5-8.5 scenarios, respectively. This will lead to more ground ice melting and the permafrost thawing, accelerating the permafrost degradation process.

The energy that enters the permafrost is used to increase the ground temperature and melt the ground ice. Accounting for thaw subsidence and disregarding subsidence energy consumption have the opposite effects; more energy goes toward increasing the ground temperature and less for ground ice melting in all scenarios when subsidence is not considered than when it is considered before 2200. Still, the energy that goes to increasing ground temperature and melting ground ice tends to be equal in both scenarios by the time permafrost is fully degraded (Figure 5). For different ground ice contents under scenarios SSP1-2.6, SSP4-6.0, and SSP5-8.5, the cumulative energy absorbed upon complete ground ice melting was more than 85%. On average, across all future scenarios, when thaw subsidence is or isn't considered, only about 10% of the energy absorbed goes to increasing ground temperature, while more than 88% of the energy goes to ground ice melting. It is worth noting that the energy consumed by ground ice melting is much greater at the outset when thaw subsidence is considered, taking up 7% more energy on average, which can result in the early and complete melting of the ground ice and an accelerated rate of thinning of the permafrost layer.

Thaw subsidence enhances ground ice meltwater release

The rates of water released increase due to ground ice melting increases after considering thaw subsidence for all ground ice content conditions (Figures 6A-D). Cumulative water release ranged from 12.79 to 25.52 m^3/m^2 from scenario SSP1-2.6 to scenario SSP5-8.5 at different ground ice levels. With increasing ground ice, the rate of water release increases, and it takes longer for the ice to melt. The released water is a gradual and slowly acceler-

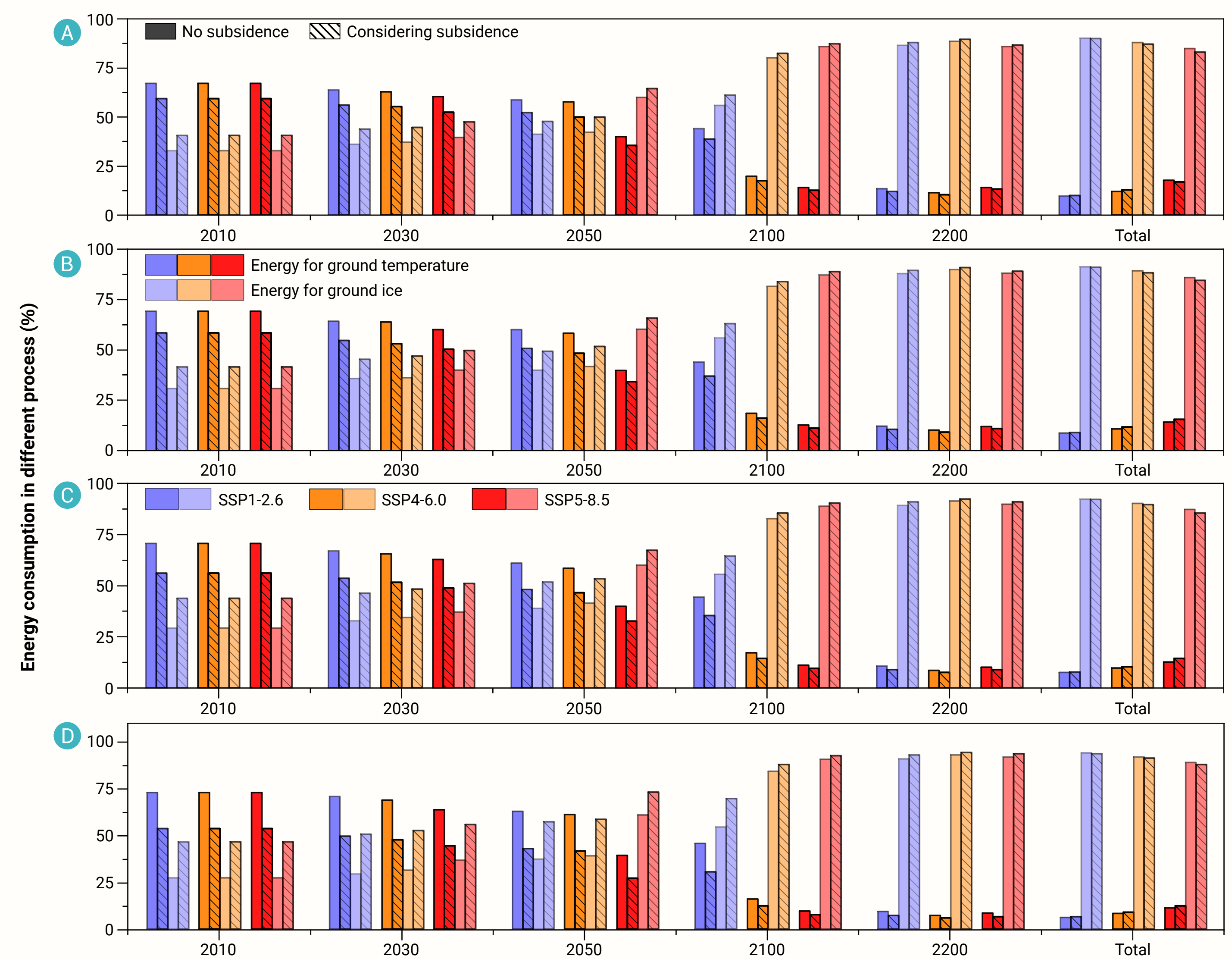

Figure 5. Proportion of total energy going to increasing ground temperatures and melting ground ice in permafrost under different ground ice content conditions at the Wudaoliang site (A) Observed ground ice; (B) +20% ground ice; (C) +50% ground ice; and (D) +100% ground ice. The labels (+20%, +50%, +100%) correspond to those in Figure 1. Total energy: cumulative energy required to degrade permafrost completely.

ating process (Figures 6A-D). In addition, the water release rate accelerated significantly after accounting for thaw subsidence, and this acceleration became more pronounced as ground ice content increased, with the maximum difference in rates reaching 0.024 m^3/m^2/year under the SSP5-8.5 scenario with a doubling of ground ice (Figures 6A-D). The rate of water release increases with increasing ground ice content, from a minimum of 0.028 m^3/m^2/year under the SSP1-2.6 scenario to a maximum of 0.103 m^3/m^2/year under the SSP8.5 scenario. On average, under different climate scenarios, the rates of water release with and without accounting for thaw subsidence were 0.046 and 0.040 m^3/m^2/year, 0.053 and 0.045 m^3/m^2/year, 0.062 and 0.051 m^3/m^2/year, and 0.080 and 0.060 m^3/m^2/year, when ground ice content was as observed and increased by 20%, 50%, and 100%, respectively.

Thaw subsidence accelerates the thawing of permafrost carbon

The cumulative thawed permafrost carbon rate increases when thaw subsidence is considered, as does the rate of permafrost carbon thawing. Furthermore, the acceleration of permafrost carbon thawing is greater when ground ice content is not considered, as much as four times faster without considering thaw subsidence, and more than 3.5 times faster with thaw subsidence considered (Figures S5a–d). This difference in thawing rate is mainly reflected in depths up to 20 m, and as the depth of the stored permafrost carbon decreases, and the permafrost carbon thawing slows. The cumulative thawed permafrost carbon rate reaches a maximum of 3.26 kg/m^2/year when ground ice is not taken into account, while it reaches maximums of 1.00 kg/m^2/year and 0.99 kg/m^2/year when thaw subsidence is and is not taken into account, respectively. On average, the permafrost carbon thawing rate under different future climate scenarios was 2.71 kg/m^2/year, 0.69 kg/m^2/year, and 0.73 kg/m^2/year, respectively, without the consideration of ground ice, and with and without accounting for thaw subsidence.

DISCUSSION

Significant thaw subsidence due to melting ground ice during permafrost degradation can damage buildings and infrastructure, cause irreversible ecological changes, and influence carbon cycling processes.[9,17,27,33] Previous results have revealed that thaw subsidence can reach 0.4 cm·yr^{-1} where ground ice content is low, and as high as 7.5 cm·yr^{-1} in ice-rich permafrost regions.[34,35] Our results project that permafrost thaw subsidence will exceed 13 m upon complete permafrost degradation when using actual ground ice content values, with rates of increase in cumulative thaw subsidence ranging from 0.43 m/decade to 0.77 m/decade under future climate scenarios (Figure 1). This process significantly affects the rate of degradation of permafrost in the context of climate change. This means that, because thaw subsidence can increase the active layer thickness, permafrost simulations that do not account for it may underestimate the original thickness of permafrost that has thawed because of miscalculations regarding the

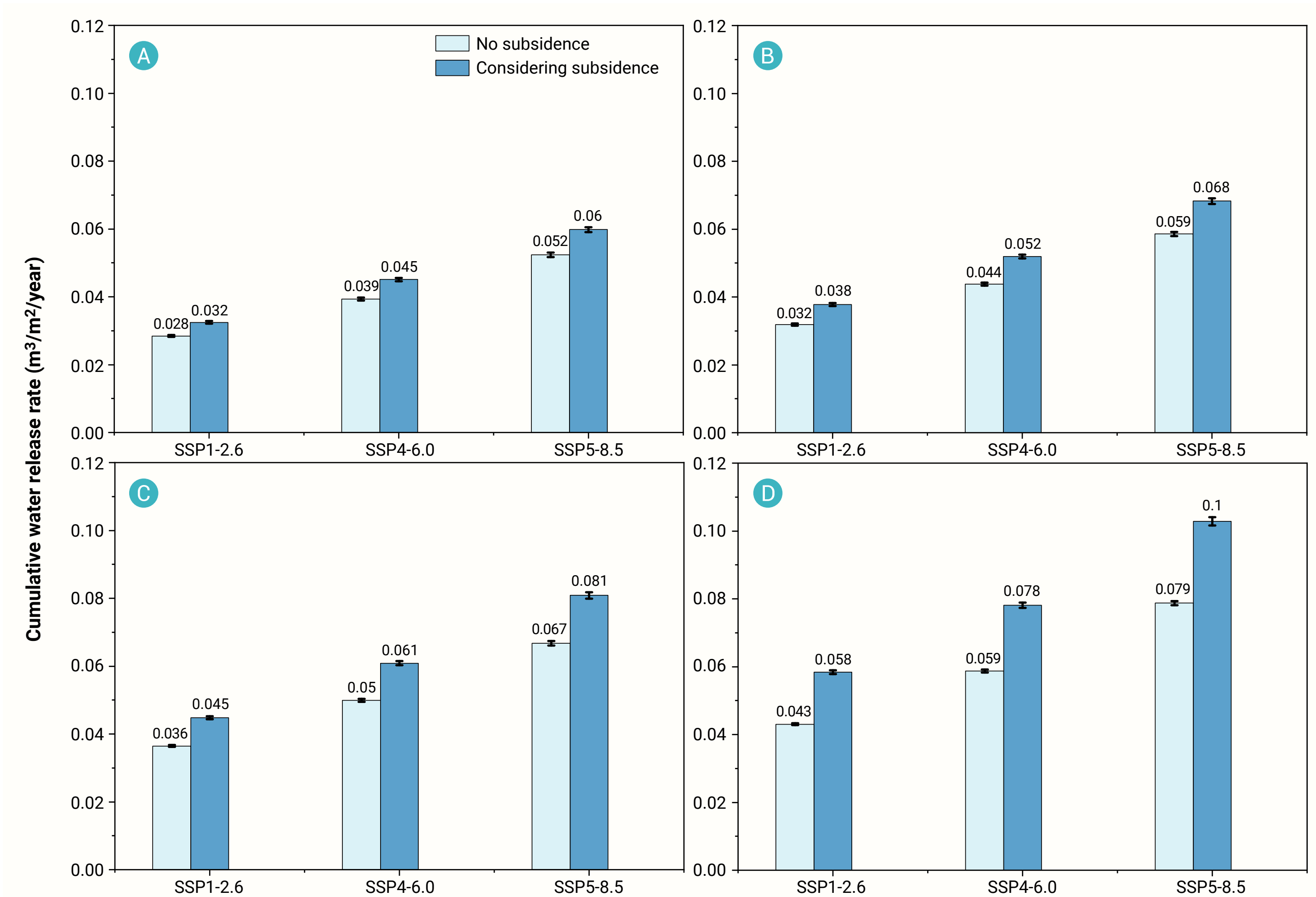

Figure 6. Change in water release from ground ice melted under different climate scenarios at the Wudaoliang site (A) Observed ground ice; (B) +20% ground ice; (C) +50% ground ice; and (D) +100% ground ice. The labels (+20%, +50%, +100%) correspond to those in Figure 1.

distance between the ground surface and permafrost layer, especially in permafrost regions with high ground ice content.[20,21,25] It has been confirmed that the rate of upward degradation of permafrost is significantly accelerated, the permafrost table declining is slowed, and the time to complete permafrost degradation is reduced when thaw subsidence is considered (Figures 2A-D). Therefore, thaw subsidence plays a key role in the permafrost change and can accelerate the rate of degradation of permafrost. However, a higher ground ice content may result in more substantial potential thaw subsidence when permafrost completely degrades (Figure 1).[20] This estimate involves some uncertainty, primarily because empirical settlement coefficients are usually derived from the active layer and may not accurately represent conditions in deeper permafrost. Additionally, thermal parameters for deep permafrost are also based on empirical data, which could potentially lead to overestimation of thaw subsidence.

Thaw subsidence can influence the energy that enters the permafrost layer during permafrost simulations.[21,22] The energy consumed increases when thaw subsidence is accounted for, but more than 88% of that energy goes to consumed in ground ice melting (Figure 5), which can lead to more ground ice melting and permafrost thawing in warm and ice-rich permafrost since most of the heat entering the soil layer is used for the phase change.[1,6,36] The latent heat required for the ice–water phase transition is much larger than the heat required to change the temperature in ice or water in ice-rich permafrost, which can delay deeper thawing and slow the active layer thickening rate.[6,37] This clearly demonstrates that ignoring thaw subsidence may lead to large quantities of heat in the energy budget being allocated to other climate system components rather than going to ice-rich permafrost thaw, which will affect the accuracy of regional climate modeling.[15,17,20,21,25] In addition, the rate of water release due to ground ice melting is also faster when thaw subsidence is considered (Figure 6). Indeed, previous studies have shown that thaw subsidence and ground ice melting are well correlated, which will lead to more ground ice meltwater in the hydrological cycle processes in permafrost regions.[38,39] This indicates that thaw subsidence will likely lead to more runoff and significantly accelerate drying in tundra landscapes in a warming climate.[28]

The estimates of carbon release from the thawing of ice-rich permafrost double when thaw subsidence is accounted for, compared to estimates obtained when only considering an increase in active layer thickness.[11] It is clear that the thawing of permafrost carbon is much faster when ground ice content is not considered, as much as four times faster when thaw subsidence is not considered, and more than 3.5 times faster when thaw subsidence is considered (Figures S5a–d). The main reason for the small difference in thawed permafrost carbon between models considering and not considering subsidence is that the soil carbon stocks at the Wudaoliang site are mainly concentrated within the top 15 m, and the soil carbon stocks decrease with increasing depth. Thaw-induced subsidence is often nonuniform and can influence the carbon cycle in permafrost regions.[28,39] Therefore, to comprehensively estimate the water release from ground ice melt and the thawed permafrost carbon and its feedback on the carbon cycle, it is necessary to quantify subsidence more broadly across permafrost regions.[11,15,17]

The results of the MGPM model simulations confirm that thaw subsidence not only has a significant effect on the rate of permafrost degradation, but it also affects the processes related to hydrology and the carbon cycle in permafrost regions. Earth system models should include the thaw subsidence process when modeling permafrost. Notably, thaw subsidence accelerated the rate of upward degradation of permafrost, possibly due to energy being transferred from bottom layers to the top. This indicates that the warming leads to permafrost thawing is not caused by top-down heating, but rather by the warming of the upper boundary obstructing the upward transfer of geothermal energy from the lower boundary (canopy effect). This means energy is not smoothly discharged from the soil layer to the atmosphere, and instead accumulates and causes permafrost to thaw.[19,40] Because thawing subsidence can enhance this canopy effect, it will further accelerate permafrost thawing and its effects.

These effects of subsidence increase over time as permafrost degrades. The energy change, water release, and thawing of permafrost carbon caused by thaw subsidence depend on the stage of permafrost degradation and, more specifically, on ground temperature and ground ice content.[25] These factors are also influenced on small spatial scales by differences in surface vegetation, soil properties, soil water content, and so forth.[20,22,37] While estimates of ground ice meltwater discharge and permafrost carbon storage in this study are subject to uncertainty—due to unrepresented drainage pathways and limited field data—they collectively emphasize the critical importance of explicitly accounting for thaw subsidence. In addition, the current model does not account for thermal convection-related processes, such as groundwater flow and the warming effect of surface water. Neglecting these non-climatic heating factors could underestimate permafrost degradation and its effects.[31] High-resolution simulations that consider soil moisture dynamics and include a widely applicable parameterized scheme for dynamic thawing subsidence coefficients—based on large amounts of laboratory experiments, site-scale observations, or catchment-scale observations—are expected to improve future modeling of permafrost change.[14,22]

CONCLUSION

Thaw subsidence is a widespread phenomenon in permafrost regions. This study demonstrates that thaw subsidence is a critical process that profoundly amplifies permafrost degradation under climate change. The results demonstrate that thaw subsidence exhibits a strong positive correlation with ground ice content—complete permafrost degradation could result in exceeding 25 m of subsidence under SSP5-8.5 if ice content is doubled, far exceeding predictions that ignore subsidence. Incorporating thaw subsidence advances the timing of complete permafrost loss by 17–47 years on average across scenarios, with the most pronounced effect (> 80 years earlier) occurring under low-emission (SSP1-2.6) conditions when ice content is high. Subsidence fundamentally alters permafrost boundary dynamics: while the permafrost table descends more slowly, basal thaw accelerates markedly upward, driving rapid thinning of the permafrost layer. Accounting for subsidence increases cumulative energy input into the permafrost with over 88% of absorbed energy used for ice melt rather than temperature rise—highlighting the dominant role of phase change. Consequently, meltwater release rates and permafrost carbon thaw are both enhanced, particularly in the upper 20 m, where subsidence-induced acceleration is most evident. These findings underscore those accurate projections of permafrost fate—and its associated hydrological shifts, carbon–climate feedbacks, and infrastructure risks in cold regions—require explicit representation of thaw subsidence in Earth system models. Neglecting this process leads to substantial underestimations in subsidence magnitude, thaw rates, energy absorption, meltwater discharge, and carbon mobilization.

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AUTHOR CONTRIBUTIONS

Guojie Hu and Zhe Sun contributed to the methodology, modeling, analysis, and writing. Guojie Hu, Lin Zhao, Defu Zou, Yao Xiao, and Guangyue Liu were responsible for conceptualization, methodology, funding acquisition, supervision, and writing. Chien-Lu Ping, Yifan Wu, Bowen Zhang, and Wenxin Zhang contributed to the analysis and interpretation of the results. Ren Li, Xiaodong Wu, Tonghua Wu, and Youqi Su contributed to data curation and result interpretation. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

The moving-grid permafrost model (MGPM) used is also available from Github (https://github.com/sunjack0227/moving-grid-permafrost-model/). The detailed parameterization process is described in previous studies.[29,30]

SUPPLEMENTAL INFORMATION

It can be found online at https://doi.org/10.59717/j.xinn-geo.2026.100242.