Li, Jialing; Wu, Chaoyang; Peñuelas, Josep; [et al.]. «The start of frozen dates over northern permafrost regions with the changing climate». Global change biology, Vol. 29, issue 16 (Aug. 2023), p. 4556-4568. DOI 10.1111/gcb.16752

The start of frozen dates over northern permafrost regions with the changing climate

Jialing Li[1], Chaoyang Wu[2,3*], Josep Peñuelas[4,5], Youhua Ran[6], Yongguang Zhang[1,7]

1. International Institute for Earth System Sciences, Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing University, Nanjing, 210023, China;
2. The Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, 100101, China;
3. University of the Chinese Academy of Sciences, Beijing, 100049, China;
4. CSIC, Global Ecology Unit CREAF-CSIC-UAB, Bellaterra, Barcelona 08193, Catalonia, Spain;
5. CREAF, Cerdanyola del Valles, Barcelona 08193, Catalonia, Spain;
6. Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
7. Jiangsu Provincial Key Laboratory of Geographic Information Science and Technology, Key Laboratory for Land Satellite Remote Sensing Applications of Ministry of Natural Resources, School of Geography and Ocean Science, Nanjing University, Nanjing, 210023, China;

***Corresponding author:** C Wu (wucy@igsnrr.ac.cn)

Abstract: The soil freeze-thaw cycle in the permafrost regions has a significant impact on regional surface energy and water balance. Although increasing efforts have been made to understand the responses of spring thawing to climate change, the mechanisms controlling the global interannual variability of the start date of permafrost freezing (SOF) remain unclear. Using long-term satellite observations of SOF between 1979–2020, and analytical techniques, including partial correlation, ridge regression, structural equation modelling (SEM), and machine learning, we explored the responses of SOF to multiple climate change factors, including warming (skin and air temperature), start date of permafrost thawing (SOT), soil properties (soil temperature and volume of water), and the snow depth water equivalent (SDWE). Overall, climate warming exhibited the maximum control on SOF, but SOT in spring was also an important driver of SOF variability; among the 65.9% significant SOT and SOF correlations, 79.3% were positive, indicating an overall earlier thawing. The machine learning analysis also suggested that apart from warming, SOT ranked as the second most important determinant of SOF. Therefore, we identified the mechanism responsible for the SOT-SOF relationship, and SEM analysis revealed that soil temperature change exhibited the maximum effect on this relationship, irrespective of the permafrost type. Finally, we analysed the temporal changes in these responses using the moving window approach and found increased effect of soil warming on SOF. Therefore, these results provide important insights into understanding and predicting SOF variations with future climate change.

Key words: start date of freezing; permafrost; climate warming; start date of thawing

1. Introduction

Permafrost occupies 25% of land in the northern hemisphere and is highly sensitive to climate change (Schuur et al., 2015; Obu et al., 2019; Smith et al., 2022). With warming three times the global mean, significant changes have been observed in the permafrost regions, which have affected the global carbon cycle and other environmental factors because the permafrost regions could release approximately half of the global soil carbon stock in the form of methane, carbon dioxide (Hugelius, et al., 2014; Vikhamar-Schuler et al., 2016; McGuire et al., 2018; Biskaborn et al., 2019; Irrgang et al., 2022), and other poisonous elements, such as mercury (Schaefer et al., 2020; Miner et al., 2021), that may threaten the infrastructure and ecosystems of the region (Nielsen et al., 2022; Ran et al., 2022a; Wang et al., 2022).

Several studies have reported the degradation of permafrost based on soil warming, deepened active layers, reduced permafrost extent, and decreased surface freezing duration (Biskaborn et al., 2019; Zhang et al., 2005; Peng et al., 2018; Li et al., 2022a; Ran et al., 2022b). The soil freeze-thaw cycle has significantly changed due to permafrost degradation, which has impacted the surface energy and water balance by influencing the hydrothermal properties of the soil; therefore, it has been considered as an indicator of the interactions between permafrost and climate change (Li et al., 2012; Smith et al., 2022). Permafrost thawing triggers emission of soil organic carbon (SOC), which accelerates global warming and impacts soil nutrients, river flow, and vegetation productivity (Grosse et al., 2011; Olefeldt et al., 2016; Mu et al., 2020; Liu et al., 2022; Rößger et al., 2022). Previous studies have investigated the impact of climate change on the start date of permafrost thawing (SOT) in spring (Chen et al., 2022), based on the importance of SOT in characterising land surface change and its effect on climate (Miner et al., 2021; Domine et al., 2022). For example, permafrost thawing causes a significant decline in water level, which could restructure the regional energy balance (Webb, et al., 2022). However, compared to the data on available on spring thawing, the start date of permafrost freezing (SOF) has not been substantially investigated. Therefore, research on SOF as an important permafrost-related factor will help in the elucidation of the underlying mechanisms and factors causing permafrost degradation. Moreover, the link between vegetation growth and SOF suggests that SOF plays an important role in bridging climate change and carbon uptake by the permafrost regions (Li et al., 2022b).

Therefore, to understand the impact of climate change on SOF on the permafrost regions of the northern hemisphere, we used long-term satellite-observed SOF data between 1979–2020 and data pertaining to various climate change variables, including skin temperature (T_{skin}), air temperature (T_{air}), SOT, soil temperature (T_{soil}), volume of water in soil (SWV), and the snow depth water equivalent (SDWE), to comprehensively analyse the response of SOF to climate change over the past four decades. The key objectives of our study were (1) to understand the impacts of climate change on the interannual variability of SOF; (2) to explore potential carry-over effects between thawing and freezing and their mechanisms; and (3) to analyse the temporal evolution of the strength of these climate change factors on SOF variability.

3. Results

3.1. Spatial and temporal patterns of SOF

We observed spatial variations in SOF over northern lands, with 75% SOFs ranging between day of year (DOY) 260 and 290 (Figure 4a). SOFs earlier than DOY 260 were observed in the northern Tibetan Plateau, whereas SOFs later than DOY 290 were mostly found in the boreal regions of Canada. Overall, the regions with earlier SOFs exhibited smaller standard deviations (SD). For example, large areas in Eurasia with an SOF between DOY 260–280 exhibited a lower SD of <15 days (Figure 4b). Moreover, 7.7% of the region exhibited significantly delayed SOF dates, whereas 8.6% of the region exhibited earlier SOFs (Figure 4c). Nevertheless, high-latitude permafrost regions exhibited delayed SOFs over the past four decades.

We also analysed climate change factors from to 1979–2020 and found warming in all permafrost regions analysed in this study based on significant increase in both T_{skin} (59.2%) and T_{air} (67.4%) (Figure 4d–e). However, 91.8% of all regions exhibited earlier SOT, among which data for 66.1% regions were significant (Figure 4f). Moreover, T_{soil} significantly increased in 70.5% of the regions that underwent significant soil warming (Figure 4g). The SWV exhibited an overall declining trend, with significant proportions for negative and positive trends of 16.5% and 8.2%, respectively. Similar results were observed for SDWE; 19.2% of the regions exhibited significant decrease in SDWE, whereas 4.7% of the regions exhibited an increasing trend (Figure 4i).

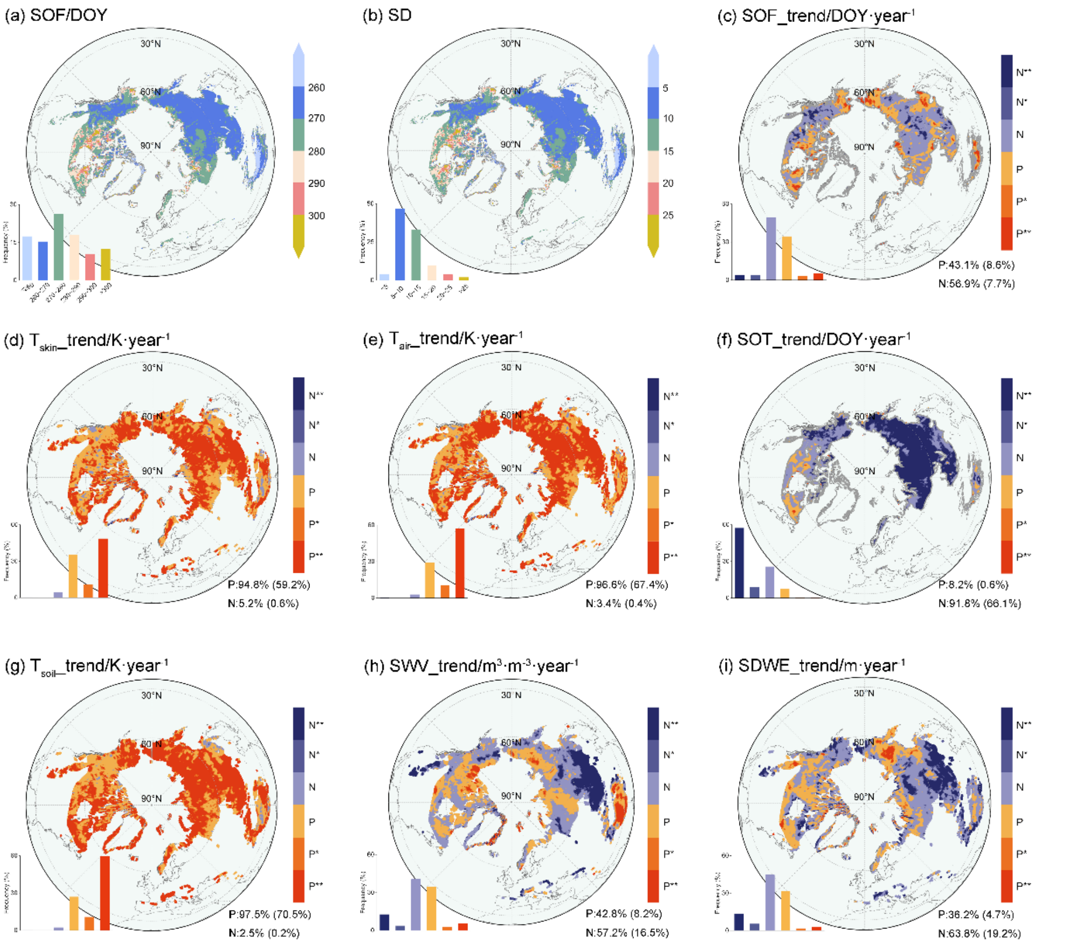

Figure 4 Spatial and temporal patterns of the start date of permafrost freezing (SOF) and trends in climate factors. a and b are SOF and its standard deviation (SD), whereas c represents its temporal trends between 1979–2020. d–f represent trends of skin temperature (T_{skin}), air temperature (T_{air}), start date of permafrost thawing (SOT), soil temperature (T_{soil}), volume of water in soil (SWV), and the snow depth water equivalent (SDWE). N and P indicate negative and positive correlations, respectively. ** and * represent significance at p=0.01 and p=0.05, respectively.

3.2. Relationship between SOF and climate change

We elucidated the relationships between SOF and climate factors using partial correlation analysis and found that T_{skin} was negatively correlated with SOF, and among the 89.3% negative correlations, 77.8% were significant (Figure 5a). However, T_{air} was positively correlated with SOF (Figure 5b). An overall positive correlation was also observed between SOT and SOF; 52.3% (out of 72.3%) of the regions exhibited a significant positive relationship between SOT and SOF (Figure 5c). Significant positive correlations were also found between SOF and T_{soil}, but both SWV and SDWE were negatively correlated with SOF (Figure 5d–f). We also determined the sensitivity of SOF to these factors using ridge regression analysis (Figure 5 g–l). The signs of the sensitivity values were consistent with those obtained through partial correlation analysis. For example, the slopes of the SOT-T_{skin} correlations were mostly negative, whereas an increase in T_{air} implied a later SOF, as shown by a positive sensitivity value. Moreover, we used machine learning techniques and found that T_{skin}-dominated SOF changed in 42% of the areas (Figure 5m). However, SOT was the second-most important determinant of SOF; SWV exhibited the least effect on SOF among all variables.

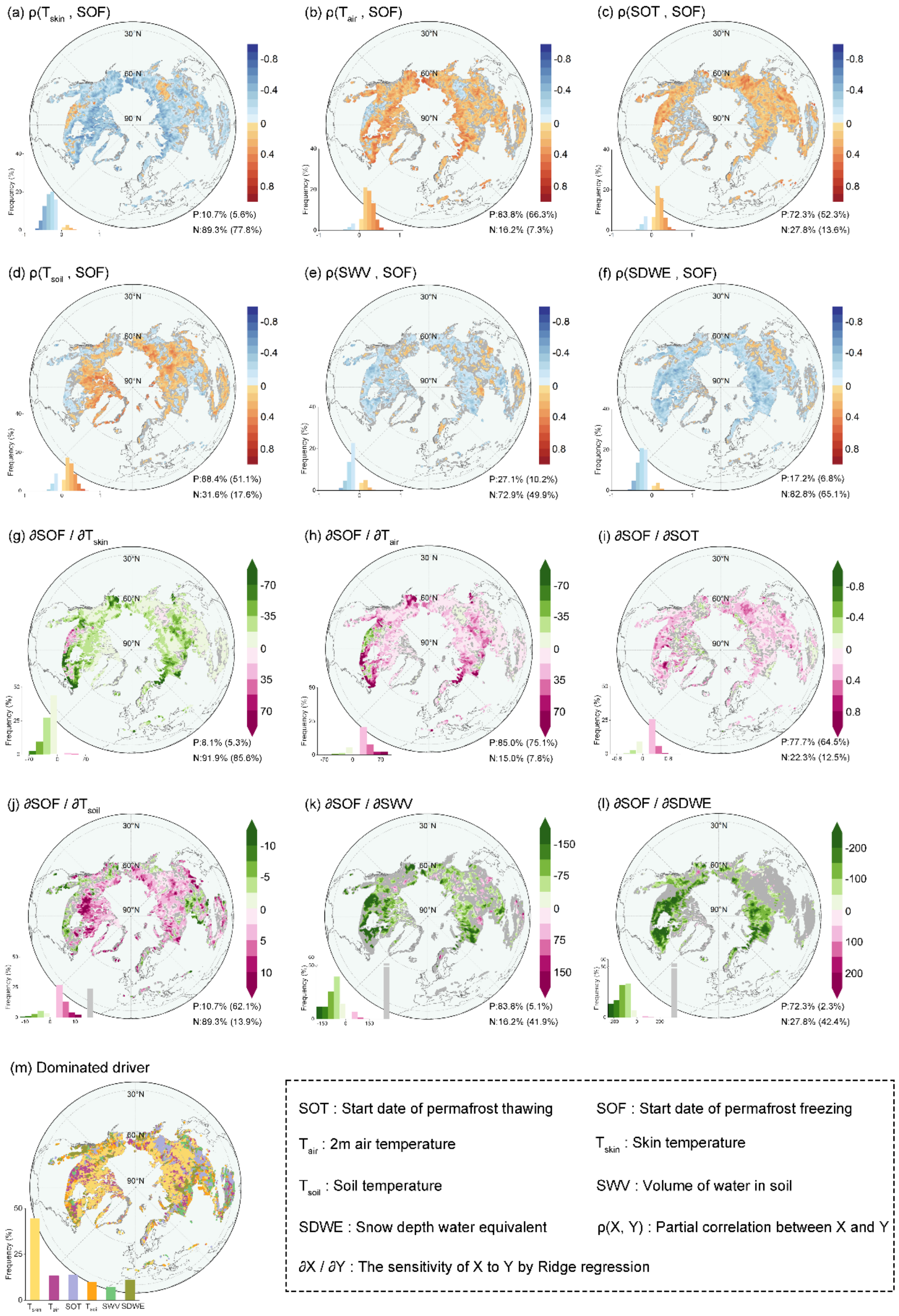

Figure 5 Partial correlations and sensitivities of the start date of permafrost freezing (SOF) and climate change. a–f are partial correlations between SOF and skin temperature (T_{skin}), air temperature (T_{air}), start date of permafrost thawing (SOT), soil temperature (T_{soil}), volume of water in soil (SWV), and the snow depth water

equivalent (SDWE); g–l represent their sensitivities. m shows the dominant factors for each grid as per the machine learning technique. Significance was set at p <0.05.

3.3. Underlying mechanisms of the correlation between SOT and SOF

We used structural equation modelling (SEM) path analysis to elucidate the underlying reasons for the correlation between SOT and SOF in different permafrost types to elucidate the changes expected in SOF in the future (Figure 6). We found that among the four paths through which SOT can be connected to SOF, the most important path was the positive correlation of SOT with T_{soil}, and because T_{soil} was positively correlated with SOF, SOT was positively correlated with SOF. These linkages were dominant in all paths and were independent of the permafrost type. Although changes in SWV explained changes in SOF, the overall impact of this path was minor.

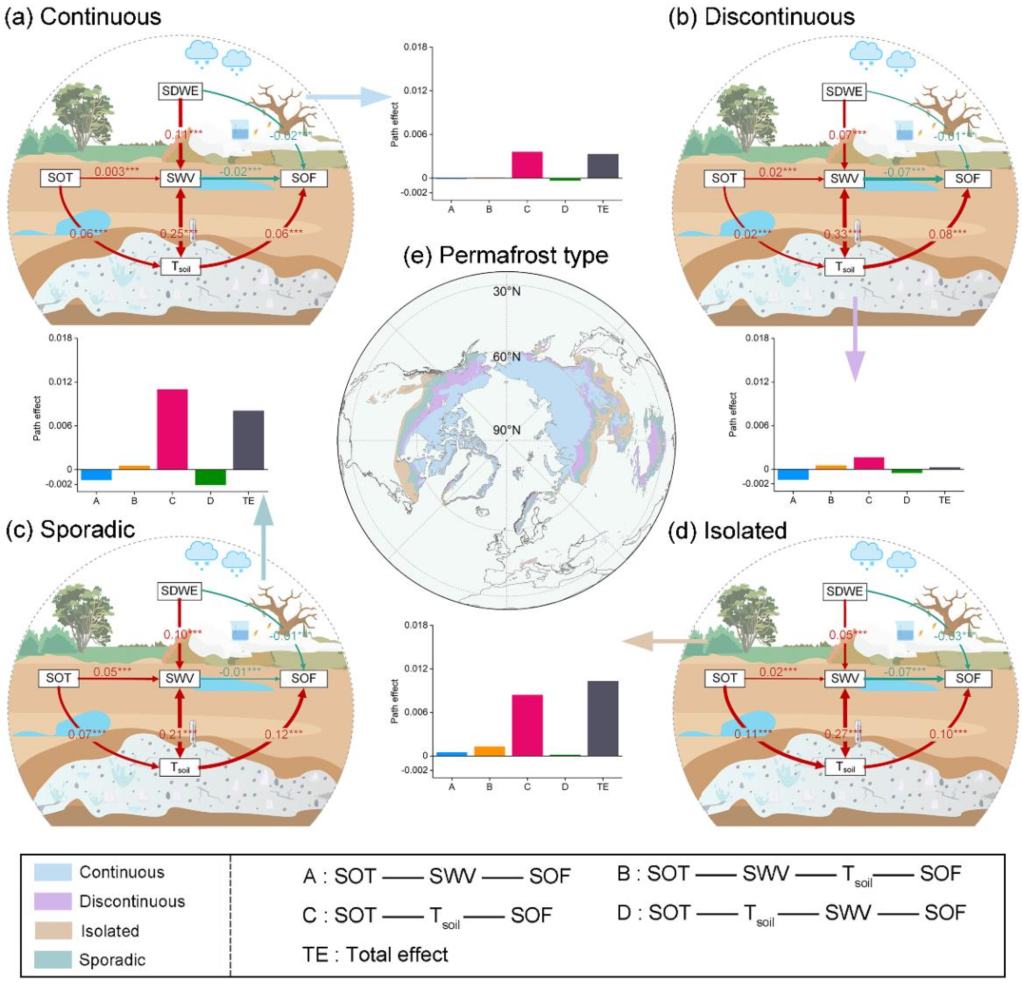

Figure 6 Structural equation models for the correlation between the start date of permafrost thawing (SOT) and start date of permafrost freezing (SOF). a–d represent results for (e) continuous, discontinuous, isolated, and sporadic permafrost types, respectively. T_{soil}, SWV, and SDWE are soil temperature, volume of water in soil, and snow depth water equivalent, respectively. * represent $p < 0.001$.**

3.4. Temporal changes in the response of SOF to climate change

We further analysed the temporal trends in the effect of these factors on SOF and changes in their sensitivity towards SOF (Figure 7). Overall, we found divergent patterns among (66.7%) regions where T_{skin} had a significant impact on SOF and 33.9% regions exhibited increased effect of T_{skin}; this proportion is comparable with that of the regions with reduced effect of T_{skin} (Figure 7a). Most of the regions exhibiting enhanced control of warming were located in the highlands of Eurasia (e.g. Siberia), whereas mid-latitude regions exhibited weakened control. Similar results were observed for T_{air}, SOT, SWV, and SDWE, but the proportion of the regions where these factors exhibited enhanced and weakened control varied. For example, T_{air} exhibited enhanced control of SOF in 34.8% of permafrost regions and 31.7% of counterparts. However, we found that the overall T_{soil} exhibited increased control over SOF, and among the 67.2% of regions where T_{soil} trends were significant, 42.8% exhibited enhanced control (Figure 7d). We further grouped the enhanced/weakened trends by permafrost type (Figure 8). We found that most of these factors, including T_{skin}, T_{air}, T_{soil}, and SWV, exhibited enhanced control on SOF for continuous permafrost, whereas SOT and SDWE exhibited the opposite effect. For the other three types (discontinuous, isolated, and sporadic), weakened control was more evident. However, T_{soil} was an exception, as it exhibited enhanced control in case of all permafrost types.

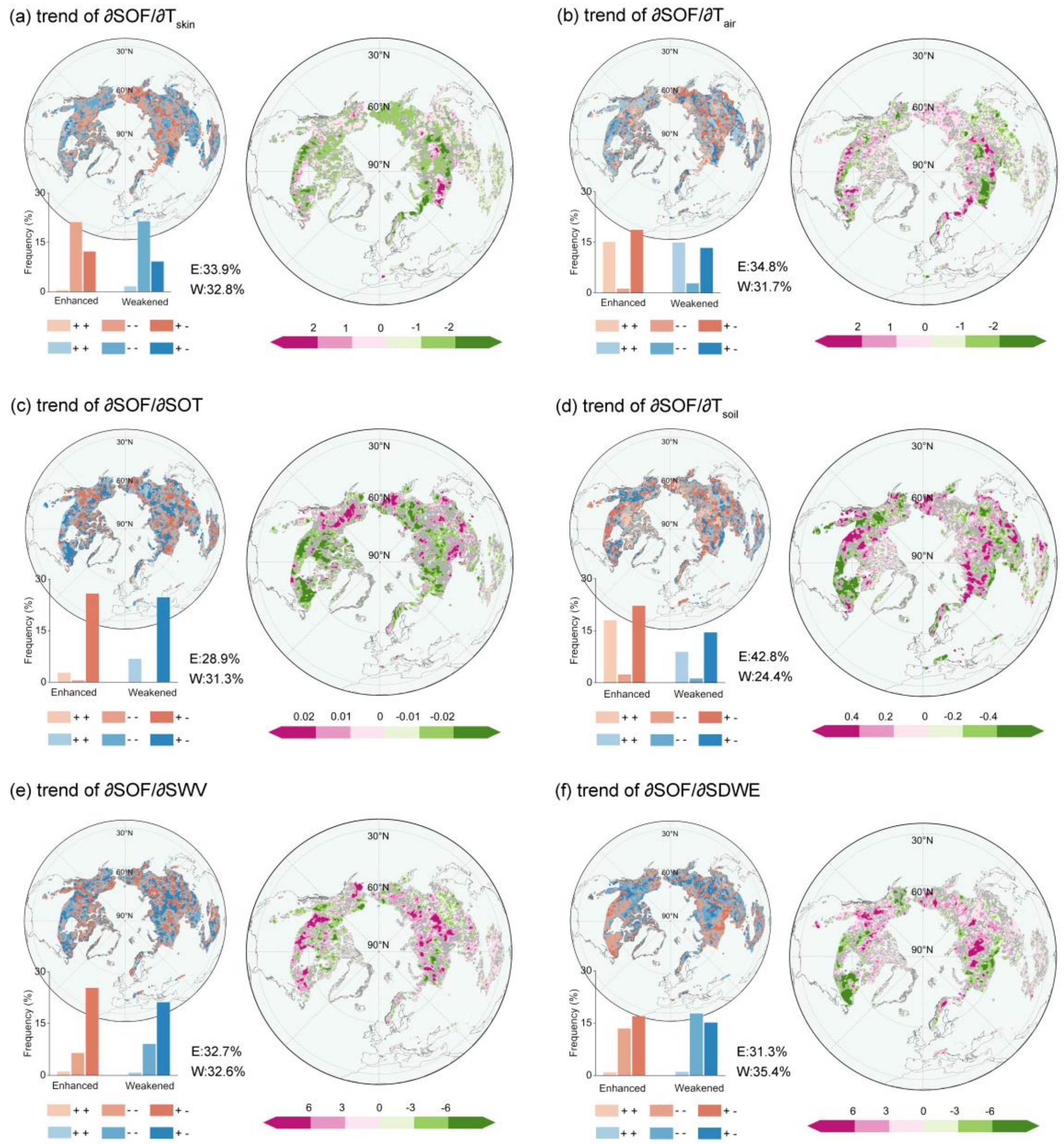

Figure 7 Spatial distribution and sensitivity of the temporal changes in climate change factors on the start date of permafrost freezing (SOF). a–f are spatial distributions of the enhanced and weakened regions and their slopes for skin temperature (T_{skin}), air temperature (T_{air}), start date of permafrost thawing (SOT), soil temperature (T_{soil}), volume of water in soil (SWV), and the snow depth water equivalent (SDWE). Significance was set at p <0.05.

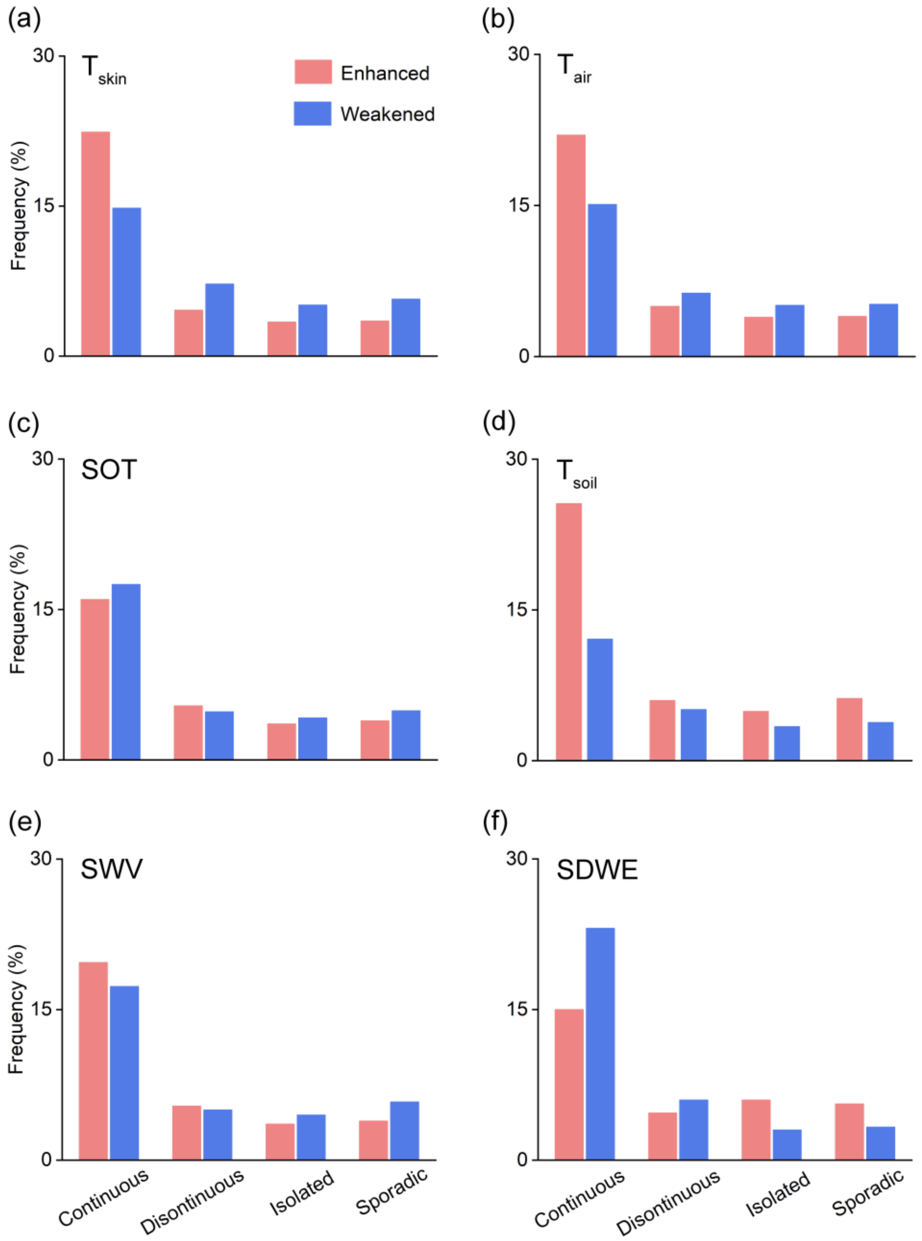

Figure 8 Effect of temporal changes in climate change factors on the start of date of permafrost freezing (SOF) according to permafrost types. a–f are spatial distributions of the enhanced and weakened regions and their slopes for skin temperature (T_{skin}), air temperature (T_{air}), start date of permafrost thawing (SOT), soil temperature (T_{soil}), volume of water in soil (SWV), and the snow depth water equivalent (SDWE).

4. Discussion

The timing of freezing represents a significant transition of the status of permafrost soil, and changes in the frozen/thawing processes significantly influence the hydrothermal properties of the soil, resulting in significant changes in the surface energy and water balance (Guo et al., 2011; Li et al., 2012; Smith et al., 2022; Webb et al., 2023). Previous studies have reported that permafrost thawing is highly sensitive to climate change, with far-reaching implications on regional climate and vegetation that can mitigate or amplify permafrost thawing (Jafarov et al., 2018; Polvani et al., 2020; Heijmans et al., 2022). Here, we elucidated the impacts of climate change factors on SOF in late autumn and winter, which has received much less attention than spring thawing in previous studies. We found that that the proportion of regions with significantly delayed and advanced SOF was comparable (8.6% vs. 7.7%, Figure 4c), but with clear spatial distribution. Delayed SOF was mostly observed in the highlands and the Tibetan Plateau, i.e. in areas with more pronounced warming, whereas earlier SOF was observed in the western boreal regions of Canada. Several climate change indicators were analysed in this study, which exhibited substantial impacts on SOF variability. These results contribute to a better understanding of permafrost change, given that the timing of freezing could impact snow-related soil warming in winter through biogeophysical feedbacks, such as changes in albedo and soil moisture (Li et al., 2022b); this could cause uncertainty in the evaluation of consequences of thaw-related disturbances (Heijmans et al., 2022). Moreover, SOF responded differently to these climate factors, and complicated patterns were observed; besides warming, other environmental cues (e.g. SWC, soil temperature) could also be responsible for SOF variability in the changing climate (Guo et al., 2012; Koven et al., 2013).

Global warming is the main driver of permafrost change, as it deepens the thickness of the active layer (Peng et al., 2018) and collapses the ground or thermokarst (Farquharson et al., 2019; Turetsky et al., 2020). Our results confirm the importance of global warming, as per the sensitivity of SOF to T_{skin}. Moreover, we identified the importance of SOT in regulating SOF variability. The overall positive correlation between SOF and SOT implies that an earlier thawing in spring could be associated with an earlier timing of freezing. These carry-over effects have been reported in previous phenological analyses (Fu et al., 2014; Xu et al., 2020; Shen et al., 2022); in accordance with these results, we observed a linkage between the thawing/frozen phenology of permafrost, which will be useful to obtain a comprehensive view of permafrost degradation. Using machine learning analysis, we found that SOT in spring was ranked as the second most important driver of SOF in the later years (Figure 5m), and this linkage can be explained by the changes in soil temperature, using the SEM path analysis for all permafrost types. Although the specific mechanism underlying this correlation is unclear, these results support previous reports on the importance of complex soil hydrothermal processes underlying permafrost degradation (Lawrence et al., 2005). Moreover, the positive correlation between SOT and SOF established in this study demonstrates that freezing/thawing cycle of a permafrost region can be understood based on soil warming and moisture changes throughout the year (Figure 6). Moreover, we observed increased effect of SOT on SOF at mid-low latitudes, where warming might not be that strong compared with highlands. This is important because mid-low latitude ecosystems have larger productivity, and including the SOT-SOF correlation could be useful in understanding the interaction between permafrost degradation and vegetation change.

We further identified the temporal evolution of the effects of different climate change factors on SOF variability; this will provide insights into the sensitivity of SOF to future climate change, although our current prediction of future scenarios regarding permafrost degradation could be biased (Webb and Liljedahl, 2023). We found differential changes in the sensitivity of SOF to most factors, but the differences were spatially distributed. Moreover, we observed a consistently increased control of T_{soil} on SOF, indicating an urgent need to investigate soil warming trends with respect to future climate change. Since warmer soil delays SOF (Figure 5d), the enhanced effect of T_{soil} on SOF could aggravate later freezing and accelerate permafrost degradation in the future. Our results are in line with the reported fast response of cold ice-rich permafrost to global warming (Nitzbon et al., 2020), considering that the enhanced regions are more in continuous permafrost (Figure 8d). Moreover, future studies should characterise soil types (Fisher et al., 2016), soil nutrition (Mao et al., 2020), and soil age (Tanentzap et al., 2021) to understand permafrost degradation under a changing climate.

ACKNOWLEDGMENTS: This work was funded by the National Natural Science Foundation of China (42125101) and the CAS Interdisciplinary Innovation Team (JCTD-2020-05). JP acknowledges support from the Spanish Government Grant TED2021-132627B-I00 funded by MCIN, AEI/10.13039/501100011033 European Union Next GenerationEU/PRTR, the Catalan Government Grant SGR2021-1333, and the Fundación Ramón Areces Grant CIVP20A6621.

References

Biskaborn, B.K., Smith, S.L., Noetzli, J. et al. (2019). Permafrost is warming at a global scale. Nature Communications, 10, 264. https://doi.org/10.1038/s41467-018-08240-4

Chen, X., Jeong, S., Park, C. E., et al. (2022). Different responses of surface freeze and thaw phenology changes to warming among Arctic permafrost types. Remote Sensing of Environment, 272, 112956.

Domine, F., Fourteau, K., Picard, G. et al. Permafrost cooled in winter by thermal bridging through snow-covered shrub branches. Nature Geoscience, 15, 554–560 (2022). https://doi.org/10.1038/s41561-022-00979-2.

Farquharson, L. M., Romanovsky, V. E., Cable, W. L., Walker, D. A., Kokelj, S., & Nicolsky, D. (2019). Climate change drives widespread and rapid thermokarst development in very cold permafrost in the Canadian High Arctic. Geophysical Research Letters, 2019GL082187. https://doi.org/10.1029/2019GL082187.

Fisher, J. P. , C Estop-Aragonés, Thierry, A. , Charman, D. J. , Wolfe, S. A. , & Hartley, I. P. , et al. (2016). The influence of vegetation and soil characteristics on active-layer thickness of permafrost soils in boreal forest. Global Change Biology, 22, 3127-3140.

Fu, Y., Campioli, M., Vitasse, Y., Boeck, H., Berge, J., Abdelgawad, H., et al. (2014). Variation in leaf flushing date influences autumnal senescence and next year's flushing date in two temperate tree species. Proceedings of the National Academy of Sciences, 111, 7355-7360.

Grosse, G. et al. (2021). Vulnerability of high-latitude soil organic carbon in North America to disturbance. Journal of Geophysical Research, Biogeosciences 116, 1–23.

Guo, D., Yang, M., & Wang, H. (2011). Characteristics of land surface heat and water exchange under different soil freeze/thaw conditions over the central Tibetan Plateau. Hydrological Processes, 25(16), 2531-2541.

Guo, D.,Wang, H., Li, D. (2012). A projection of permafrost degradation on the Tibetan Plateau during the 21st century, Journal of Geophysical Research Atmospheres, 117.

Heijmans, M.M.P.D., Magnússon, R.Í., Lara, M.J. et al. (2022). Tundra vegetation change and impacts on permafrost. Nature Reviews on Earth and Environment, 3, 68–84. https://doi.org/10.1038/s43017-021-00233-0

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., O’Donnell, J. A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., & Kuhry, P. (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. Biogeosciences, 11(23), 6573-6593. https://doi.org/10.5194/bg-11-6573-2014.

Irrgang, A.M., Bendixen, M., Farquharson, L.M. et al. Drivers, dynamics and impacts of changing Arctic coasts. Nature Reviews on Earth and Environment, 3, 39–54 (2022). https://doi.org/10.1038/s43017-021-00232-1

Jafarov, E., MacDougall, A. H., Marchenko, S., and Nicolsky, D.: Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change, Proceedings of the National Academy of Sciences, 115, 3882-3887, 2018.

Koven, C. D., Riley,W. J., and Stern, A. (2013). Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth System Models. Journal of Climate, 26, 1877-1900.

Lawrence, D. M. Slater, A. G. (2005). A projection of severe near-surface permafrost degradation during the 21st century, Geophysical Research Letters, 32.

Li, X., Jin, R., Pan, X., et al. (2012). Changes in the near-surface soil freeze–thaw cycle on the Qinghai-Tibetan Plateau. International Journal of Applied Earth Observation and Geoinformation, 17, 33-42.

Mao, C., Kou, D., Chen, L., Qin, S., Zhang, D., & Peng, Y., et al. (2020). Permafrost nitrogen status and its determinants on the tibetan plateau. Global Change Biology, 26(9), 5290-5302.

McGuire, A. D., Lawrence, D. M., Koven, C., Clein, J. S., Burke, E., Chen, G., et al. (2018). Dependence of the evolution of carbon dynamics in the northern permafrost region on the trajectory of climate change. Proceedings of the National Academy of Sciences, 115(15), 3882-3887. https://doi.org/10.1073/pnas.1719903115.

Miner, K.R., D'Andrilli, J., Mackelprang, R. et al. Emergent biogeochemical risks from Arctic permafrost degradation. Nature Climate Change, 11, 809–819 (2021). https://doi.org/10.1038/s41558-021-01162-y

Mu, C., Abbott, B. W., Norris, A. J., et al. (2020). The status and stability of permafrost carbon on the Tibetan Plateau. Earth-Science Reviews, 211, 103433.

Nielsen, D.M., Pieper, P., Barkhordarian, A. et al. Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. Nature Climate Change, 12, 263–270

(2022). https://doi.org/10.1038/s41558-022-01281-0.

Nitzbon, J., Westermann, S., Langer, M. et al. Fast response of cold ice-rich permafrost in northeast Siberia to a warming climate. Nature Communications, 11, 2201 (2020). https://doi.org/10.1038/s41467-020-15725-8.

Obu, J., Westermann, S., Bartsch, A., Berdnikov, N., Christiansen, H. H., Dashtseren, A., Delaloye, R., Elberling, B., Etzelmüller, B., Kholodov, A., Khomutov, A., Kääb, A., Leibman, M.O., Lewkowicz, A.G., Panda, S.K., Romanovsky, V., Way, R. G., Westergaard-Nielsen, A., Wu, T., et al. (2019). Northern Hemisphere permafrost map based on TTOP modelling for 2000–2016 at 1 km^2 scale. Earth-Science Reviews, 193, 299–316. https://doi.org/10.1016/j.earscirev.2019.04.023.

Olefeldt, D. et al. Circumpolar distribution and carbon storage of thermokarst landscapes. Nature Communications, 7, 13043 (2016).

Peng, X., Zhang, T., Frauenfeld, O. W., et al. (2018). Spatiotemporal changes in active layer thickness under contemporary and projected climate in the Northern Hemisphere. Journal of Climate, 31(1), 251-266.

Polvani, L. M., Previdi, M., England, M. R., Chiodo, G., & Smith, K. L. (2020). Substantial twentieth-century Arctic warming caused by ozone-depleting substances. Nature Climate Change, 1-4. https://doi.org/10.1038/s41558-019-0677-4.

Ran, Y., Cheng, G., Dong, Y. et al. Permafrost degradation increases risk and large future costs of infrastructure on the Third Pole. Communications Earth and Environment, 3, 238 (2022a). https://doi.org/10.1038/s43247-022-00568-6

Rößger, N., Sachs, T., Wille, C. et al. Seasonal increase of methane emissions linked to warming in Siberian tundra. Nature Climate Change, 12, 1031–1036 (2022).

Schaefer, K., Elshorbany, Y., Jafarov, E. et al. (2020). Potential impacts of mercury released from thawing permafrost. Nature Communications, 11, 4650. https://doi.org/10.1038/s41467-020-18398-5.

Schuur, E. A. G. et al. Climate change and the permafrost carbon feedback. (2015), Nature, 520, 171-179.

Shen, M., Wang, S., Jiang, N. et al. (2022). Plant phenology changes and drivers on the Qinghai–Tibetan Plateau. Nature Reviews on Earth and Environment, 3, 633–651. https://doi.org/10.1038/s43017-022-00317-5

Smith, S.L., O'Neill, H.B., Isaksen, K. et al. (2022). The changing thermal state of permafrost. Nature Reviews on Earth and Environment, 3, 10–23. https://doi.org/10.1038/s43017-021-00240-1

Tanentzap, A. J., Burd, K., Kuhn, M.K., C Estop-Aragonés, Tank, S.E. , Olefeldt, D. (2021). Aged soils contribute little to contemporary carbon cycling downstream of thawing permafrost peatlands. Global Change Biology, 27, 5368-5382.

Turetsky, M. R., Abbott, B. W., Jones, M. C., Anthony, K. W., Olefeldt, D., Schuur, E. A. G., Grosse, G., Kuhry, P., Hugelius, G., Koven, C., Lawrence, D. M., Gibson, C., Sannel, A. B. K., & McGuire, A. D. (2020). Carbon release through abrupt permafrost thaw. Nature Geoscience, 13(2), 138-143. https://doi.org/10.1038/s41561-019-0526-0.

Vikhamar-Schuler, D., Isaksen, K., Haugen, J.E., 2016. Changes in winter warming events in the nordic arctic region. Journal of Climate, 29, 6223–6244.

Wang, J., Liu, D. (2022). Vegetation green-up date is more sensitive to permafrost degradation than climate change in spring across the northern permafrost region. Global Change Biology, 28, 1569-1582.

Webb, E.E., Liljedahl, A.K. (2023). Diminishing lake area across the northern permafrost zone. Nature Geoscience, https://doi.org/10.1038/s41561-023-01128-z.

Webb, E.E., Liljedahl, A.K., Cordeiro, J.A. et al. (2022). Permafrost thaw drives surface water decline across lake-rich regions of the Arctic. Nature Climate Change, 12, 841–846 (2022). https://doi.org/10.1038/s41558-022-01455-w

Xu, X., Riley, W.J., Koven, C.D. et al. Earlier leaf-out warms air in the north. Nature Climate Change, 10, 370–375 (2020). https://doi.org/10.1038/s41558-020-0713-4