Response to Reviewer 2

In black: Reviewer's comments.

In blue: Response to reviewer.

In red: Revised manuscript.

This study attempted to investigate the impact of snow on winter ecosystem respiration from the perspective of the snow insulation effect. This is an interesting and significant topic given that numerous previous studies payed extensive attention to the effect of snowmelt water in spring and summer seasons. However, I find that the analyses of this study did not provide sufficient evidence to support its topic. Moreover, there are some problems regarding the methods.

We sincerely thank you for the thoughtful and constructive review. Your comments substantially improved the mechanistic clarity, causal coherence, and interpretive rigor of our study. In response, we (1) reframed the study's claims to avoid cross-domain impact comparisons and replaced them with an explicit mechanism-first interpretation; (2) introduced a snowpack insulation indicator (SII) and used stepwise partial correlations to substantiate the thermal chain "snowpack → SII → $\mathrm{Reco}_{\mathrm{winter}}$"; (3) implemented a partial least squares structural equation model that decomposes snowpack effects into direct, thermal (via soil temperature), and moisture (via soil water content) pathways; and (4) strengthened data support by validating ERA5-Land snow products against multiple in-situ networks across the Northern Hemisphere. Respectfully, the revision now provides convergent, mechanistically grounded, and statistically robust evidence, thereby fully supporting the study's central claims and resolving the methodological concerns. The manuscript has been revised accordingly.

I list my comments as follow:

As a reader, what I mainly expect to get from this paper is how snow insulation regulates ecosystem respiration. However, authors only show the statistical relationships between some snow metrics and respiration, and attribute these relationships to the impact of snow insulation effect without any analysis on the underlying physical and biological mechanisms. It is very arbitrary and not convincing. I suggest that authors should define an index to indicate the snow insulation effect, for example, the difference of temperature between land surface and overlying atmosphere over the snow-covered regions. Then, the relationships between snow and respiration should be explained by introducing the snow insulation index.

Thank you for your suggestion. To address this concern, we introduced a snowpack insulation indicator (SII), defined as the difference between soil surface temperature and overlying air temperature (T_{soil} - T_{air}), to explicitly quantify the thermal insulation effect of snowpack. Partial correlation analysis was then applied to examine two sequential pathways: snowpack indicator → SII, and SII → $Reco_{winter}$. Both the snowpack-SII, and the SII–$Reco_{winter}$ relation were stronger and more spatially consistent than the direct partial correlations between individual snowpack indicators and $Reco_{winter}$, confirming that SII functions as a critical mediating variable that mechanistically bridges snowpack and winter ecosystem respiration.

The SII framework we added to Section 3.3 is as follows:

Lines 237–257: We further introduced a snowpack insulation indicator (SII), defined as the difference between soil surface temperature and overlying air temperature, to explicitly quantify the thermal insulation effect of snowpack. Partial correlation analysis was then applied to examine two sequential linkages: 1) snowpack → SII, and 2) SII → $Reco_{winter}$. When analyzing the relation between each snowpack indicator and SII, the impacts of other two snowpack indicators and air temperature were controlled. The impact of soil moisture and air temperature are also controlled when analyzing the relation between SII and $Reco_{winter}$.

Snowpack depth and snowpack duration exhibited comparable positive relations with SII, exhibited comparable positive relations with SII, with significant positive correlations observed across 20.96% and 23.79% of the study area, respectively, while significant negative correlations were limited to 5.66% and 5.59%. The positive correlations were predominantly observed in Siberia and high-latitude North America, where characterized by deep and stable seasonal snowpack. It is consistent with the physical principle that greater snowpack depth and prolonged snowpack amplify the soil–atmosphere temperature differential, thereby enhancing thermal insulation. In contrast, snowpack density, displayed a predominantly negative partial correlation with SII, with significant negative correlations covering 11.00% of the study area. This inverse relation is physically coherent, as elevated snowpack density increases thermal conductivity of the snowpack, which diminishes its insulating capacity and consequently reduces SII.

SII exhibited the highest proportion of significant positive partial correlations with $\text{Reco}_{\text{winter}}$ among all variables examined (26.81%), while negative correlations were confined to only 2.30%, indicating a highly directionally consistent relation. The spatial distribution of significant SII–$\text{Reco}_{\text{winter}}$ correlations showed substantial overlap with that of snowpack depth–SII correlations, suggesting a coherent mechanistic chain in which deep and persistent snowpack enhances thermal insulation, sustains elevated soil temperatures throughout winter, and consequently promotes respiration. Moreover, the SII–$\text{Reco}_{\text{winter}}$ relation was both stronger and more spatially consistent than the direct partial correlations between individual snowpack indicators and $\text{Reco}_{\text{winter}}$, providing evidence that SII functions as an effective mediating indicator that bridges snowpack and winter ecosystem respiration.

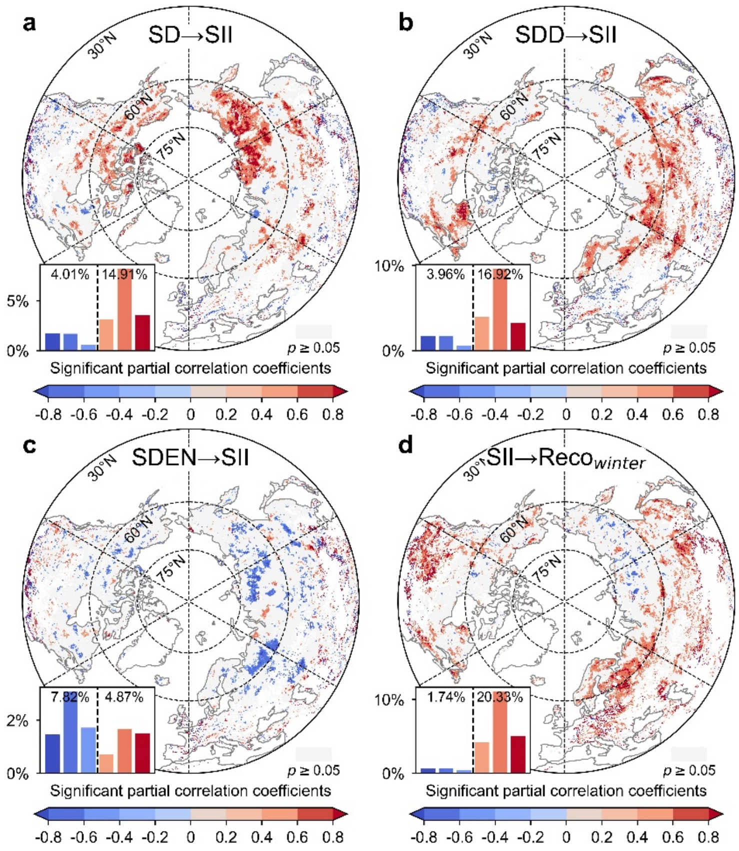

Figure 5. Spatial patterns of partial correlation coefficients between snowpack insulation and winter ecosystem respiration ($\text{Reco}_{\text{winter}}$). The region shaded in gray denotes areas of non-significance ($p \geqslant 0.05$). (a-c) The partial correlation coefficients between snowpack indicators and snowpack insulation indicator. (d) The partial correlation coefficients between snowpack insulation indicator and $\text{Reco}_{\text{winter}}$. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days. SII, snowpack insulation indicator.

From figures 1 and 2, snow variability can account for ecosystem respiration at very limited regions (at most 20% area for SD). In addition, the correlations for both positive and negative values are scattered at any region with no apparent spatial distribution pattern. I thus doubt whether these correlations simply arise by chance. Although authors found a negative correlation between R2 improvement and temperature gradient, this can only indicate that snow is more important in colder regions. We do not yet know how the magnitude and sign of the snow-respiration relationships vary along some variables, such as the gradients of temperature, precipitation, snow volume, and soil moisture, etc. That is to say, we can not understand why this correlation value between snow and respiration appears at this site and can not predict the snow-respiration relationship using snow and some other variables. Revealing the rule of distribution pattern of snow-respiration connection is of great significance for revealing the mechanisms and calibrating Earth system models. Authors should address this issue.

We acknowledge that simple partial correlation alone is insufficient to capture the full complexity of snowpack–$Reco_{winter}$ relations. Partial correlation was employed solely as an initial screening step to identify snowpack indicators with meaningful impact on $Reco_{winter}$. To address the mechanistic and spatial heterogeneity concerns raised, we have made two substantive additions:

Firstly, we introduced the snowpack insulation index (SII) as an integrated thermal insulation indicator and demonstrated that the snowpack → SII → $Reco_{winter}$ pathway is spatially prevalent across the Northern Hemisphere. The revised manuscript is detailed in previous reply.

Secondly, we incorporated a partial least squares structural equation model (PLS-SEM) framework that explicitly decomposes the snowpack – $Reco_{winter}$ relation into three pathways: a direct effect, a thermal pathway (snowpack → soil temperature → $Reco_{winter}$), and a moisture pathway (snowpack → soil water content → $Reco_{winter}$). Analyses were stratified by hydrothermal zones defined by mean annual temperature and aridity index. Results demonstrate that pathway direction and relative contribution vary systematically with hydrothermal conditions, providing a mechanistic explanation for the observed spatial heterogeneity. The revised manuscript is as follows:

Lines 130–143: We incorporated a partial least squares structural equation model (PLS-SEM) to explain the mechanism of the impact of snowpack on $Reco_{winter}$. PLS-SEM inherently embeds a mediation structure by simultaneously estimating direct and indirect pathways, and imposes no distributional assumptions and is more robust under small sample sizes of data. We explicitly decomposes the impact of snowpack on $\mathrm{Reco}_{\mathrm{winter}}$ into three pathways: 1) direct effect, 2) thermal pathway (snowpack → soil temperature → $\mathrm{Reco}_{\mathrm{winter}}$), and 3) moisture pathway (snowpack → soil water content → $\mathrm{Reco}_{\mathrm{winter}}$). To account for climatic context, analyses were conducted across regions defined by hydrothermal conditions. Thermal regime was determined by annual mean air temperature, with regions classified as cold (annual mean air temperature ⩽ 0℃) or warm (annual mean air temperature > 0℃). Moisture regime was determined using the aridity index (AI) from the Global Aridity Index and Potential Evapotranspiration Database (Version 3), with regions classified as arid (AI < 0.2), semi-arid (0.2 ⩽ AI < 0.5), semi-humid (0.5 ⩽ AI < 0.65), or humid (AI ⩾ 0.65) (Jiao et al., 2021; Zomer et al., 2022). Specifically, one latent variable (snowpack) and three observed variables (soil temperature, soil water content, and $\mathrm{Reco}_{\mathrm{winter}}$) were included in PLS-SEM. For the latent variable “snowpack”, three reflective indicators (snowpack depth, snowpack density, and snowpack duration) were considered. The goodness-of-fit index (GOFI) is used to determine whether the constructed model is effective. A GOFI value higher than 0.36 indicates that the results obtained from the model are reliable (Wetzels et al., 2009).

Line 284–318: To explain the mechanism of the impact of snowpack on $\mathrm{Reco}_{\mathrm{winter}}$ across different thermal conditions, we applied PLS-SEM analysis. PLS-SEM results revealed that snowpack affects $\mathrm{Reco}_{\mathrm{winter}}$ through three pathways, with the direction and relative contribution of each pathway showing significant regional differences. The GoFI of the models for each region ranged from 0.36 to 0.42, indicating that the models have acceptable interpretability.

The thermal pathway was significant across all climate zones, with snowpack enhancing soil temperature through its insulating effect (standardized path coefficients: 0.31–0.72) and thereby positively promoting ecosystem respiration. This finding is consistent with previous findings that snowpack affects $\mathrm{Reco}_{\mathrm{winter}}$ through snowpack insulation (Christiansen et al., 2018; Slater et al., 2017; Zhang et al., 2018). In ecosystems characterized by low air temperatures, snowpack functions as an insulation layer, thereby significantly affecting the heat exchange between the soil and the atmosphere (Christiansen et al., 2018; Slater et al., 2017; Yi et al., 2020). This results in higher ground surface temperatures than snowpack-free scenes (Zhang, 2005), which favors the maintenance of respiration.

The moisture pathway also exhibited regional differentiation. Across most climate zones, standardized path coefficients ranged from –0.025 to –0.006, indicating that winter snowpack reduces soil liquid water availability through freezing and thereby suppresses respiration. In the warm and semi-arid zone, the moisture pathway coefficient shifted to positive (0.018), though this did not reach statistical significance. The replenishment of soil moisture by snowpack contributes to microbial activities beneath snowpack (Brooks et al., 1996), but snowmelt signals were not observed in most Arctic regions because of low soil temperatures, and the partial correlation between snowmelt and $\mathrm{Reco}_{\mathrm{winter}}$ is weak (Figure 1c, g). However, site studies have revealed that snowmelt is increasing during the winter in the North America and is sensitive to climate warming (Musselman et al., 2021). This implies that future studies should pay attention to the impacts of snowpack on the winter soil water content.

The direct effect of snowpack varied in direction across climate zones, exhibiting significant negative values in cold regions ranging from –0.415 to –0.102, reflecting the physical suppression of soil–atmosphere gas exchange by the snowpack. In warm regions, the direct effect shifted to positive values (0.044–0.109). It should be noted that this direct effect represents the residual impact of snowpack on $\mathrm{Reco}_{\mathrm{winter}}$ after statistically controlling for both the thermal and moisture pathways. Therefore, it indicates that snowpack exerts an additional effect on respiration that is independent of soil temperature and soil moisture regulation. This may be explained by changes in the dominant microbial communities and the total microbial population (Li et al., 2016; Schimel et al., 2004; Wang et al., 2020). In regions with warmer climates, higher baseline respiration rates reduce the relative contribution of snowpack to ecosystem respiration, thereby limiting the overall impact of snowpack on respiration.

Integrating all three pathways, the mechanism by which snowpack influences winter ecosystem respiration is not uni-dimensional. In cold regions, the positive promotion via the thermal pathway co-exists with the negative suppression of the direct effect, while in warm regions, the three pathways all showed positive impact of snowpack on respiration. These results demonstrate that the spatial heterogeneity of the snowpack–Reco$_{\mathrm{winter}}$ relation is rooted in the differential combination of multiple impact mechanisms under varying hydrothermal conditions, rather than the dominance of any single pathway.

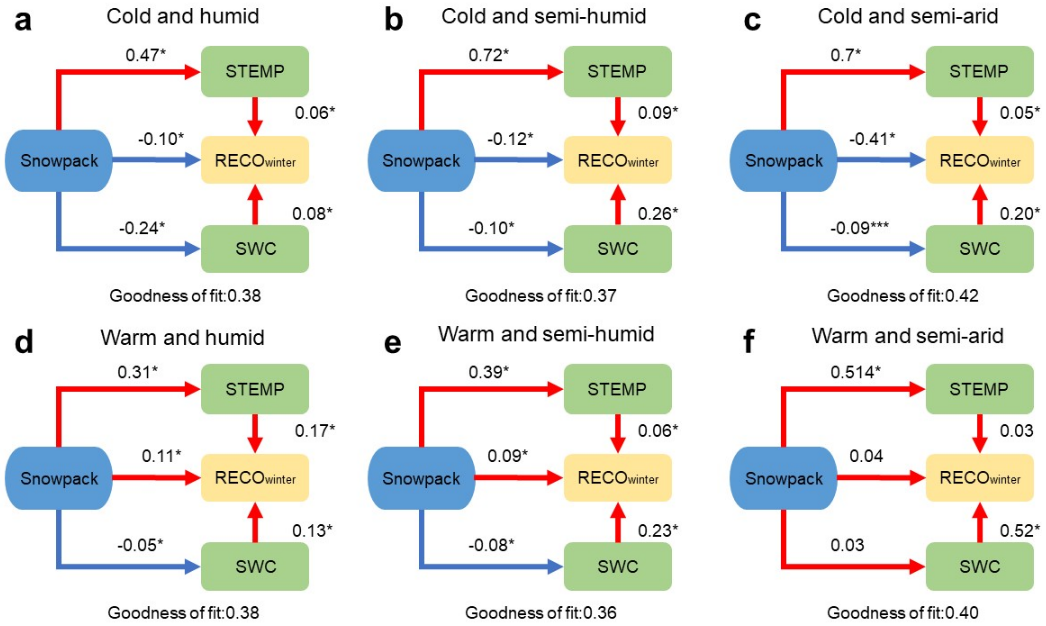

Figure 6. Path coefficient diagrams of snowpack on winter ecosystem respiration (Reco$_{\mathrm{winter}}$) over different climatic zones. The values are standardized path coefficients (* represents $p < 0.05$). The blue and red lines indicate negative and positive effects, respectively. The latent variable snowpack is composed of snowpack depth, snowpack density, and snowpack duration days. STEMP: soil temperature, SWC: soil water content.

Table 1. Comparison of the direct and indirect effects of snowpack on winter ecosystem respiration ($Reco_{winter}$) over different climatic zones.

	Cold and humid	Cold and semi-humid	Cold and semi-arid	Warm and humid	Warm and semi-humid	Warm and semi-arid
Direct path effect	–0.1022	–0.1213	–0.4148	0.1088	0.0856	0.0442
Thermal path effect	0.0283	0.0613	0.0335	0.0541	0.0238	0.0168
Moisture path effect	–0.0204	–0.0252	–0.0175	–0.0058	–0.0185	0.0180

Although this study used three observational ecosystem respiration datasets, the results were obtained based solely on the ERA5 snow data, which is a reanalysis product. To enhance the reliability of the results, I strongly suggest authors adding additional analyses using observational snow data, such as GlobSnow or SNOW-CCI. At least, multiple reanalysis data (including MERRA2, GLDAS and so on) should be analyzed.

We appreciate your suggestion. Regarding GlobSnow and SNOW-CCI, these products provide only snow water equivalent (SWE) estimates derived using a constant snowpack density of 0.24 g cm^{-3}, and do not provide independent snowpack density retrievals. Since our analysis explicitly examines the role of snowpack density as a distinct indicator, incorporating these products would preclude any meaningful assessment of snowpack density effects, and we therefore did not include them.

To address the concern about reliance on a single reanalysis product, we conducted a multi-dataset evaluation of SWE against in-situ station observations. The results show that ERA5-Land achieved the highest accuracy (R=0.64), while GlobSnow (R=0.47) and GLDAS (R=0.21) performed substantially worse. Given this performance gap, we selected ERA5-Land as the primary snow dataset to ensure the reliability of our analyses. Furthermore, we validated ERA5-Land snowpack depth and snowpack density products separately against station observations, and the results are provided in the response and supplementary material to further support the robustness of our conclusions.

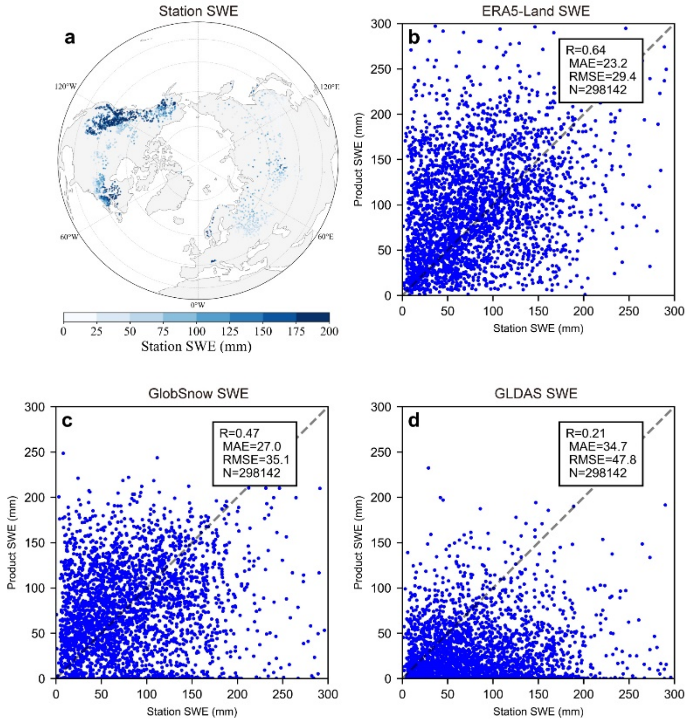

Figure S6. Comparison of ERA5-Land, GlobSnow, and GLDAS snow water equivalent (SWE) products with station observations.

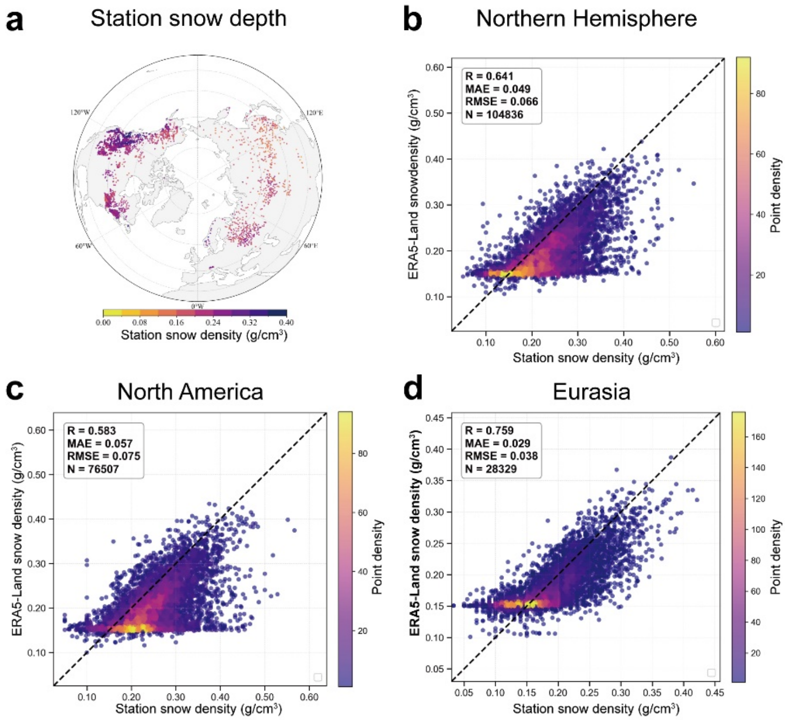

Figure S7. Comparison of ERA5-Land snowpack density with station observations.

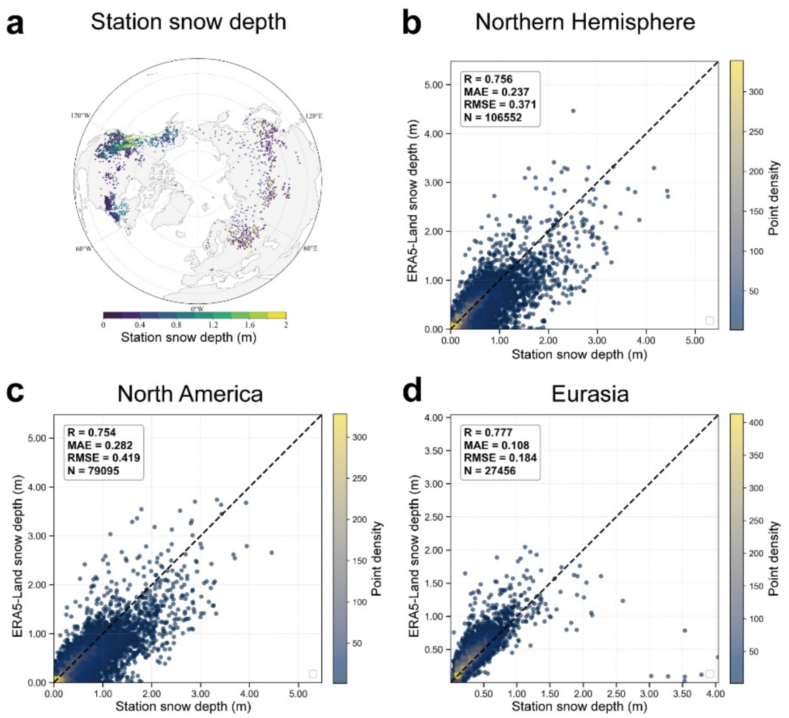

Figure S8. Comparison of ERA5-Land snowpack depth with station observations.

Table S3. Description of snow station observation datasets.

Country	Data source
Canada	CanSWE v6 (Environment and Climate Change Canada)
United states	USDA NRCS Snow Survey & SNOTEL
	Maine Geological Survey
	Northeast Regional Climate Center (NRCC)
	U.S. National Snow & Ice Center
	New Hampshire DES Dams
Finland	Finnish Environmental Institute (SYKE)
Russia	All-Russia Research Institute of Hydrometeorological Information (RIHMI-WDC)
	FSU Snow Survey (Hydromet Service of USSR)
Norway	Norwegian Water Resources and Energy Directorate (NVE)
Switzerland	WSL / SLF (Institute for Snow and Avalanche Research)
France	FMA Weather Station & Col de Porte Observatory (CENACLAM Project)

Austria	Weisssee AWS (Kaunertal Research Site)
China	China Meteorological Administration, National Climate Center

In Abstract, there are only two so-called key findings (lines 4-6), which is too weak to support the title of the study. In addition, lines 7-9 should not be presented in abstract as the main results, because the study did not analyze any models' results regarding the effect of the inaccurate snow process on the simulated ecosystem respiration.

We thank you for this thoughtful comment. We acknowledge that the original abstract may have caused some confusion, as the key findings were not presented with sufficient clarity to fully reflect the scope of the study, and certain statements in lines 7–9 could have been misread as implying model-based analyses that were not part of this work. We have removed the statements in lines 7–9 to avoid any potential misinterpretation regarding model performance analysis. The revised abstract now focuses on findings that are directly supported by our analyses. We expanded the key findings in the abstract to better reflect the scope of the study. Specifically, we added results from the multi-indicator PLSR analysis, and included the snowpack insulation indicator and partial least squares structural equation model, which demonstrate that snowpack influences $\mathrm{Reco}_{\mathrm{winter}}$ through multiple pathways—including thermal insulation, soil moisture regulation, and direct impact—with significant regional differentiation under varying hydrothermal conditions.

We revised the title to better reflect the complexity of snowpack impacts: Impacts of Snowpack on Northern Hemisphere Winter Ecosystem Respiration.

The revised abstract has been updated accordingly.

Lines 1–12: Climate-driven snowpack changes across the Northern Hemisphere introduce substantial uncertainty into the global carbon budget, but how winter ecosystem respiration ($\mathrm{Reco}_{\mathrm{winter}}$) responds to these changes remains unclear. In this study, we investigated the complex impacts of seasonal snowpack on $\mathrm{Reco}_{\mathrm{winter}}$ in the Northern Hemisphere (NH, >30°N) using multi-source datasets. Our analysis revealed that in 30.43% of NH ecosystems, snowpack (depth, duration, and density) exerted the most critical impact on respiration. Incorporating all three snowpack indicators improved R^2 by an average of 0.24 over 50.18% of the study area compared with no-snowpack models, which demonstrated the necessity of adopting a multi-indicator approach. By introducing a snowpack insulation indicator and applying structural equation models, we further demonstrated that snowpack influences $\text{Reco}_{\text{winter}}$ through multiple pathways, including direct impact, thermal insulation, and soil moisture regulation, with the direction and relative contribution of each pathway exhibiting significant regional differentiation under varying hydrothermal conditions. These findings highlight the complex and spatially heterogeneous nature of snowpack impacts on winter ecosystem carbon fluxes, and underscore the importance of adopting a multi-indicator, multi-mechanism perspective in understanding ecosystem responses to ongoing snowpack changes.

Line 87, both respiration and snow data have high spatial resolution, why did the authors interpolate all the data to a 0.25 grid? As stated in this study and previous literatures, the relationship between snow and respiration shows obvious spatial heterogeneity. The coarse spatial resolution may conceal some important signals. In addition, why did author restrict the study period to 2001-2015? It is too short to investigate the snow-respiration relation.

We acknowledge your concern regarding spatial resolution. Although ERA5-Land provides data at 0.1° resolution, GLDAS and GlobSnow datasets are available at 0.25° resolution. To ensure consistency during the snowpack validation process, all datasets were resampled to 0.25°. Furthermore, to assess whether this resampling introduced significant information loss, we conducted a sensitivity analysis comparing results at three spatial resolutions (0.1°, 0.25°, and 0.5°). As shown in the table below, the proportions of grid cells with significant partial correlations between snowpack indicators and $\text{Reco}_{\text{winter}}$ remained largely stable across resolutions, suggesting that the spatial resolution does not substantially affect our conclusions.

Table S5. Significantly partial correlated proportions of snowpack indicators and $\text{Reco}_{\text{winter}}$.

	0.1°	0.25°	0.5°
Snowpack depth	22.49%	23.32%	20.45%
Snowpack density	9.91%	9.29%	10.17%
Snowpack duration	9.50%	10.95%	9.76%

The study period (2001–2015) was determined by the temporal coverage of the FLUXCOM dataset, which is the primary ecosystem respiration product used in this study. To maintain consistency with this primary dataset, we aligned the analysis period accordingly. We agree that a longer time series would be beneficial; however, the temporal coverage of datasets constrains the study period.

Did authors remove the linear trend for all data before analysis?

For all the data, considering the natural differences between pixels due to variations in latitude, ecological type, etc., the multi-year average of each pixel was subtracted from the observed values before conducting any studies. Subsequently, first-order linear regression was used to remove the long-term linear trend caused by climate change. This part has been supplemented in the Data and Methods section.

Lines 91–93: Accounting for inherent inter-pixel differences arising from ecological baselines, the multi-year average of each pixel was subtracted from the observed values prior to analysis. Linear regression was then applied to remove the long-term linear trend associated with climate change.

I am puzzled by all the “proportion” in the MS. For example, figures 1g, 2, and 3, does it mean the proportion of the grid points of a certain value to the total number of land grid points?

In the original manuscript, we did use the proportion of a specific number of grid points to the total number of grid points to represent the "proportion". We have modified the calculating methods to latitude-weighting according to Reviewer 1's comments. We did notice a change in proportion counts, e.g., in Figure 1, the proportion that snowpack depth and FLUXCOM $\mathrm{Reco}_{\mathrm{winter}}$ are significantly correlated shifted from 20.45% to 23.32%. However, the main concept is not affected.

The methods are detailed in supplementary part as follows:

Due to the large latitudinal span of the study area (30°N–90°N), the area of raster cells decreases significantly with increasing latitude. Directly counting the number of cells without projection transformation would overestimate the area proportion of high-latitude regions. We subsequently used a latitude-weighted averaging method to represent the area statistics, optimizing for differences in grid cell areas across different latitude ranges.

$$A_{i,j} = R^2 \cdot \cos(\varphi_i) \cdot \Delta\varphi \cdot \Delta\lambda$$

where $A_{i,j}$ is the actual area (km^2) of the pixel in the i-th row and j-th column; R is the average radius of the Earth (6371 km); φ_i is the latitude (rad) of the center of the pixel in the i-th row; $\Delta\varphi$ and $\Delta\lambda$ are the latitude and longitude resolution (rad) of the pixel, respectively.

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