# Impacts of Snowpack Insulation on Winter Ecosystem Respiration: A Synergistic Analysis in the Northern Hemisphere

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1 **Abstract.** Climate-driven snowpack changes across the Northern Hemisphere introduce substantial uncertainty into the global
2 carbon budget, but how winter ecosystem respiration ($Reco_{winter}$) responds to these changes remains unclear. In this study,
3 we investigated the impact of seasonal snowpack on $Reco_{winter}$ in the Northern Hemisphere (NH, >30°N) from the perspec-
4 tive of snowpack insulation using multi-source datasets. Our analysis revealed that in 30.43% of NH ecosystems, snowpack
5 (thickness, duration, and density) exerted the most critical impact on respiration, surpassing climatic impacts (by 19.27%). The
6 positive impact of snowpack on $Reco_{winter}$ operates through snowpack insulation, with a stronger effect in colder regions.
7 Neglecting the various aspects of the snowpack may systematically underestimate the ecological impacts of snowpack. Accu-
8 rate assessments of snowpack ecological impacts must account for its synergistic aspects. Consequently, ignoring snowpack
9 ecological processes in future prediction models risk misrepresenting winter carbon fluxes and ecosystem responses to climate
10 change. Our study highlight the importance of snowpack on carbon source in winter ecosystems.

## 1 Introduction

12 High-latitude terrestrial ecosystems in the Northern Hemisphere (NH) are extremely rich in carbon stocks, with more than 200
13 million tons of carbon stored in the region's biomass and soils (Schimel et al., 2015; Friedlingstein et al., 2023; Bruhwiler et al.,
14 2021; Hugelius et al., 2014), and winter ecosystem respiration ($Reco_{winter}$) in this region (377-1662 TgC per year) accounts
15 for a substantial part of global carbon emissions (Natali et al., 2019; Schuur et al., 2015; Grogan and Jonasson, 2006; Natali
16 et al., 2021; Lenton et al., 2008). As one of the most sensitive indicators of climate change, snowpack in NH ecosystems has
17 undergone tremendous changes over the past few decades (Pörtner et al., 2019; Huning and AghaKouchak, 2018; Box et al.,
18 2019; Pulliainen et al., 2020). Snowpack directly regulates the surface energy balance, heat balance (Gouttevin et al., 2018;

19  Euskirchen et al., 2007; Zhang, 2005), and hydrological processes (Callaghan et al., 2011b; Natali et al., 2011), isolating soil

20  and vegetation from the atmosphere, and therefore has a significant impact on respiration processes (Sturm et al., 2001; Yi

21  et al., 2020). Clarifying the impacts of snowpack on $\text{Reco}_{winter}$ is critical for gaining insight into the assessment of terrestrial

22  carbon stocks on a warming globe (Euskirchen et al., 2022; Li et al., 2020; Amap, 2017; Pulliainen et al., 2024).

23      The impact of snowpack on ecosystem respiration is determined primarily by its insulating properties (Yi et al., 2020; Natali

24  et al., 2011; Grogan, 2012; Ling and Zhang, 2003). The snowpack functions to reduce the exchange of heat between the soil and

25  the atmosphere, thereby stabilizing the soil temperature. This is especially advantageous for ecosystems in regions experiencing

26  extended cold weather (Zhang, 2005; Ling and Zhang, 2003). The insulating properties of snowpack are characterized in three

27  dimensions: quantity, nature, and duration, which correspond to snowpack depth, snowpack density, and snowpack phenology,

28  respectively. The combination of snowpack depth and snowpack density quantifies the magnitude of snowpack insulation. The

29  maintenance of soil temperature by snowpack depth, which subsequently augments ecosystem respiration, is evidenced by var-

30  ious snow manipulation experiments (Natali et al., 2011; Grogan, 2012; Christiansen et al., 2018; Grogan and Jonasson, 2006;

31  Morgner et al., 2010) and ecological process models (Yi et al., 2020; Christiansen et al., 2018; Slater et al., 2017; Pongracz

32  et al., 2021). Snowpack density is commonly used to represent the thermal conductivity of snowpack (Lawrence and Swenson,

33  2011; Gouttevin et al., 2012), while snowpack phenology reflects the onset, end, and duration of the snowpack insulation effect.

34  Both snowpack indicators have been proven to affect winter soil respiration (Yi et al., 2020; Mavrovic et al., 2023; Gouttevin

35  et al., 2012). Although snowpack insulation effects are widely acknowledged, the quantification of the impact of snowpack on

36  $\text{Reco}_{winter}$ at large scales requires further investigation. Moreover, previous studies mostly considered the impact of snowpack

37  depth, and other perspectives of snowpack have been neglected. This constrains a comprehensive understanding of the impacts

38  of snowpack in winter ecosystems.

39      Previous studies have found that, at a global scale, the response of ecosystem respiration to diverse geographical condi-

40  tions including temperature, water availability, biodiversity, etc. notably varies across different latitudes and between different

41  ecosystems (Niu et al., 2024; See et al., 2024; Zhang et al., 2024; Yi and Zhang, 2024; Huang et al., 2020; Liu et al., 2023a).

42  Nonetheless, many studies have focused on annual or summer, snowpack-free scenarios (Niu et al., 2021; Zhang et al., 2024;

43  Niu et al., 2024; Du et al., 2020). However, the sources of ecosystem respiration (vegetation and microbial communities) can

44  significantly differ between cold winter and hot summer conditions (Grogan and Jonasson, 2006; Reichstein et al., 2005).

45  Moreover, the thermal insulation effect of snowpack makes the respiration process in snowpack-covered scenes more complex

46  than that in snowpack-free scenes (Ryan and Law, 2005). Considering the variability in the spatial distribution of snowpack

47  (Pulliainen et al., 2020; Hale et al., 2023), the influence of snowpack on $\text{Reco}_{winter}$ is expected to similarly exhibit spatial

48  heterogeneity. However, the precise spatial distribution of this impact and the factors driving it remain uncertain. This limits a

49  comprehensive understanding of the ecological impacts of snowpack in winter ecosystems.

50      In this study, we introduce a novel multi-indicator snowpack blanket framework to comprehensively investigate the impacts

51  of snowpack on $\text{Reco}_{winter}$ in NH ecosystems (>30°N, Supplementary Materials Figure 1) using multi-source remote sensing

52  data. This innovative approach addresses critical gaps in our understanding of winter carbon dynamics and their response to

53  changing snowpack conditions. Our research objectives are described as follows: First, we quantify the extent and magnitude of

54 the impact of seasonal snowpack on $\text{Reco}_{winter}$. Second, we explore the factors contributing to the variability in the impacts of

55 snowpack on $\text{Reco}_{winter}$, providing insights into potential climate change feedbacks. Our research provides a more refined and

56 precise insight into the influence of snowpack on carbon sources in winter terrestrial ecosystems by collaboratively integrating

57 multiple snowpack properties. This research is pivotal for improving climate models, refining carbon budget calculations, and

58 informing policy decisions related to northern ecosystems under global change scenarios.

## 2 Materials and methods

### 2.1 Dataset

61 We used three types of ecosystem respiration products to enhance the robustness of our results, including the 8-day FLUX-

62 COM product at a 0.05° spatial resolution(Jung et al., 2019), the daily BEPS product at a ~0.07° spatial resolution(He et al.,

63 2021), and the daily LGS product at a 500 m spatial resolution(Tagesson et al., 2024). These ecosystem respiration products

64 demonstrated good reliability through comparisons with ground observations(Tagesson et al., 2024; Tramontana et al., 2016),

65 and showed a high degree of concordance with one another (Supplementary Figure 11). These three products are widely used

66 in ecological studies (Huang et al., 2021; Zhong et al., 2023; Tang et al., 2022; Yang and Noormets, 2024). As FLUXCOM

67 provides carbon flux data generated by a variety of methods, we used the average flux product of all nine machine learning

68 methods.

69 Snowpack data were derived from the ERA5-Land daily dataset at a 0.1° spatial resolution (Muñoz-Sabater et al., 2021).

70 The dataset used an intermediate complexity snowpack scheme (Boone and Etchevers, 2001), which provided up to five layers

71 of snowpack parameters including temperature, mass, density, liquid water content, and albedo (ECMWF, 2023; Arduini et al.,

72 2019). Six snowpack indicators were extracted from the ERA5-Land dataset, including three snowpack physical indicators

73 (mean snowpack depth, mean snowpack density, and total snowmelt) and three snowpack phenology indicators (snowpack

74 onset date, snowpack end date, and snowpack duration). In accordance with the seasonal variations in snowpack in the NH,

75 the duration spanning from 1 August of the present year to 31 July of the following year is termed a snowpack year (Dong,

76 2018; Mudryk et al., 2020). To minimize the impact of ephemeral snowpack in the process of extracting snowpack phenology

77 (Peng et al., 2010; Chen et al., 2015), the snowpack onset date was defined as the first day of the first five consecutive days

78 of snowpack presence within each snowpack year (Supplementary Materials Equation 1), the snowpack end date was defined

79 as the final day of the last five consecutive days of snowpack presence within each snowpack year (Supplementary Materials

80 Equation 2), and the snowpack duration was defined as the number of days between the snowpack onset date and the snowpack

81 end date.

82 In addition, climate and soil data were collected to explore the drivers of ecosystem respiration. The daily air temperature,

83 precipitation, wind speed, downward shortwave radiation, soil temperature, and soil water content data were obtained from the

84 ERA5-Land dataset. The Northward component and the Eastward component of the surface 10-m wind data were converted

85 into the surface 10-m wind speed data using the Pythagorean Theorem (Conant and Beyer, 1974). The mean soil temperature

86 and mean soil water content were synthesized via depth weighting in the four soil layers (Albergel et al., 2015).

87  All datasets used in this study were restricted to 2001–2015 and interpolated to a resolution of $0.25 \times 0.25$ degrees. Given

88  the significant differences in winter length between high and low latitude regions in the NH, we uniformly restricted the

89  study period to span from November to March of the following year. The study area is restricted to locations with stable

90  seasonal snowpack ($>30°$N, and snowpack duration length between 60 and 300 days) where the natural vegetation has remained

91  unchanged. The land cover classification is based on the ESA CCI land cover map (CCI, 2017).

## 2.2  Statistic analysis

93  This study examined the impacts of different snowpack indicators on $\text{Reco}_{winter}$ by conducting a partial correlation analysis on

94  a per-pixel basis. This methodology was employed to mitigate the confounding effects of other climate variables, including air

95  temperature, precipitation, solar radiation, and wind speed during the corresponding period. Notably, our analysis was confined

96  to pixels with significant correlations ($p<0.05$) and the magnitude of the significant correlations. Therefore, we identified the

97  key snowpack indicators in the relation between snowpack and $\text{Reco}_{winter}$.

98  Partial least squares regression (PLSR) analysis per pixel was used to identify the main factors affecting $\text{Reco}_{winter}$ to

99  reduce the correlation between different snowpack indicators. Combining the advantages of multiple linear regression and

100  principal component analysis, PLSR analysis not only avoids multi-collinearity between different snowpack indicators, but

101  also enables accurate prediction of the complex relation between independent and dependent variables, and has been widely

102  used in ecological studies (Liu et al., 2023b; Guo et al., 2021; Carrascal et al., 2009). Variable importance to prediction (VIP)

103  values were then applied in the PLSR model to reveal the contributions of different impacts to $\text{Reco}_{winter}$ (Supplementary

104  Materials Equation 6). The VIP values represented the ability of indicators to explain changes in $\text{Reco}_{winter}$, and indicators

105  with VIP values greater than 1 were considered relatively important (Wold et al., 1987). We utilized snowpack, soil, and climate

106  indicators as independent variables in the PLSR models, facilitating a comparative assessment of the importance of snowpack

107  in relation to other influential factors. Soil indicators include soil water equivalent and soil temperature, and climate indicators

108  include air temperature, precipitation, radiation and wind speed. We conducted pixel-to-pixel analysis to reveal the spatial

109  patterns of the snowpack impacts on $\text{Reco}_{winter}$ and compared the relative importance of snowpack, climate, and soil indicators

110  for $\text{Reco}_{winter}$. We further determined the proportion of each indicator type that had the maximum VIP value for comparison

111  of the relative importance of snowpack, climate, and soil indicators for $\text{Reco}_{winter}$ within the NH regions with stable seasonal

112  snowpack. Subsequently, we calculated the proportion of each indicator type that exhibited the maximum VIP value in the

113  PLSR analysis, in order to compare the relative significance of snowpack, climate, and soil indicators for $\text{Reco}_{winter}$ within

114  the study area. To highlight the importance of considering multiple snowpack indicators in revealing the snowpack-$\text{Reco}_{winter}$

115  relation, we calculated the determination coefficients ($R^2$) of models utilizing different snowpack indicators. We then compared

116  these coefficients with $R^2$ of model that did not use any snowpack indicators, allowing us to determine the enhancements in $R^2$

117  resulting from the inclusion of different snowpack indicators.

118  We divided the study area according to different geographical conditions to explore the variations in the relation between

119  snowpack and $\text{Reco}_{winter}$. The annual mean air temperature and annual total precipitation were used as partitioning rules. The

120  air temperature conditions were defined as different air temperatures with intervals of $1°C$. The precipitation conditions were

**4**

121  binned every 50 mm. For each partition, we calculated the proportion of the most important factors and the average regression

122  coefficient of the snowpack indicators in the PLSR analyses. To further determine where the relation between snowpack and

123  $\text{Reco}_{winter}$ might vary across regions with different geographical conditions, piecewise linear regression was employed (Wang

124  et al., 2011). A t-test was employed to evaluate the slope in the linear regression, with a $p$ value <0.05 deemed significant.

125  Intervals with fewer than 50 observations were excluded from the linear regression, and a minimum of five intervals were

126  required for the linear regression. The purpose was to ensure the reliability of the fitting trend. Furthermore, considering

127  the variations in biomass and biological composition across different ecosystems, we examined the variations in the relation

128  between snowpack and $\text{Reco}_{winter}$ among five vegetation types (broadleaf forests, needleleaf forests, grasslands, shrublands,

129  and tundras) within the study area. These vegetation types constituted the majority of the NH regions with stable snowpack

130  and were highly representative. Vegetation classification data were obtained from the ESA CCI land cover map (CCI, 2017).

## 3   Results

### 3.1   Dominant snowpack indicators affecting $\text{Reco}_{winter}$

133  We obtained an insight into the impacts of snowpack dynamics on the variability of $\text{Reco}_{winter}$ by conducting partial correla-

134  tion analyses between six snowpack indicators and $\text{Reco}_{winter}$ (Figure 1, Supplementary Materials Figure 9-10). The impacts

135  of air temperature, precipitation, wind speed, and solar radiation were regulated during correlation coefficient calculations. This

136  approach allowed us to identify the key snowpack indicators that are crucial for characterizing $\text{Reco}_{winter}$. We conducted par-

137  tial correlation analyses between six snowpack indicators and $\text{Reco}_{winter}$ using FLUXCOM, BEPS, and LGS datasets (Figure

138  1, Supplementary Materials Figure 9-10). The results were similar for all three products, with similar significant correlation

139  directions, proportions, and spatial patterns. We selected FLUXCOM $\text{Reco}_{winter}$ for further analysis.

140      Spatial heterogeneity was observed in the magnitude and regions of significant correlations between different snowpack

141  indicators and $\text{Reco}_{winter}$. Snowpack indicators generally showed a stronger positive correlation with $\text{Reco}_{winter}$, with the

142  exception of snowpack onset date. The snowpack indicator with the strongest partial correlation with $\text{Reco}_{winter}$ was snowpack

143  depth, which was significantly positively/negatively correlated in 11.82%/8.62% of the study area, with average significant

144  correlations of 0.79/–0.74, respectively. Snowpack depth and $\text{Reco}_{winter}$ were positively correlated in the interior of North

145  America, West Siberia, and Northeast China, whereas negative correlations were observed in the coastal areas of Canada,

146  Ukraine, and the interior of Eurasia. Snowpack duration and $\text{Reco}_{winter}$ were significantly positively correlated in 11.06% of

147  the study area (0.73), mainly in Central Siberia and Northeast Canada. Snowpack density and $\text{Reco}_{winter}$ were significantly

148  positively/negatively correlated in 6.78%/3.40% of the study area, with an average degree of significance of 0.71/–0.73. The

149  areas with significant partial correlations between snowpack density and $\text{Reco}_{winter}$ showed notable fragmentation. Positive

150  correlations were predominantly observed on the Eurasian continent, whereas negative correlations were primarily concentrated

151  in northern Canada. The correlations between snowpack end date and $\text{Reco}_{winter}$ paralleled those observed between snowpack

152  duration and $\text{Reco}_{winter}$. This was evidenced by the proportion of significant positive correlations greatly exceeding that of

153  significant negative correlations. Furthermore, significant positive correlations were predominantly found within the Eurasian
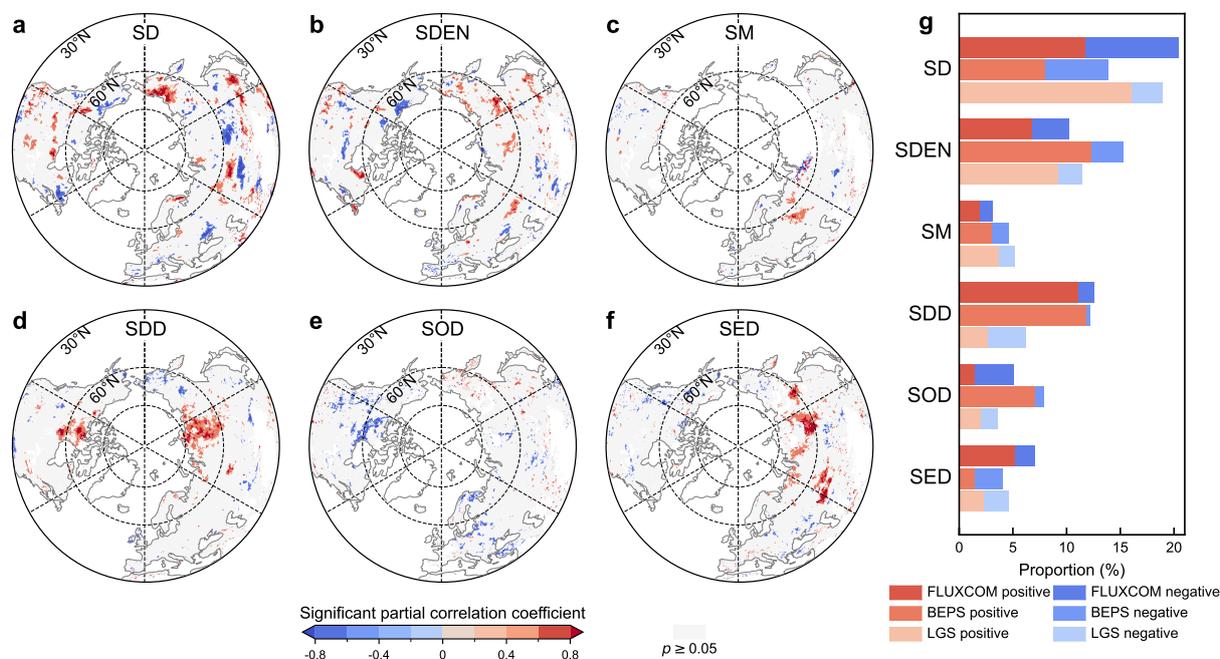
**Figure 1.** (a–f) Spatial patterns of the significant partial correlation coefficients between the snowpack indicators and winter ecosystem respiration ($Reco_{winter}$) based on the FLUXCOM product. The region shaded in gray denotes areas of non-significance ($p \geq 0.05$). (g) Proportions of the significant partial correlation coefficients between the snowpack indicators and $Reco_{winter}$ based on FLUXCOM, BEPS, and LGS product. The red and blue bars indicate the proportions of significantly positive and negative correlations, respectively. SD, snowpack depth; SDEN, snowpack density; SM, total snowmelt; SDD, snowpack duration days; SOD, snowpack onset date; SED, snowpack end date.

154   continent despite variations in spatial patterns. For snowpack onset dates and total snowmelt, the significant correlations with

155   $Reco_{winter}$ were observed only within a confined area exhibiting a sporadic and non-uniform spatial distribution.

156        Upon examining the intensity and proportion of significant correlations, we assumed that snowpack depth, snowpack density,

157   and snowpack duration could serve as the key snowpack indicators for characterizing the relation between snowpack and

158   $Reco_{winter}$, upon examining the intensity (0.71-0.79) and proportion (6.78%-11.82%) of significant correlations. Therefore,

159   the three snowpack indicators were used as proxies for snowpack in subsequent studies. These three snowpack indicators

160   comprehensively characterized the physical properties and temporal information of snowpack, thus reflecting a comprehensive

161   picture of the impact of snowpack. Although there was a relatively strong partial correlation between snowpack end date and

162   $Reco_{winter}$, snowpack end date was not considered because of its similarity to snowpack duration.

163        As several snowpack indicators were applied in the analysis, a degree of covariance was inevitable due to the intrinsic links

164   between the indicators. However, our results revealed that strong correlations between different snowpack indicators were

165   not universal, which is visualized in Supplementary Materials Figure 3. We did find a relatively strong correlation between

166   snowpack depth and snowpack density (24.71%, 0.68), as together they characterize the physical nature of snowpack. However,

167   the regions that exhibited strong correlations (central Europe, Yukon in Canada, and central Siberia) did not exactly overlap

168  with the areas significantly influenced by these indicators. The correlations between snowpack depth and snowpack duration

169  (7.91%, 0.27), as well as those between snowpack density and snowpack duration (6.50%, 0.25), were weak. The results imply

170  that integrating various snowpack indicators facilitates a comprehensive analysis of the impact of snowpack from diverse and

171  complementary perspectives. This multi-perspective approach enhances the thorough comprehension and evaluation of the

172  ecological impacts of snowpack.

173  ### 3.2  Impacts of snowpack dynamics on $\text{Reco}_{winter}$ variability

174  We further quantified the contributions of snowpack to $\text{Reco}_{winter}$ using PLSR analysis (Figure 2). The most dominant factor

175  for $\text{Reco}_{winter}$ was identified for each pixel using VIP values, and the impacts of snowpack, soil, and climate were compared.

176  The three snowpack indicators (snowpack depth, snowpack density, and snowpack duration) were the dominant factors influ-

177  encing $\text{Reco}_{winter}$ changes in 30.43% of the region, exceeding the contributions of the four climate indicators (11.26%, Figure

178  2a). Among the three snowpack indicators, snowpack depth was the dominant factor influencing $\text{Reco}_{winter}$ variability in ap-

179  proximately 13.85% of the region, followed by snowpack duration (8.83%) and snowpack density (7.75%). By evaluating the

180  spatial distribution of the VIP values for snowpack indicators (Figure 2 b–d), we found that the impact of snowpack depth was

181  more important within the Eurasian continent south of 60°N, whereas snowpack density and snowpack duration were more

182  important north of 60°N. The intensity and proportion of positive impacts exceeded those of negative impacts for all snowpack

183  indicators. The magnitude, direction, and distribution patterns of the impacts of different snowpack indicators on $\text{Reco}_{winter}$

184  showed strong spatial heterogeneity (Figure 2e–g). The snowpack density had positive impacts on $\text{Reco}_{winter}$ in Eurasia north

185  of 50°N, and had negative impacts on $\text{Reco}_{winter}$ in northern North America, and Eurasia south of 40°N. Snowpack duration

186  had a positive impact on $\text{Reco}_{winter}$ in central Canada north of 60°N and the Eurasian continent except for West Siberia, and

187  a negative impact on $\text{Reco}_{winter}$ in West Siberia.

188  Furthermore, the utilization of three snowpack indicators represents a more efficacious approach than the use of a single

189  snowpack indicator or two snowpack indicators for the characterization of $\text{Reco}_{winter}$ (Figure 3). We compared the determina-

190  tion coefficients ($R^2$) across PLSR models incorporating no, one, two, or three snowpack indicators to evaluate the incremental

191  contributions of snowpack. The integration of a single snowpack indicator into the models, in contrast to those lacking such

192  indicators, resulted in an enhancement of $R^2$ by 0.19–0.21 across 19.10% to 21.01% of the study area (Figure 3 a–c). Ad-

193  ditionally, the inclusion of two snowpack indicators increased $R^2$ by an average of 0.21–0.22 over 35.17%–38.78% of NH

194  ecosystems, compared with models without snowpack indicators (Figure 3 d–f). By utilizing all three snowpack indicators in

195  the PLSR analysis, $R^2$ improved by 0.1–0.81 (average 0.23) over 50.18% of the study area (Figure 3g). We observed that re-

196  gions exhibiting a notable improvement in model performance, which is due to the utilization of multiple snowpack indicators,

197  tend to be situated at higher latitudes. In particular, the introduction of snowpack indicators improved $R^2$ by more than 0.3 in

198  18.49% of the regions >60°N (Supplementary Materials Figure 2d), which suggested that snowpack dynamics had a relatively

199  good interpretation of $\text{Reco}_{winter}$ changes at high latitudes in the NH. The inclusion of snowpack indicators led to a notable

200  increase in $R^2$ by an average of 0.15 in regions between 30°N and 60°N, suggesting the presence of factors other than snow-

201  pack that influenced $\text{Reco}_{winter}$. Additionally, few regions (8.75%) presented no discernible increase in model accuracy. These
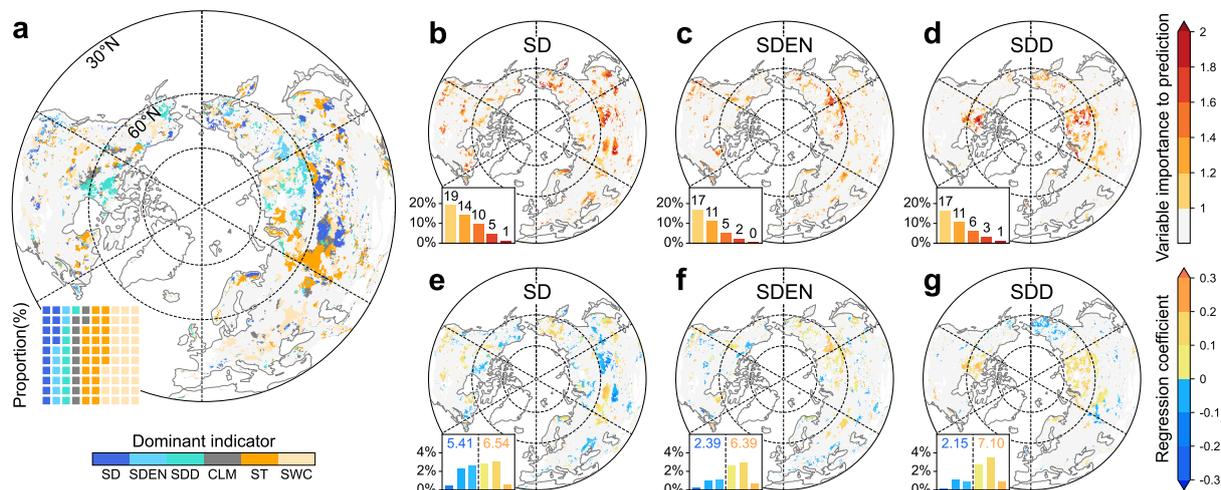
**Figure 2.** (a) Spatial pattern of the dominant indicators for winter ecosystem respiration in partial least squares regression (PLSR) analysis. Only pixels with variable importance on projection (VIP) >1 and determination coefficients ($R^2$) >0.8 are remained. The inset waffle plot indicates the proportion of the dominant indicator, with each pixel corresponding to 1%. (b–d) Spatial pattern of the VIP values of snowpack indicators The inset barplots indicate the proportions of VIPs in different intervals. (e–g) Spatial pattern of the regression coefficients of snowpack indicators. The inset barplots indicate the proportions of negative and positive regression coefficients in different intervals. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days; CLM, climate indicators; ST, soil temperature; SWC, soil water content.
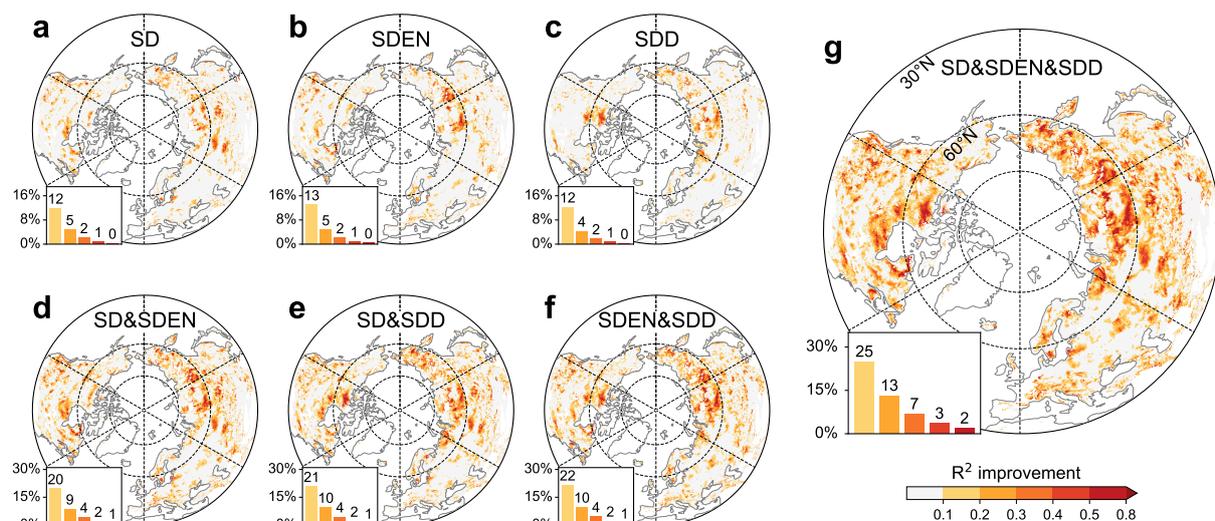


**Figure 3.** Improvements of determination coefficients ($R^2$) in the partial least squares regression analysis employing one snowpack indicator or their combinations respectively. The inset barplots indicate the proportion of $R^2$ improvement in different intervals. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days.

202   areas are more dispersed and less concentrated. In conclusion, it is more important to consider multiple snowpack indicators

203   when characterizing the variability of $\text{Reco}_{winter}$ than to rely on a single snowpack indicator, particularly in cold, high-latitude

204   regions. Given the spatial variability in the impact of snowpack indicators, investigating various aspects of snowpack could

205   contribute to a thorough understanding of the variations in $\text{Reco}_{winter}$.

## 3.3   Impacts of snowpack on $\text{Reco}_{winter}$ under different thermal conditions

207   The relation between snowpack and $\text{Reco}_{winter}$ showed great spatial variability, influenced by environmental factors. We par-

208   titioned the study area according to different geographical conditions, and analyzed whether there were significant differences

209   in the intensity and extent of the relation between snowpack and $\text{Reco}_{winter}$ across the sub-zones. Our study revealed that

210   the relation between snowpack and $\text{Reco}_{winter}$ was more sensitive to variations in air temperature, rather than to variations in

211   precipitation (Figure 4).

212       Overall, the intensity and proportion of the impacts of snowpack on $\text{Reco}_{winter}$ decreased significantly along the tempera-

213   ture gradient ($p<0.01$, Figure 4d-e). However, snowpack impacts remained unchanged across the precipitation gradient. This

214   suggested that the impact of snowpack on $\text{Reco}_{winter}$ was more pronounced in regions with colder temperatures. The three

215   snowpack indicators were the dominant factors for $\text{Reco}_{winter}$ in more than 40% of the regions where the annual mean air tem-

216   perature was less than $-5°$C (Figure 4e). Among these indicators, snowpack duration and density exerted the greatest influence,

217   whereas snowpack depth impacted a relatively smaller region. However, in regions where the annual mean air temperature is

218   above $0°$C, snowpack depth became the snowpack indicator that exerted the widest impact. This finding suggested that snow-

219   pack duration and snowpack density had a wide range of impacts on $\text{Reco}_{winter}$ in cold regions; however, in relatively warmer

220   regions, the impact of snowpack depth became predominant. In regions where the annual mean air temperature was above $0°$C,

221   the proportion of areas where climate was the dominant factor exceeded that of snowpack, implying that climate had a greater

222   impact on $\text{Reco}_{winter}$ than snowpack in warm areas.

223       We further analyzed the variations in the relation between snowpack and $\text{Reco}_{winter}$ among vegetation types in the NH

224   (Figure 5). We used five vegetation types, broadleaf forest, needleleaf forest, shrubland, grassland, and tundra, as these veg-

225   etation types encompass a substantial portion of the NH regions with stable snowpack. Concurrently, the vegetation type of

226   the region underwent a transition from tundra, needleleaf forest, grassland, shrub, and broadleaf forest as the annual mean

227   air temperature increased. As the vegetation type shifted, the percentage of the regions impacted by snowpack significantly

228   declined from 54.06% to 24.47%, and the average enhancement in $R^2$ attributable to snowpack diminished from 0.19 to 0.11

229   (Figure 5a). Moreover, the impacts of different snowpack indicators on $\text{Reco}_{winter}$ varied as the vegetation type shifted. In

230   the coldest tundras, snowpack duration can affect up to 41.21% of the area. However, as vegetation types transitioned to those

231   more suitable for warmer conditions, there was a marked decrease in the impact of snowpack duration, with snowpack duration

232   acting as the dominant indicator in only 2.41% of the broadleaf forests. Moreover, the impact of snowpack depth expanded

233   considerably, from 8.13% in tundra to 19.46% in broadleaf forests. Snowpack density exhibited relatively substantial impact

234   in less cold regions (needleleaf forests and grasslands), and the overall impact was relatively minor. In addition, the effect of

235   the regional annual mean air temperature on the snowpack-$\text{Reco}_{winter}$ relation was identified in needleleaf forests, shrublands,
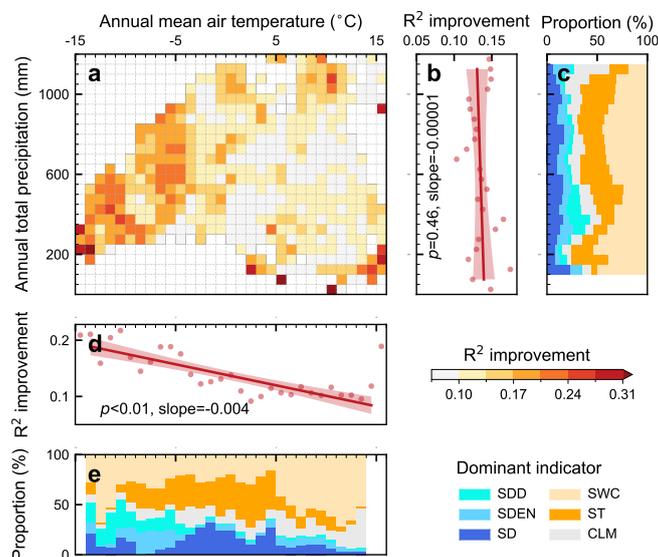
**Figure 4.** Variations in the significance of snowpack to winter ecosystem respiration ($Reco_{winter}$) along temperature and precipitation gradients. In (a), each zone represents the mean value of improvements in the determination coefficients ($R^2$) when multiple snowpack indicators are considered in a specific interval of temperature and precipitation gradients. In (b) and (d), the points represent the mean value of $R^2$ improvements along a single gradient. In (c) and (e), the barplots represent the proportions of the dominant indicators for winter ecosystem respiration ($Reco_{winter}$) in a specific interval of a single gradient. Only intervals with more than 50 observations are remained. The temperature and precipitation gradients are binned every $1°C$ and 50 mm, respectively. The shaded area indicates the 95% confidence interval. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days; CLM, climate indicators; ST, soil temperature; SWC, soil water content.

and grasslands (Figure 5b). There was a wide range of annual mean air temperatures in the regions covered by these vegetation types. However, this pattern was not found in broadleaf forests and tundras. In the regions covered by broadleaf forests or tundras, the variation in regional annual mean air temperatures was smaller than that in the former three vegetation types, and the snowpack-$Reco_{winter}$ relation showed limited variability. Tundras were located in the coldest regions where snowpack had the most significant impact on $Reco_{winter}$, whereas broadleaf forests in the warmest part of the study area exhibited the least impact.

## 4 Discussion

### 4.1 Complex and profound impacts of snowpack on $Reco_{winter}$

Our analysis revealed that snowpack had a considerable influence on $Reco_{winter}$ in NH ecosystems with a stable seasonal snowpack, especially in the pan-Arctic (Figure 1, 2). Snowpack depth, snowpack density, and snowpack duration presented
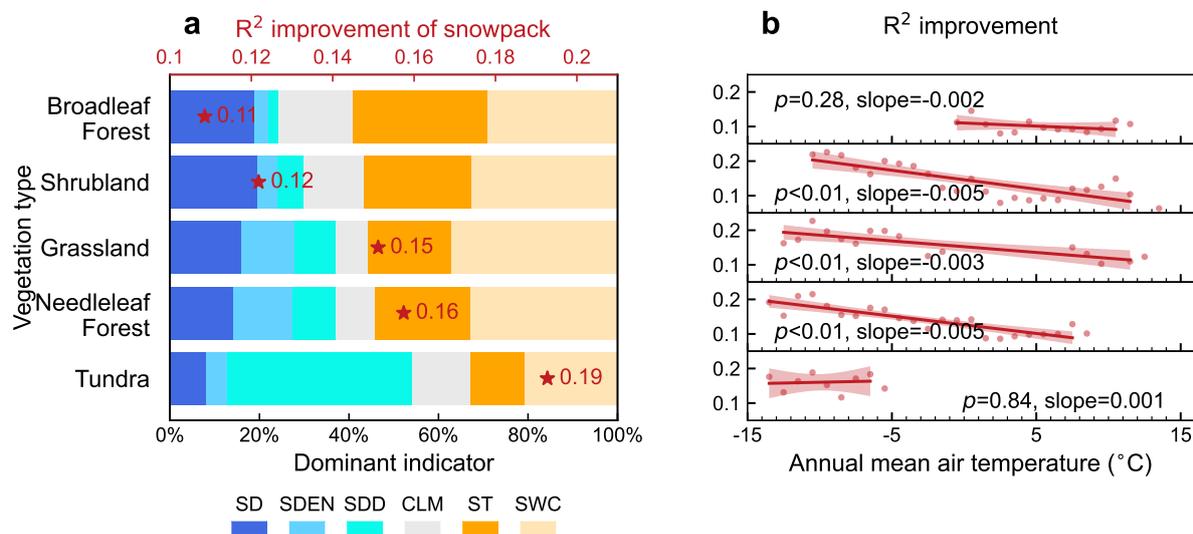
**Figure 5.** Variations in the significance of snowpack to winter ecosystem respiration ($\text{Reco}_{winter}$) among five main vegetation types. In (a), the stars with digits indicate the mean value of improvements in the determination coefficients ($R^2$) when multiple snowpack indicators are considered, and the bars represent the proportions of the dominant indicators for $\text{Reco}_{winter}$. In (b), the points represent the mean value of $R^2$ improvements along the temperature gradient among five vegetation types. The temperature gradients are binned every $1°C$. SD, snowpack depth; SDEN, snowpack density; SDD, snowpack duration days; CLM, climate indicators; ST, soil temperature; SWC, soil water content.

246    the most extensive areas of correlation and the strongest correlations. This finding is consistent with previous studies that have

247    highlighted the significance of snowpack depth (Natali et al., 2011; Slater et al., 2017; Yi et al., 2020; Christiansen et al.,

248    2018) and snowpack density (Mavrovic et al., 2023; Gouttevin et al., 2012; Lawrence and Swenson, 2011), as they jointly

249    define the physical properties of snowpack insulation. Snowpack duration provides information on the temporal impact of

250    snowpack insulation, and had a strong impact on $\text{Reco}_{winter}$ at high latitudes with an extended snowpack duration (Lafrenière

251    et al., 2013). More importantly, considering three snowpack indicators is a more comprehensive and effective method for

252    characterizing the variability of $\text{Reco}_{winter}$ (Figure 3). Employing multiple snowpack indicators inevitably resulted in some

253    level of covariance; however, our findings indicated that significant correlations among these snowpack indicators were not

254    common (Supplementary Materials Figure 3), which was consistent with previous studies that reported different magnitudes of

255    variation in snowpack depth and snowpack density at both regional and site scales (Sturm et al., 2010; Fassnacht et al., 2013).

256    The direction and magnitude of changes in different aspects of snowpack are not consistent in the presence of climate change

257    (Lawrence and Slater, 2010; Callaghan et al., 2011a; Mudryk et al., 2020). A sole focus on a single aspect of snowpack fails to

258    capture a complete understanding of the intricate patterns of snowpack changes across the NH.

259      Our studies compared the impacts of snowpack, soil, and climate indicators on $\text{Reco}_{winter}$, and revealed that the spatial

260    extent and intensity of the impacts of snowpack exceeded those of climate on $\text{Reco}_{winter}$, second to the impacts of soil

261    hydrothermal conditions, which can be explained by the distance of ecosystem contact. Soil is in direct contact with roots,

262  microorganisms, and other living organisms capable of respiration, therefore, soil indicators are the most important factors for

263  $Reco_{winter}$ (Wang et al., 2014; Natali et al., 2019). Snowpack covers the surface of soil and vegetation, maintaining the soil

264  temperature (Zhang et al., 2018; Slater et al., 2017; Wang et al., 2013; Christiansen et al., 2018) and preventing the evaporation

265  of soil moisture (Niu and Yang, 2006). In contrast, the distance between the near-surface atmosphere and the ecosystem is

266  relatively long, with snowpack acting as a medium (Slater et al., 2017; Christiansen et al., 2018); therefore, the influence of

267  climate factors will be weaker than that of snowpack in winter ecosystems.

268      Our study revealed that the influence of multiple snowpack indicators on respiration is predominantly positive. However, in

269  some regions, negative impacts have been observed. This can be attributed to the two-faceted nature of the snowpack insulation

270  effect. The snowpack acts as a blanket over vegetation and the ground, allowing the surface beneath the snowpack to maintain

271  temperatures higher than the ambient air, thus facilitating respiration (Zhang et al., 2018; Slater et al., 2017; Christiansen et al.,

272  2018). In conditions with moderate snowpack depth and density, the insulating effect of the snowpack leads to a temperature

273  increase compared to snow-free conditions, allowing effective respiration of roots and microorganisms beneath (Slater et al.,

274  2017; Yi et al., 2020). However, if the snowpack is too thick or impermeable (Kim, 2014; Mast et al., 1998), the insulation effect

275  is limited, and gas exchange within the snowpack becomes restricted, impairing the respiration of the organisms underneath.

## 4.2    Drivers behind the varied relations between snowpack and $Reco_{winter}$

277  Our study revealed that the impact of snowpack on $Reco_{winter}$ varies widely across regions with different annual mean air

278  temperature conditions (Figure 4, 5). This finding is consistent with previous findings that snowpack affects $Reco_{winter}$ through

279  snowpack insulation(Zhang et al., 2018; Slater et al., 2017; Christiansen et al., 2018). In ecosystems characterized by low

280  air temperatures, snowpack functions as an insulation layer, thereby significantly affecting the heat exchange between the

281  soil and the atmosphere (Slater et al., 2017; Christiansen et al., 2018; Yi et al., 2020). This results in higher ground surface

282  temperatures than snowpack-free scenes (Zhang, 2005), which favors the maintenance of respiration. The impact of snowpack

283  on $Reco_{winter}$ is most pronounced in the coldest regions, highlighting the importance of measuring the carbon balance of

284  winter terrestrial ecosystems in the pan-Arctic region. Although the replenishment of soil moisture by snowpack contributes to

285  microbial activities beneath snowpack (Brooks et al., 1996), snowmelt signals were not observed in most Arctic regions because

286  of low soil temperatures, and the partial correlation between snowmelt and $Reco_{winter}$ is weak (Figure 1c, g). However, site

287  studies have revealed that snowmelt is increasing during the winter in the North America and is sensitive to climate warming

288  (Musselman et al., 2021). This implies that future studies should pay attention to the impacts of snowpack on the winter soil

289  water content. Our study did not identify significant differences in the impact of snowpack on $Reco_{winter}$ across regions with

290  varying annual total precipitation or winter soil water content. Nonetheless, further investigation is required to confirm this

291  result, particularly by incorporating site observations and model validation.

292      The impact of snowpack on $Reco_{winter}$ is most pronounced in the coldest regions, and diminishes with increasing annual

293  mean air temperatures (Figure 4d). This can be explained by changes in the dominant microbial communities and the total

294  microbial population (Schimel et al., 2004; Li et al., 2016; Wang et al., 2020). Previous studies have shown that the temperature

295  sensitivity of soil respiration is greater when the temperature is less than $0°C$ (Segura et al., 2019; Arndt et al., 2023), suggesting

296  that $Reco_{winter}$ is more sensitive to temperature changes below $0°C$ compared to those above $0°C$.

297  The impact of snowpack on $Reco_{winter}$ diminishes in regions with higher annual mean air temperatures (Figure 4d), in-

298  dicating that in colder regions, the insulating effect of snowpack is greater, and $Reco_{winter}$ is more facilitated. This can be

299  explained by changes in the dominant microbial communities and the total microbial population (Schimel et al., 2004; Li et al.,

300  2016; Wang et al., 2020). Previous studies have shown that the temperature sensitivity of soil respiration is greater when the

301  temperature is less than $0°C$ (Segura et al., 2019; Arndt et al., 2023; Zheng et al., 2025), suggesting that $Reco_{winter}$ is more

302  sensitive to temperature changes below $0°C$ compared to those above $0°C$. In regions with warmer climates, respiration is less

303  constrained by ambient temperatures, and the impact of snowpack on respiration is limited.

## 4.3  Uncertainties and perspectives

305  Our results are subject to uncertainties stemming from two primary sources: the quality of the input datasets and the method-

306  ology of the analysis. The FLUXCOM and LGS product both used multiple machine learning methods to spatially interpolate

307  respiration observations from FLUXNET sites to global scales, and the scarcity of FLUXNET sites at high latitudes contributes

308  to dataset uncertainty (Schimel et al., 2015; Tramontana et al., 2016). There is an overestimation of snowpack depth in ERA5-

309  Land at high elevations, especially in the high mountain regions of Asia (Muñoz-Sabater et al., 2021; Monteiro and Morin,

310  2023). We considered the high uncertainty of snowpack depth and respiration measurements in areas with snowpack depths

311  greater than 2.5m, and excluded them during data preprocessing. Uncertainty also results from the interpolation of all datasets

312  to a uniform spatial resolution in data preprocessing. In this study, the analysis of the impact of snowpack on $Reco_{winter}$ did

313  not incorporate additional factors, such as microbial community richness and soil nutrients, owing to insufficient data avail-

314  ability. Owing to the absence of simultaneous in-situ measurements of snowpack and respiration, ground-based observations

315  were not utilized to validate our hypotheses. The analysis focuses on the relation between snowpack and $Reco_{winter}$ at the 25

316  km monthly scale, and the applicability of the results to other spatial–temporal scales requires further investigation.

317  Our study provides a general understanding of the impact of snowpack on $Reco_{winter}$ in NH ecosystems on the basis

318  of multi-source data. Furthermore, incorporating long-term in situ observations with high spatial–temporal resolution remote

319  sensing data will significantly assist in elucidating the relation between snowpack dynamics and ecosystem respiration in future

320  studies.

## 5  Conclusions

322  This study provides detailed evaluations of the spatial extent and magnitude of the relation between snowpack and $Reco_{winter}$

323  from multiple perspectives of snowpack insulation in the NH. Our results demonstrated that snowpack had critical impacts

324  on $Reco_{winter}$ in the NH, with the extent of influence exceeding that of climate. In this study, the Snowpack Blanket Frame-

325  work clearly identifies three pivotal parameters—snowpack depth, snowpack density, and snowpack duration—as crucial in

326  determining the snowpack-$Reco_{winter}$ relation. These parameters collectively characterize the snowpack's insulation effect on

327 the basis of the physical properties and temporal dynamics of snowpack. Snowpack functions as an insulating barrier, thereby

328 significantly affecting the temperature difference between the near-surface and the atmosphere, thus protecting ecosystem res-

329 piration from harsh external cold. The insulation effects of snowpack are characterized by positive impacts of snowpack on

330 $Reco_{winter}$, where increased snowpack amplifies these impacts, leading to a larger amount of $Reco_{winter}$. The Snowpack

331 Blanket Framework addresses the limitations inherent in single-parameter models, thereby providing a more thorough com-

332 prehension of the ecological impacts associated with snowpack. If fewer snowpack indicators are considered, there would be a

333 reduction in the explanation of $Reco_{winter}$ across a significant portion of the study area. The impacts of snowpack indicators

334 on $Reco_{winter}$ were spatially heterogeneous, and were moderated by different temperature conditions rather than precipitation

335 conditions. In regions with lower annual mean air temperatures, the impact of snowpack was more pronounced. These find-

336 ings emphasize the significant impact of snowpack on $Reco_{winter}$ at large scales, thereby enhancing the comprehension of the

337 ecological impacts of snowpack. Integrating snowpack-regulated ecological processes will be essential for future predictions

338 of ecosystem carbon stocks in the NH.

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346 Writing – review & editing. Yantao Liu: Writing – review & editing. Petri Pellikka: Writing – review & editing. Yumeng Jia: Writing –

347 review & editing. Yumeng Jia: Writing – review & editing.

# References

Albergel, C., Dutra, E., Muñoz-Sabater, J., Haiden, T., Balsamo, G., Beljaars, A., Isaksen, L., de Rosnay, P., Sandu, I., and Wedi, N.: Soil temperature at ECMWF: An assessment using ground-based observations, Journal of Geophysical Research: Atmospheres, 120, 1361–1373, https://doi.org/10.1002/2014JD022505, 2015.

Amap: Snow, water, ice and permafrost in the Arctic (SWIPA) 2017, Arctic Monitoring and Assessment Programme (AMAP), 2017.

Arduini, G., Balsamo, G., Dutra, E., Day, J. J., Sandu, I., Boussetta, S., and Haiden, T.: Impact of a multi-layer snow scheme on near-surface weather forecasts, Journal of Advances in Modeling Earth Systems, 11, 4687–4710, https://doi.org/10.5194/egusphere-egu2020-22247, 2019.

Arndt, K. A., Hashemi, J., Natali, S. M., Schiferl, L. D., and Virkkala, A.-M.: Recent advances and challenges in monitoring and modeling non-growing season carbon dioxide fluxes from the arctic boreal zone, Current Climate Change Reports, 9, 27–40, https://doi.org/10.1007/s40641-023-00190-4, 2023.

Boone, A. and Etchevers, P.: An intercomparison of three snow schemes of varying complexity coupled to the same land surface model: Local-scale evaluation at an Alpine site, Journal of Hydrometeorology, 2, 374–394, https://doi.org/10.1175/1525-7541(2001)002<0374:aiotss>2.0.co;2, 2001.

Box, J. E., Colgan, W. T., Christensen, T. R., Schmidt, N. M., Lund, M., Parmentier, F.-J. W., Brown, R., Bhatt, U. S., Euskirchen, E. S., Romanovsky, V. E., Walsh, J. E., Overland, J. E., Wang, M., Corell, R. W., Meier, W. N., Wouters, B., Mernild, S., Mård, J., Pawlak, J., and Olsen, M. S.: Key indicators of Arctic climate change: 1971–2017, Environmental Research Letters, 14, 045 010, https://doi.org/10.1088/1748-9326/aafc1b, 2019.

Brooks, P. D., Williams, M. W., and Schmidt, S. K.: Microbial activity under alpine snowpacks, Niwot Ridge, Colorado, Biogeochemistry, 32, 93–113, https://doi.org/10.1007/bf00000354, 1996.

Bruhwiler, L., Parmentier, F.-J. W., Crill, P., Leonard, M., and Palmer, P. I.: The Arctic carbon cycle and its response to changing climate, Current Climate Change Reports, 7, 14–34, https://doi.org/10.1007/s40641-020-00169-5, 2021.

Callaghan, T. V., Johansson, M., Brown, R. D., Groisman, P. Y., Labba, N., Radionov, V., Barry, R. G., Bulygina, O. N., Essery, R. L., Frolov, D., et al.: The changing face of Arctic snow cover: A synthesis of observed and projected changes, Ambio, 40, 17–31, https://doi.org/10.1007/s13280-011-0212-y, 2011a.

Callaghan, T. V., Johansson, M., Brown, R. D., Groisman, P. Y., Labba, N., Radionov, V., Bradley, R. S., Blangy, S., Bulygina, O. N., Christensen, T. R., et al.: Multiple effects of changes in Arctic snow cover, Ambio, 40, 32–45, https://doi.org/10.1007/s13280-011-0213-x, 2011b.

Carrascal, L. M., Galván, I., and Gordo, O.: Partial least squares regression as an alternative to current regression methods used in ecology, Oikos, 118, 681–690, https://doi.org/10.1111/j.1600-0706.2008.16881.x, 2009.

CCI, E. L. C.: Land Cover CCI Product User Guide Version 2, UCL-Geomatics: London, UK, https://doi.org/10.5194/ems2022-31, available at: maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf, 2017.

Chen, J. M., Ju, W., Ciais, P., Viovy, N., Liu, R., Liu, Y., and Lu, X.: Vegetation structural change since 1981 significantly enhanced the terrestrial carbon sink, Nature communications, 10, 4259, 2019.

Chen, X., Liang, S., Cao, Y., He, T., and Wang, D.: Observed contrast changes in snow cover phenology in northern middle and high latitudes from 2001–2014, Scientific Reports, 5, 16 820, https://doi.org/10.1038/srep16820, 2015.

387  Christiansen, C. T., Lafreniére, M. J., Henry, G. H. R., and Grogan, P.: Long-term deepened snow promotes tundra evergreen shrub
388    growth and summertime ecosystem net CO2 gain but reduces soil carbon and nutrient pools, Global Change Biology, 24, 3508–3525,
389    https://doi.org/10.1111/gcb.14084, 2018.

390  Conant, D. and Beyer, W.: Generalized pythagorean theorem, The American Mathematical Monthly, 81, 262–265, 1974.

391  Dong, C.: Remote sensing, hydrological modeling and in situ observations in snow cover research: A review, Journal of Hydrology, 561,
392    573–583, https://doi.org/10.1016/j.jhydrol.2018.04.027, 2018.

393  Du, Y., Wang, Y.-P., Su, F., Jiang, J., Wang, C., Yu, M., and Yan, J.: The response of soil respiration to precipitation change is asymmetric
394    and differs between grasslands and forests, Global Change Biology, 26, 6015–6024, 2020.

395  ECMWF: IFS Documentation CY48R1 - Part IV: Physical Processes, 4, ECMWF, https://doi.org/10.21957/02054f0fbf, 2023.

396  ESA: Land Cover CCI Product User Guide Version 2. Tech. Rep, available at: maps.elie.ucl.ac.be/CCI/viewer/download/
397    ESACCI-LC-Ph2-PUGv2_2.0.pdf, 2019.

398  Euskirchen, E., McGuire, A., and CHAPIN III, F.: Energy feedbacks of northern high-latitude ecosystems to the climate system
399    due to reduced snow cover during 20th century warming, Global Change Biology, 13, 2425–2438, https://doi.org/10.1111/j.1365-
400    2486.2007.01450.x, 2007.

401  Euskirchen, E. S., Bruhwiler, L. M., Commane, R., Parmentier, F.-J. W., Schädel, C., Schuur, E. A., and Watts, J.: Current knowl-
402    edge and uncertainties associated with the Arctic greenhouse gas budget, Balancing Greenhouse Gas Budgets, pp. 159–201,
403    https://doi.org/10.1016/b978-0-12-814952-2.00007-1, 2022.

404  Fassnacht, S., Heath, J., and Musselman, K.: Small scale spatial variability of snow density and depth over complex alpine terrain: Impli-
405    cations for estimating snow water equivalent, Advances in Water Resources, 55, 40–52, https://doi.org/10.1016/j.advwatres.2012.08.010,
406    2013.

407  Friedlingstein, P., O'sullivan, M., Jones, M. W., Andrew, R. M., Bakker, D. C., Hauck, J., Landschützer, P., Le Quéré, C., Luijkx, I. T., Peters,
408    G. P., et al.: Global carbon budget 2023, Earth System Science Data, 15, 5301–5369, https://doi.org/10.5194/essd-15-5301-2023, 2023.

409  Gouttevin, I., Menegoz, M., Dominé, F., Krinner, G., Koven, C., Ciais, P., Tarnocai, C., and Boike, J.: How the insulating properties
410    of snow affect soil carbon distribution in the continental pan-Arctic area, Journal of Geophysical Research: Biogeosciences, 117,
411    https://doi.org/10.1029/2011JG001916, 2012.

412  Gouttevin, I., Langer, M., Löwe, H., Boike, J., Proksch, M., and Schneebeli, M.: Observation and modelling of snow at a polygonal tundra
413    permafrost site: spatial variability and thermal implications, The Cryosphere, 12, 3693–3717, https://doi.org/10.5194/tc-12-3693-2018,
414    2018.

415  Grogan, P.: Cold season respiration across a low arctic landscape: the influence of vegetation type, snow depth, and interannual climatic
416    variation, Arctic, Antarctic, and Alpine Research, 44, 446–456, https://doi.org/10.1657/1938-4246-44.4.446, 2012.

417  Grogan, P. and Jonasson, S.: Ecosystem CO2 production during winter in a Swedish subarctic region: the relative importance of climate and
418    vegetation type, Global Change Biology, 12, 1479–1495, https://doi.org/10.1111/j.1365-2486.2006.01184.x, 2006.

419  Guo, M., Wu, C., Peng, J., Lu, L., and Li, S.: Identifying contributions of climatic and atmospheric changes to autumn phenology over mid-
420    high latitudes of Northern Hemisphere, Global and Planetary Change, 197, 103 396, https://doi.org/10.1016/j.gloplacha.2020.103396,
421    2021.

422  Hale, K. E., Jennings, K. S., Musselman, K. N., Livneh, B., and Molotch, N. P.: Recent decreases in snow water storage in western North
423    America, Communications Earth & Environment, 4, 170, https://doi.org/10.1038/s43247-023-00751-3, 2023.

He, Q., Ju, W., Dai, S., He, W., Song, L., Wang, S., Li, X., and Mao, G.: Drought Risk of Global Terrestrial Gross Primary Productivity Over the Last 40 Years Detected by a Remote Sensing-Driven Process Model, Journal of Geophysical Research: Biogeosciences, 126, e2020JG005 944, https://doi.org/https://doi.org/10.1029/2020JG005944, 2021.

Huang, N., Wang, L., Song, X.-P., Black, T. A., Jassal, R. S., Myneni, R. B., Wu, C., Wang, L., Song, W., Ji, D., Yu, S., and Niu, Z.: Spatial and temporal variations in global soil respiration and their relationships with climate and land cover, Science Advances, 6, eabb8508, https://doi.org/10.1126/sciadv.abb8508, 2020.

Huang, Y., Ciais, P., Luo, Y., Zhu, D., Wang, Y., Qiu, C., Goll, D. S., Guenet, B., Makowski, D., De Graaf, I., et al.: Tradeoff of CO2 and CH4 emissions from global peatlands under water-table drawdown, Nature Climate Change, 11, 618–622, https://doi.org/10.1038/s41558-021-01059-w, 2021.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., et al.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps, Biogeosciences, 11, 6573–6593, https://doi.org/10.5194/bg-11-6573-2014, 2014.

Huning, L. S. and AghaKouchak, A.: Mountain snowpack response to different levels of warming, Proceedings of the National Academy of Sciences, 115, 10932–10937, https://doi.org/10.1073/pnas.1805953115, 2018.

Jung, M., Koirala, S., Weber, U., Ichii, K., Gans, F., Camps-Valls, G., Papale, D., Schwalm, C., Tramontana, G., and Reichstein, M.: The FLUXCOM ensemble of global land-atmosphere energy fluxes, Scientific Data, 6, 74, https://doi.org/10.1038/s41597-019-0076-8, 2019.

Jung, M., Schwalm, C., Migliavacca, M., Walther, S., Camps-Valls, G., Koirala, S., Anthoni, P., Besnard, S., Bodesheim, P., Carvalhais, N., Chevallier, F., Gans, F., Goll, D. S., Haverd, V., Köhler, P., Ichii, K., Jain, A. K., Liu, J., Lombardozzi, D., Nabel, J. E. M. S., Nelson, J. A., O'Sullivan, M., Pallandt, M., Papale, D., Peters, W., Pongratz, J., Rödenbeck, C., Sitch, S., Tramontana, G., Walker, A., Weber, U., and Reichstein, M.: Scaling carbon fluxes from eddy covariance sites to globe: synthesis and evaluation of the FLUXCOM approach, Biogeosciences, 17, 1343–1365, https://doi.org/10.5194/bg-17-1343-2020, 2020.

Kim, Y.: Effect of ablation rings and soil temperature on 3-year spring CO2 efflux along the Dalton Highway, Alaska, Biogeosciences, 11, 6539–6552, https://doi.org/10.1016/j.polar.2012.11.002, 2014.

Lafrenière, M. J., Laurin, E., and Lamoureux, S. F.: The impact of snow accumulation on the active layer thermal regime in high Arctic soils, Vadose Zone Journal, 12, 1–13, https://doi.org/10.2136/vzj2012.0058, 2013.

Lawrence, D. M. and Slater, A. G.: The contribution of snow condition trends to future ground climate, Climate Dynamics, 34, 969–981, https://doi.org/10.1007/s00382-009-0537-4, 2010.

Lawrence, D. M. and Swenson, S. C.: Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming, Environmental Research Letters, 6, 045 504, https://doi.org/10.1088/1748-9326/6/4/045504, 2011.

Lenton, T. M., Held, H., Kriegler, E., Hall, J. W., Lucht, W., Rahmstorf, S., and Schellnhuber, H. J.: Tipping elements in the Earth's climate system, Proceedings of the National Academy of Sciences, 105, 1786–1793, https://doi.org/10.1073/pnas.0911106106, 2008.

Li, P., Sayer, E. J., Jia, Z., Liu, W., Wu, Y., Yang, S., Wang, C., Yang, L., Chen, D., Bai, Y., and Liu, L.: Deepened winter snow cover enhances net ecosystem exchange and stabilizes plant community composition and productivity in a temperate grassland, Global Change Biology, 26, 3015–3027, https://doi.org/10.1111/gcb.15051, 2020.

Li, W., Wu, J., Bai, E., Guan, D., Wang, A., Yuan, F., Wang, S., and Jin, C.: Response of terrestrial nitrogen dynamics to snow cover change: a meta-analysis of experimental manipulation, Soil Biology and Biochemistry, 100, 51–58, https://doi.org/10.1016/j.soilbio.2016.05.018, 2016.

462    Ling, F. and Zhang, T.: Impact of the timing and duration of seasonal snow cover on the active layer and permafrost in the Alaskan Arctic,
463      Permafrost and Periglacial Processes, 14, 141–150, https://doi.org/10.1002/ppp.445, 2003.

464    Liu, H., Xiao, P., Zhang, X., Chen, S., Wang, Y., and Wang, W.: Winter snow cover influences growing-season vegetation productivity
465      non-uniformly in the Northern Hemisphere, Communications Earth & Environment, 4, 487, 2023a.

466    Liu, H., Xiao, P., Zhang, X., and Wu, Y.: Increased snow cover enhances gross primary productivity in cold and dry regions of the Tibetan
467      Plateau, Ecosphere, 14, e4656, https://doi.org/10.1002/ecs2.4656, 2023b.

468    Mast, M. A., Wickland, K. P., Striegl, R. T., and Clow, D. W.: Winter fluxes of $CO_2$ and $CH_4$ from subalpine soils in Rocky Mountain
469      National Park, Colorado, Global Biogeochemical Cycles, 12, 607–620, https://doi.org/10.1029/98gb02313, 1998.

470    Mavrovic, A., Sonnentag, O., Lemmetyinen, J., Voigt, C., Rutter, N., Mann, P., Sylvain, J.-D., and Roy, A.: Environmental controls of winter
471      soil carbon dioxide fluxes in boreal and tundra environments, Biogeosciences, 20, 5087–5108, https://doi.org/10.5194/bg-20-5087-2023,
472      2023.

473    Monteiro, D. and Morin, S.: Multi-decadal analysis of past winter temperature, precipitation and snow cover data in the European Alps from
474      reanalyses, climate models and observational datasets, The Cryosphere, 17, 3617–3660, https://doi.org/10.5194/tc-17-3617-2023, 2023.

475    Morgner, E., Elberling, B., Strebel, D., and Cooper, E. J.: The importance of winter in annual ecosystem respiration in the High Arctic:
476      effects of snow depth in two vegetation types, Polar Research, 29, 58–74, https://doi.org/10.3402/polar.v29i1.6052, 2010.

477    Mudryk, L., Santolaria-Otín, M., Krinner, G., Ménégoz, M., Derksen, C., Brutel-Vuilmet, C., Brady, M., and Essery, R.: Historical North-
478      ern Hemisphere snow cover trends and projected changes in the CMIP6 multi-model ensemble, The Cryosphere, 14, 2495–2514,
479      https://doi.org/10.5194/tc-14-2495-2020, 2020.

480    Muñoz-Sabater, J.: ERA5-Land hourly data from 1950 to present, https://doi.org/10.24381/cds.e2161bac, 2019.

481    Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hers-
482      bach, H., et al.: ERA5-Land: A state-of-the-art global reanalysis dataset for land applications, Earth System Science Data, 13, 4349–4383,
483      https://doi.org/10.5194/essd-13-4349-2021, 2021.

484    Musselman, K. N., Addor, N., Vano, J. A., and Molotch, N. P.: Winter melt trends portend widespread declines in snow water resources,
485      Nature Climate Change, 11, 418–424, https://doi.org/10.1038/s41558-021-01014-9, 2021.

486    Natali, S. M., Schuur, E. A. G., Trucco, C., Hicks Pries, C. E., Crummer, K. G., and Baron Lopez, A. F.: Effects of experimental warming
487      of air, soil and permafrost on carbon balance in Alaskan tundra: Warming OF Alaskan Tundra, Global Change Biology, 17, 1394–1407,
488      https://doi.org/10.1111/j.1365-2486.2010.02303.x, 2011.

489    Natali, S. M., Watts, J. D., Rogers, B. M., Potter, S., Ludwig, S. M., Selbmann, A.-K., Sullivan, P. F., Abbott, B. W., Arndt, K. A., Birch,
490      L., Björkman, M. P., Bloom, A. A., Celis, G., Christensen, T. R., Christiansen, C. T., Commane, R., Cooper, E. J., Crill, P., Czimczik, C.,
491      Davydov, S., Du, J., Egan, J. E., Elberling, B., Euskirchen, E. S., Friborg, T., Genet, H., Göckede, M., Goodrich, J. P., Grogan, P., Helbig,
492      M., Jafarov, E. E., Jastrow, J. D., Kalhori, A. A. M., Kim, Y., Kimball, J. S., Kutzbach, L., Lara, M. J., Larsen, K. S., Lee, B.-Y., Liu, Z.,
493      Loranty, M. M., Lund, M., Lupascu, M., Madani, N., Malhotra, A., Matamala, R., McFarland, J., McGuire, A. D., Michelsen, A., Minions,
494      C., Oechel, W. C., Olefeldt, D., Parmentier, F.-J. W., Pirk, N., Poulter, B., Quinton, W., Rezanezhad, F., Risk, D., Sachs, T., Schaefer, K.,
495      Schmidt, N. M., Schuur, E. A. G., Semenchuk, P. R., Shaver, G., Sonnentag, O., Starr, G., Treat, C. C., Waldrop, M. P., Wang, Y., Welker,
496      J., Wille, C., Xu, X., Zhang, Z., Zhuang, Q., and Zona, D.: Large loss of $CO_2$ in winter observed across the northern permafrost region,
497      Nature Climate Change, 9, 852–857, https://doi.org/10.1038/s41558-019-0592-8, 2019.

498  Natali, S. M., Holdren, J. P., Rogers, B. M., Treharne, R., Duffy, P. B., Pomerance, R., and MacDonald, E.: Permafrost
499     carbon feedbacks threaten global climate goals, Proceedings of the National Academy of Sciences, 118, e2100163 118,
500     https://doi.org/10.1073/pnas.2100163118, 2021.

501  Niu, B., Zhang, X., Piao, S., Janssens, I. A., Fu, G., He, Y., Zhang, Y., Shi, P., Dai, E., Yu, C., et al.: Warming homogenizes apparent
502     temperature sensitivity of ecosystem respiration, Science Advances, 7, eabc7358, 2021.

503  Niu, G.-Y. and Yang, Z.-L.: Effects of frozen soil on snowmelt runoff and soil water storage at a continental scale, Journal of Hydrometeo-
504     rology, 7, 937–952, https://doi.org/10.1175/jhm538.1, 2006.

505  Niu, S., Chen, W., Liáng, L. L., Sierra, C. A., Xia, J., Wang, S., Heskel, M., Patel, K. F., Bond-Lamberty, B., Wang, J., et al.: Temperature
506     responses of ecosystem respiration, Nature Reviews Earth & Environment, 5, 559–571, 2024.

507  Peng, S., Piao, S., Ciais, P., Fang, J., and Wang, X.: Change in winter snow depth and its impacts on vegetation in China, Global Change
508     Biology, 16, 3004–3013, https://doi.org/10.1111/j.1365-2486.2010.02210.x, 2010.

509  Pongracz, A., Wårlind, D., Miller, P. A., and Parmentier, F.-J. W.: Model simulations of arctic biogeochemistry and permafrost extent are
510     highly sensitive to the implemented snow scheme in LPJ-GUESS, Biogeosciences, 18, 5767–5787, 2021.

511  Pörtner, H.-O., Roberts, D. C., Masson-Delmotte, V., Zhai, P., Tignor, M., Poloczanska, E., Weyer, N., et al.: The ocean and
512     cryosphere in a changing climate, IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, 1155, 10–1017,
513     https://doi.org/10.1017/9781009157964, 2019.

514  Pulliainen, J., Luojus, K., Derksen, C., Mudryk, L., Lemmetyinen, J., Salminen, M., Ikonen, J., Takala, M., Cohen, J., Smolander, T., and Nor-
515     berg, J.: Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018, Nature, 581, 294–298, https://doi.org/10.1038/s41586-
516     020-2258-0, 2020.

517  Pulliainen, J., Aurela, M., Aalto, T., Böttcher, K., Cohen, J., Derksen, C., Heimann, M., Helbig, M., Kolari, P., Kontu, A., et al.: Increase
518     in gross primary production of boreal forests balanced out by increase in ecosystem respiration, Remote Sensing of Environment, 313,
519     114 376, 2024.

520  Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A.,
521     et al.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Global
522     Change Biology, 11, 1424–1439, https://doi.org/10.1111/j.1365-2486.2005.001002.x, 2005.

523  Ryan, M. G. and Law, B. E.: Interpreting, measuring, and modeling soil respiration, Biogeochemistry, 73, 3–27,
524     https://doi.org/10.1007/s10533-004-5167-7, 2005.

525  Schimel, D., Pavlick, R., Fisher, J. B., Asner, G. P., Saatchi, S., Townsend, P., Miller, C., Frankenberg, C., Hibbard, K., and Cox, P.: Observing
526     terrestrial ecosystems and the carbon cycle from space, Global Change Biology, 21, 1762–1776, https://doi.org/10.1111/gcb.12822, 2015.

527  Schimel, J. P., Bilbrough, C., and Welker, J. M.: Increased snow depth affects microbial activity and nitrogen mineralization in two Arctic
528     tundra communities, Soil Biology and Biochemistry, 36, 217–227, https://doi.org/10.1016/j.soilbio.2003.09.008, 2004.

529  Schuur, E. A., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M.,
530     et al.: Climate change and the permafrost carbon feedback, Nature, 520, 171–179, https://doi.org/10.1038/nature14338, 2015.

531  See, C. R., Virkkala, A.-M., Natali, S. M., Rogers, B. M., Mauritz, M., Biasi, C., Bokhorst, S., Boike, J., Bret-Harte, M. S., Celis, G.,
532     et al.: Decadal increases in carbon uptake offset by respiratory losses across northern permafrost ecosystems, Nature Climate Change, 14,
533     853–862, https://doi.org/10.1038/s41558-024-02057-4, 2024.

534 Segura, J. H., Nilsson, M. B., Schleucher, J., Haei, M., Sparrman, T., Székely, A., Bertilsson, S., and Öquist, M. G.: Microbial
535      utilization of simple carbon substrates in boreal peat soils at low temperatures, Soil Biology and Biochemistry, 135, 438–448,
536      https://doi.org/10.1016/j.soilbio.2019.06.006, 2019.

537 Slater, A. G., Lawrence, D. M., and Koven, C. D.: Process-level model evaluation: a snow and heat transfer metric, The Cryosphere, 11,
538      989–996, https://doi.org/10.5194/tc-11-989-2017, 2017.

539 Sturm, M., Holmgren, J., McFadden, J. P., Liston, G. E., Chapin, F. S., and Racine, C. H.: Snow–Shrub Interactions
540      in Arctic Tundra: A Hypothesis with Climatic Implications, Journal of Climate, 14, 336–344, https://doi.org/10.1175/1520-
541      0442(2001)014<0336:SSIIAT>2.0.CO;2, 2001.

542 Sturm, M., Taras, B., Liston, G. E., Derksen, C., Jonas, T., and Lea, J.: Estimating snow water equivalent using snow depth data and climate
543      classes, Journal of Hydrometeorology, 11, 1380–1394, https://doi.org/10.1175/2010jhm1202.1, 2010.

544 Tagesson, T., Kelly, J., Schurgers, G., Tian, F., Ardö, J., Horion, S., Ahlström, A., Olin, S., and Fensholt, R.: Increasing global ecosystem
545      respiration between 1982 and 2015 from Earth observation-based modelling, Global Ecology and Biogeography, 33, 116–130, 2024.

546 Tang, R., He, B., Chen, H. W., Chen, D., Chen, Y., Fu, Y. H., Yuan, W., Li, B., Li, Z., Guo, L., et al.: Increasing terrestrial ecosystem carbon
547      release in response to autumn cooling and warming, Nature Climate Change, 12, 380–385, https://doi.org/10.1038/s41558-022-01304-w,
548      2022.

549 Tramontana, G., Jung, M., Schwalm, C. R., Ichii, K., Camps-Valls, G., Ráduly, B., Reichstein, M., Arain, M. A., Cescatti, A., Kiely, G., et al.:
550      Predicting carbon dioxide and energy fluxes across global FLUXNET sites with regression algorithms, Biogeosciences, 13, 4291–4313,
551      https://doi.org/10.5194/bg-2015-661-rc1, 2016.

552 Wang, C., Han, Y., Chen, J., Wang, X., Zhang, Q., and Bond-Lamberty, B.: Seasonality of soil $CO_2$ efflux in a temper-
553      ate forest: Biophysical effects of snowpack and spring freeze–thaw cycles, Agricultural and Forest Meteorology, 177, 83–92,
554      https://doi.org/10.1016/j.agrformet.2013.04.008, 2013.

555 Wang, X., Piao, S., Ciais, P., Li, J., Friedlingstein, P., Koven, C., and Chen, A.: Spring temperature change and its implication in the
556      change of vegetation growth in North America from 1982 to 2006, Proceedings of the National Academy of Sciences, 108, 1240–1245,
557      https://doi.org/10.1073/pnas.1014425108, 2011.

558 Wang, X., Bai, X., Ma, L., He, C., Jiang, H., Sheng, L., and Luo, W.: Snow depths' impact on soil microbial activities and carbon dioxide
559      fluxes from a temperate wetland in Northeast China, Scientific Reports, 10, 8709, https://doi.org/10.1038/s41598-020-65569-x, 2020.

560 Wang, Y., Liu, H., Chung, H., Yu, L., Mi, Z., Geng, Y., Jing, X., Wang, S., Zeng, H., Cao, G., et al.: Non-growing-season soil respiration
561      is controlled by freezing and thawing processes in the summer monsoon-dominated Tibetan alpine grassland, Global Biogeochemical
562      Cycles, 28, 1081–1095, https://doi.org/10.1002/2013gb004760, 2014.

563 Wold, S., Esbensen, K., and Geladi, P.: Principal component analysis, Chemometrics and Intelligent Laboratory Systems, 2, 37–52,
564      https://doi.org/10.1016/j.chemolab.2005.01.003, 1987.

565 Yang, L. and Noormets, A.: Asynchrony of the seasonal dynamics of gross primary production and ecosystem respiration, Environmental
566      Research Letters, 19, 084 049, 2024.

567 Yi, C. and Zhang, Q.: A threshold precipitation function determines when ecosystem respiration depends on water, Nature Ecology &
568      Evolution, 8, 1792–1793, https://doi.org/10.1038/s41559-024-02502-9, 2024.

569 Yi, Y., Kimball, J. S., Watts, J. D., Natali, S. M., Zona, D., Liu, J., Ueyama, M., Kobayashi, H., Oechel, W., and Miller, C. E.: Investigating
570      the sensitivity of soil heterotrophic respiration to recent snow cover changes in Alaska using a satellite-based permafrost carbon model,
571      Biogeosciences, 17, 5861–5882, https://doi.org/10.5194/bg-17-5861-2020, 2020.

572  Zhang, Q., Yi, C., Destouni, G., Wohlfahrt, G., Kuzyakov, Y., Li, R., Kutter, E., Chen, D., Rietkerk, M., Manzoni, S., et al.: Water limitation
573      regulates positive feedback of increased ecosystem respiration, Nature Ecology & Evolution, pp. 1–7, https://doi.org/10.1038/s41559-
574      024-02501-w, 2024.

575  Zhang, T.: Influence of the seasonal snow cover on the ground thermal regime: An overview, Reviews of Geophysics, 43,
576      https://doi.org/10.1029/2004RG000157, 2005.

577  Zhang, Y., Sherstiukov, A. B., Qian, B., Kokelj, S. V., and Lantz, T. C.: Impacts of snow on soil temperature observed across the circumpolar
578      north, Environmental Research Letters, 13, 044 012, https://doi.org/10.1088/1748-9326/aab1e7, 2018.

579  Zheng, Q., Wang, S., Chen, W., Li, T., Liáng, L. L., Chu, H., Wang, Y., and Niu, S.: The optimal temperature of ecosystem respiration
580      homogenizes under global warming, Earth's Future, 13, e2025EF006 440, 2025.

581  Zhong, Z., He, B., Wang, Y.-P., Chen, H. W., Chen, D., Fu, Y. H., Chen, Y., Guo, L., Deng, Y., Huang, L., et al.: Disentangling the effects of va-
582      por pressure deficit on northern terrestrial vegetation productivity, Science Advances, 9, eadf3166, https://doi.org/10.1126/sciadv.adf3166,
583      2023.