

Initial Author Response for “Snow thermal conductivity controls future winter carbon emissions in shrub-tundra”, Rutherford *et al.*

The authors would like to thank the editor and reviewers for taking the time to read and review the manuscript and for the suggested improvements. The reviewer comments are included here in black and our initial responses are in green. Where we refer to line numbers in our response, this relates to the original submitted document.

Reply to comments from Reviewer 1:

Major comments:

The study is highly relevant for future climate projections and its relevance is nicely stated in the manuscript: Snow cover plays an important role in regulating soil temperatures through thermal insulation. Changing snow properties such as snow density, wetness, and snow cover duration will affect the insulating function of snow which will influence soil temperatures and thus alter wintertime CO₂ and CH₄ production. It is therefore crucial to accurately represent the insulating property of snow in model simulations, that is to use a suitable parameterization of the snow effective thermal conductivity K_{eff} . Further investigating the influence of snow on soil temperatures and greenhouse gas emissions might also help to explain higher observed than modelled wintertime carbon emissions.

Overall, the manuscript is written in a very concise and well-structured way that is easy to follow. Smooth transitions between the individual chapters further enhance the readability. The figures are well-designed and nicely support the findings described in the text.

Thank you for your positive feedback on the manuscript’s relevance and structure, we are pleased that the importance of accurately representing snow thermal conductivity and its impacts are clearly conveyed.

One strength of the study its very clear focus – it investigates the effect of using a refined K_{eff} parameterization on future wintertime greenhouse gas emissions. This focus is clearly stated in the title of the manuscript and I think that the manuscript could be further streamlined by strongly emphasizing this focus throughout the manuscript.

This could be achieved by more strongly relating the findings on future developments (e.g. on the zero-curtain period) to the revised K_{eff} parameterization. For this it would greatly help if the future development of K_{eff} according to the Jordan and Sturm parameterizations could be shown explicitly – both their seasonal cycle (as shown for SWE, soil temperature, and soil moisture in Fig. 3) as well as their development over time (as shown for CO₂ and CH₄ emissions in Fig. 6).

Simulated seasonal and interannual changes in K_{eff} could then be discussed with respect to changes in the underlying snow properties which could potentially be related to the development of precipitation vs. temperature shown in Figure 2. More explicit discussion of future changes in K_{eff} could help to relate previous findings, such as stated in II. 288-299, to the findings obtained from this study.

More clearly focusing on the influence of K_{eff} parameterization will further highlight the novelty of the study and make it stand out from the numerous studies that model future Arctic greenhouse gas emissions.

We will follow the suggestion of the reviewer and visualize K_{eff} as modelled by CLM5.0 under Jordan (1991) and Sturm et al. (1997) parameterisations to 2100. We will show K_{eff} seasonally across two time frames: 2016-2046 and 2066-2096 which presents K_{eff} over the seasonal cycle as well as demonstrating its development over time. This visualization will form part of the refined Figure 3:

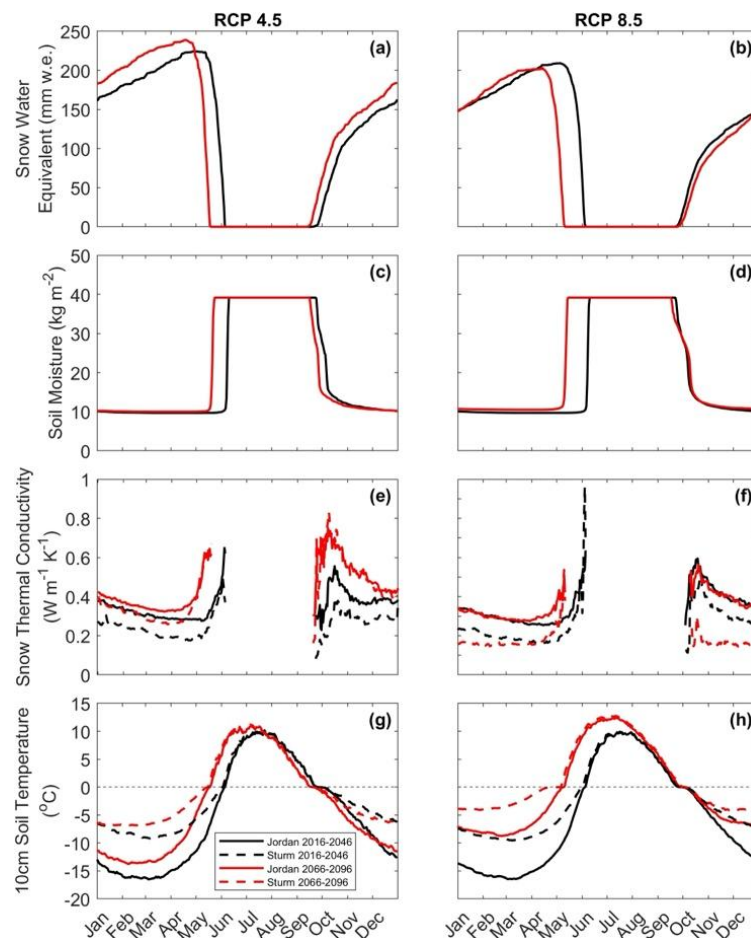


Figure 3 – CLM5.0 simulated median daily snow water equivalent (SWE; a,b), soil liquid water (12cm) content (c,d) snow thermal conductivity (e,f) and 10cm soil temperature (g,h) over two 30-year time periods: 2016-2046 (black) and 2066-2096 (red) under RCP 4.5 and RCP 8.5, for TVC using input meteorological data from an ensemble of 33 RCM-GCM combinations (RCP 4.5 n=6, RCP 8.5 n=27). Solid and dashed lines show ensemble median values for CORDEX-Jordan and CORDEX-Sturm experiments respectively.

We add the following text to the description of Figure 3 results:

“Compared to CORDEX-Jordan, Snow thermal conductivity using CORDEX-Sturm is lower on average by 0.07 and 0.14 W m⁻¹ K⁻¹ under RCP 4.5 and RCP 8.5 respectively.”

Specific comments:

Abstract:

I. 15: The transition from background information to the findings obtained in this study could be made clearer.

Added text: “To address this, we investigated the impacts of implementing a K_{eff} parameterisation more suitable to Arctic snowpacks into the Community Land Model (CLM5.0).”

II. 20-22: It would help if this statement could be elaborated a bit more in the main text or in the discussion section of the manuscript, if possible referring to one of the figures.

We will emphasise the impacts of the refined K_{eff} throughout the manuscript as per other comments below.

II. 22-24: The changes in duration and penetration depth of the zero-curtain period could be more explicitly related to the revised parameterization of K_{eff} .

This section of the abstract is refined as follows:

“Furthermore, CLM5.0 simulations using the refined K_{eff} show an extension of the early winter (Sept-Oct) zero-curtain, by nearly a month under RCP 8.5. Consequently, recent increases in both zero-curtain duration and winter CO_2 emissions appear set to continue to 2100.”

II. 24-26 The concluding statement should be more closely related to the role of snow and thereby to the title of the manuscript. As the current concluding remark is highly relevant as well, maybe a more specific statement could be added before.

Added text: “The average difference in refined K_{eff} compared with the default K_{eff} raises minimum winter soil temperatures by 4-7 °C by the end of the century under RCP 4.5 and 8.5.”

Introduction:

The introduction could be streamlined and shortened by introducing future wintertime CO_2 and CH_4 emissions only once. Currently those are introduced in II. 36-47 and in II. 60-65.

Lines 61-65 are removed to be more concise.

II. 67-74: This definition of “shoulder seasons” suggests a strong focus of on these transitional seasons throughout the manuscript. However, the reference to time periods around the snow cover period is not always clear in the results section. Maybe the season-specific role of snow could be clarified through showing and discussing the seasonal development of K_{eff} and the underlying snow properties.

Our current focus on the shoulder seasons in the manuscript are as follows:

- 1. The examination of shoulder season months (April, May, September, October) in Figure 2.**
- 2. Visualisation and discussion of shoulder season soil temperature, the zero-curtain period (Figure 3&4).**
- 3. The impact of shoulder season emissions on the overall winter budget (Figure 5).**

To build on this we will visualize the seasonal development of K_{eff} to reinforce the impact of snow on the seasonal cycle of soil temperature and carbon fluxes, and add the following text to demonstrate emphasis on shoulder season effects:

“This study addresses this knowledge gap by examining how projected changes in shoulder season air temperature, precipitation, snow thermal conductivity and soil temperature influence cold season carbon dynamics (Figures 2-5).”

“In shoulder season months (April, May, September and October), projected air temperatures increase on average by 1.6°C under RCP 4.5 and 3.7°C under RCP 8.5.”

“In the future under RCP 8.5, autumn shoulder season (Sep – Oct) near-zero temperatures penetrate up to 6m deeper into the soil column compared with the present day in the CORDEX-Sturm simulations (Figure 4h).”

“By the start of November, cumulative CO_2 emissions have reached 50-90% of their winter totals, highlighting the importance of autumn shoulder season emissions to the winter CO_2 budget. Under RCP 4.5 there is minimal increase in cumulative CO_2 after mid-late November (after day 80) with increases of $0.02 \text{ gCO}_2 \text{ m}^{-2} \text{ day}^{-1}$ and $0.00015 \text{ gCH}_4 \text{ m}^{-2} \text{ day}^{-1}$. Comparatively, under RCP 8.5, higher levels of emissions continue deeper into the winter with average increases of $0.07 \text{ gCO}_2 \text{ m}^{-2} \text{ day}^{-1}$ and $0.003 \text{ gCH}_4 \text{ m}^{-2} \text{ day}^{-1}$ (day 80 to day 240) (Figure 5).”

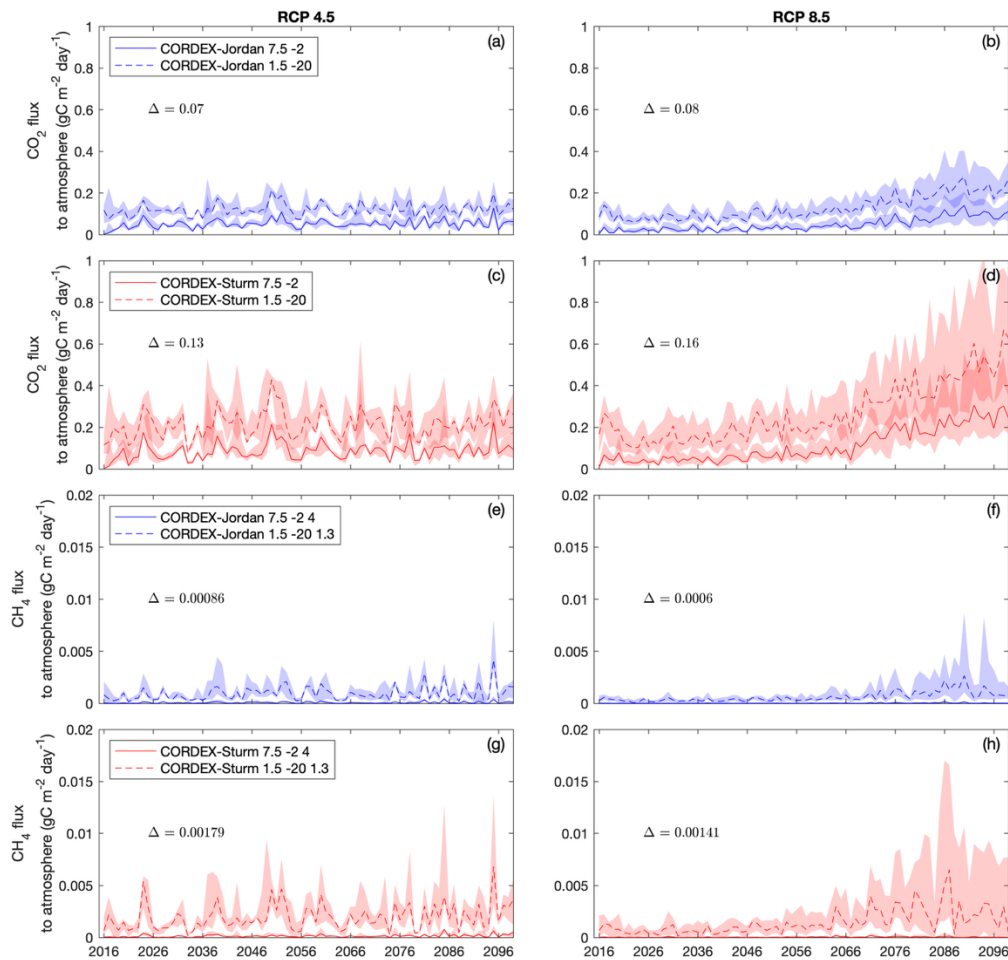
II. 75-91: Here you could highlight even more the novel contribution of your study – it builds on the findings by Dutch et al. (2023) who showed that the Sturm K_{eff} parameterization better reproduces observed soil temperatures at TVC. In your study, you now investigate the influence of this revised K_{eff} parameterization of future projections of greenhouse gas emissions from TVC.

We now include the following:

“Our study applies Q_{10} and Ψ_{\min} values suitable for tundra soil as defined by Dutch et al. (2023) to investigate the influence of different K_{eff} parameterisations on future projections of soil temperature and carbon emissions.”

II. 90-91: The findings on the sensitivity of CO₂ and CH₄ fluxes to Ψ_{\min} , Q_{10} , and $Q_{10\text{ch4}}$ are not mentioned in the main text although the parameters are mentioned both here in the study aim as well as explained in the methods section. Would it be possible to state a key finding related to these parameters in the main text and refer to Appendix E?

We now display the mean difference between carbon fluxes under different values Ψ_{\min} , Q_{10} , and $Q_{10\text{ch4}}$ from 2016-2100 in Appendix E1:



APPENDIX E1 – CLM5.0 simulated median soil respiration for the winter season, comparing the CORDEX-Jordan (blue) ensemble with CORDEX-Sturm (red) for two RCP scenarios (RCP 4.5 $n=6$, RCP 8.5 $n=27$). Shaded areas represent 75th and 25th percentiles and represent the CORDEX ensemble distribution. Each plot shows the extremes of Q_{10} , Ψ_{\min} and $Q_{10\text{ch4}}$ from the chosen parameter values seen in Appendix C1, where the lower end $\Psi_{\min} = -2$, $Q_{10} = 7.5$, $Q_{10\text{ch4}} = 4$ suppresses carbon output to and upper end $\Psi_{\min} = -20$, $Q_{10} = 1.5$, $Q_{10\text{ch4}} = 1.3$ which stimulates carbon output. The average difference between the displayed parameters (solid versus dashed lines, Δ) is included on each subplot.

We also add the following text to the results:

“Simulations with reduced Ψ_{\min} and (-20) consistently stimulate higher carbon fluxes under RCP 4.5 and 8.5 compared to simulations using the default Ψ_{\min} value (-2) (Appendix E1). This is particularly evident under CORDEX-Sturm which shows average increases of 0.13-0.16 gCO₂ m⁻² day⁻¹ and 0.0014-0.0018 gCH₄ m⁻² day⁻¹ from 2016-2100.”

We also add the following text to the discussion:

“Soil moisture and temperature are critical controls of soil carbon emissions and adjustments to Ψ_{\min} , Q_{10} and $Q_{10\text{ch4}}$ bring CLM5.0 simulations into closer alignment with field measurements

(Dutch et al., 2023). Future CO₂ and CH₄ emissions show greater seasonal variability under CORDEX-Sturm compared with CORDEX-Jordan, particularly under RCP 8.5, which suggests that soil moisture and thermal dynamics are more sensitive to snow cover in the CORDEX-Sturm configuration (Appendix E). “

Methodology:

Section 2.3: Definitions of h_{sl} and r_w are missing. Also, abbreviations ρ , K_{air} , and K_{ice} could be introduced explicitly.

We now include explicit definitions of these variables in section 2.3.

Results:

II. 192-193: Figure 2 shows shoulder season conditions only. Did you produce these graphs also for other months and could they potentially be included as an appendix figure to prove your statement that the shift in precipitation from snow to rain is most pronounced in the shoulder seasons?

We now include a visualisation of March, June, August and November as ‘Appendix F’ which shows all precipitation events falling either as snow or rain. This visualization supports our choice of visualizing April, May, September, October in the main body of the manuscript, which show shifts in precipitation phase from present to future.

I. 195: Figure 2 is very well-designed and informative. As it contains a lot of information a very clear description of what exactly is shown in the figure would be helpful. To me the variable of “precipitation frequency” was not intuitive at first. Maybe you could replace the term “median monthly precipitation” in the figure caption and explain instead that the graphs represent a frequency distribution of precipitation events related to the air temperatures.

We have revised the caption of Figure 2 as follows:

“Half-violin plots show the frequency distribution of precipitation events as a function of air temperature for TVC in April, May, September and October under RCP 4.5 (left) and RCP 8.5 (right). from an ensemble of 33 NA-CORDEX GCM-GCM combinations (RCP 4.5 n=6, RCP 8.5 n=27). White violins with black outlines represent 2016-2046 and red violins 2066-2096. The height of each violin represents the frequency of precipitation events at a given temperature. The solid and dashed black lines at 0 and 2 °C show transitional temperatures between snow and rain where CLM5.0 treats the transition in precipitation phase as a linear ramp. Inset boxplots show monthly total precipitation for the two 30-year periods.”

Section 3.2: This section could be split into two subsections (3.2.1 and 3.2.2): One on the simulations of environmental conditions (SWE, soil temperature, soil moisture; II. 210-243) and one on the simulated CO₂ and CH₄ emissions (II. 245 - 279).

These new subsections are now included: 3.2.1 Environmental conditions, 3.2.2 CO₂ and CH₄ emissions.

I. 216: Either “where” or “because” needs to be removed.

“Because” is removed.

I. 222: Reference error.

This cross-reference error is resolved.

I. 240: While one could argue that they would fit better into the discussion section of the manuscript, I very much like the smooth transitions between the individual chapters such as in II. 206-208, 241-244. However, some additional interpretations that do not directly serve as transitional sentences could be moved from the results to the discussion section. Those include II. 240-241, 253-255, and 261-262.

Line 240-241 has been moved to the discussion and modified as follows:

“Such increases in soil temperature and zero-curtain duration demonstrates both the influence of snow on soil temperatures at depth and the risks of climate warming on permafrost degradation and possible mobilisation of legacy carbon from Arctic soils.”

Line 253-255 and 261-262 are removed as these points repeat text elsewhere in the discussion.

II. 249-259 & Fig. 5: The results shown here are highly interesting and relevant. However, I find their description in the text a little confusing.

We have read through lines 249-259 and anticipate that the sections the reviewer is referring to are these:

[1] – “which suggests that the contribution of early winter emissions to the overall accumulation of winter emissions is key, in the period where the snowpack is accumulating and soil temperatures are cooling.”

And

[2] – “The importance of the early winter autumn shoulder season CO₂ release to the overall carbon budget under RCP 4.5 is clear as there is minimal increase in cumulative carbon after mid-late November with increases of 0.02 gCO₂ m⁻² day⁻¹ and 0.00015 gCH₄ m⁻² day⁻¹ (day 80 to day 240) averaged across present/future and CORDEX-Jordan/Sturm. By contrast, under RCP 8.5, CO₂ emissions are prolonged into the winter due to warmer soil temperatures, with an average increase of 0.07 gCO₂ m⁻² day⁻¹ and 0.003 gCH₄ m⁻² day⁻¹ (day 80 to day 240) (Figure 5).”

We combine and amend these sections as follows:

[1] - This sentence is removed.

We then add the following text:

“By the start of November, cumulative CO₂ emissions have reached 50-90% of their winter totals, highlighting the importance of autumn shoulder season emissions to the winter CO₂ budget. Under RCP 4.5 there is minimal increase in cumulative CO₂ after mid-late November (after day 80) with increases of 0.02 gCO₂ m⁻² day⁻¹ and 0.00015 gCH₄ m⁻² day⁻¹. Comparatively, under RCP 8.5, higher levels of emissions continue deeper into the winter with average increases of 0.07 gCO₂ m⁻² day⁻¹ and 0.003 gCH₄ m⁻² day⁻¹ (day 80 to day 240) (Figure 5).”

In I. 250, do you mean an “earlier onset of snow”? If I understand correctly, looking at Figure 3, the onset of snow is earlier in both RCP 4.5 than in RCP 8.5 and earlier in 2066-2096 than 2016-2046 for RCP 4.5.

This is now corrected to “earlier”.

In Figure 5, are CO₂ and CH₄ emissions zero before the onset of snow or were emissions not simulated for the snow-free period? In the latter case, I would prefer if the graphs were to start only with the onset of snow.

Cumulative carbon fluxes are plotted from 1st September to allow intercomparison across time periods in which snow season length may vary (i.e. the start date of snow accumulation >5mm SWE).

We specify the constraints of Figure 5 in the Methodology:

“A major focus of this study is the winter season when snow is on the ground (i.e. the snow-covered non-growing season). We define this period as the time when all model ensemble members (RCP 4.5 n=6, RCP 8.5 n=27) agree that SWE is >5mm. Simulations of SR and FCH₄ are filtered by these constraints so the analysis in Figures 5 and 6 is focused only on carbon fluxes across a common snow-covered, non-growing season in all scenarios and forcing datasets.”

As you describe in II. 251-252, cumulative carbon emissions during the snow-cover period are reduced under RCP 8.5 compared to RCP 4.5 due to a delayed snow onset. At first, this seems contradictory to the higher simulated future total carbon emissions (Figure 6). In II. 262-265 you refer to Appendix D to clarify the matter. However, this explanation is not entirely clear to me. Maybe it would help to more explicitly describe the relation between snow-cover season and annual carbon emissions and their future developments. This would also further highlight the importance of early winter emissions.

It should furthermore be clarified what “unconstrained by snow cover” and “irrespective of snow” means in both I. 263 and in the figure caption of Appendix D. Does it mean that the snow cover is still considered in the simulation (as indicated by the effect of the K_{eff} parameterization) and that carbon emissions are simulated for the entire 300 days following September 1st instead of for the snow-covered period only?

Our CLM5.0 simulations are year-round, however the visualised accumulation of emissions in Figure 5 are constrained by snow-down (where SWE >5mm). Hence, in the future under RCP 8.5 due to warming causing a shorter snow-covered season, the overall accumulated emissions are lower compared to the longer snow season in RCP 4.5. Appendix D1 aims to reinforce the importance of the early snow-season in the total accumulation of winter emissions. Blue and green lines in Appendix D1 show CO₂ and CH₄ cumulative emissions irrespective of whether snow is on the ground therefore containing periods of snow-free emissions as well as snow-covered emissions. This contrasts with Figure 5 which only shows snow-covered emissions.

To help clarify these visualizations we make the following amendments to the text:

“Appendix D1 presents a comparison between cumulative emissions limited to when snow is on the ground, as per Figure 5, and those unconstrained by snow cover.”

The findings from Figure 5 should be discussed in the discussion section, referring to the seasonal change in K_{eff} and soil temperatures under the different scenarios and parameterizations.

We add the following comments to the discussion to focus on the influence of K_{eff} on accumulated emissions:

“Under RCP 8.5 cumulative winter carbon emissions from soils at TVC are projected to increase in the future despite a reduction in snow-cover duration. A reduced K_{eff} , as introduced by CORDEX-Sturm (Figure 3), increases cumulative winter CO_2 and CH_4 emissions by 50-150% compared with CORDEX-Jordan under both RCP 4.5 and 8.5”.

Discussion

I think that the entire discussion section could benefit from a stronger focus on your specific findings and on the effect of snow properties as opposed to the more general speculations on future changes in snow cover and carbon emissions.

For example, do your model simulations support the previous finding of increasing K_{eff} in the future (l. 295)?

Lines 294-297 are removed as they are speculative and don't align with our visualization of K_{eff} .

We add emphasis to the refinement of K_{eff} in the discussion through addressing previous comments by:

- Discussing sensitivity of parameters to Ψ_{min} , Q10 and Q10ch4 under CORDEX-Jordan and CORDEX-Sturm.
 - “Soil moisture and temperature are critical controls of soil carbon emissions and adjustments to Ψ_{min} , Q10 and Q10ch4 bring CLM5.0 simulations into closer alignment with field measurements (Dutch et al., 2023). Future CO_2 and CH_4 emissions show greater seasonal variability under CORDEX-Sturm compared with CORDEX-Jordan, particularly under RCP 8.5, which suggests that soil moisture and thermal dynamics are more sensitive to snow cover in the CORDEX-Sturm configuration (Appendix E1). “
- Including explicit impacts of snow representation on zero-curtain duration.
 - “Simulations performed in this study indicate an increase in both the duration and depth of the early winter zero curtain under future climate conditions (Figure 4). Under CORDEX-Sturm, the projected early winter zero curtain extends up to 26 days longer and reaches depths up to 6m deeper than under CORDEX-Jordan further highlighting the impact of snow representation on simulated soil temperatures.”
- Reference to the new visualisation of K_{eff} when discussing future cumulative carbon flux simulations.
 - “A reduced K_{eff} ($0.07-0.14 \text{ W m}^{-1} \text{ K}^{-1}$), as introduced by CORDEX-Sturm (Figure 3), increases cumulative winter CO_2 and CH_4 emissions from 2016-2100 by 50-150% compared with CORDEX-Jordan under both RCP 4.5 and 8.5.”

Similarly, changes in the zero-curtain period should be discussed with a more explicit relation to the parameterization of snow properties (ll. 320-332).

We amend this discussion point and better clarify the impact of K_{eff} refinement and future climate on projected soil temperatures.

“Simulations performed in this study indicate an increase in both the duration and depth of the

early winter zero curtain under future climate conditions (Figure 4). Under CORDEX-Sturm, the projected zero-curtain duration extends up to 26 days longer than under CORDEX-Jordan further highlighting the impact of snow representation on simulated soil temperatures.”

Conclusions

I. 357: You could consider referring to Callaghan et al. (2011) already in the introduction to stress its high relevance for your study.

To further refer to this paper, and to reinforce the role of Arctic snow we add the following to the introduction:

“Arctic snow is a key determinant of ground temperature and plays a major role in the wider hydrological and ecological Arctic system (Callaghan et al., 2011).”

I. 357-358: The overall study aim here sounds different to me than the one stated in II. 90 – 91. I would suggest keeping the main focus on the snow thermal conductivity.

Lines 357-398 are removed and we add emphasis on K_{eff} with the following text:

“Projected CO_2 and CH_4 emissions are highly sensitive to parameters K_{eff} , Ψ_{min} , Q10 and Q10ch4 which govern soil respiration. We find that lower Ψ_{min} consistently increases cold season carbon fluxes and higher Q10 suppressed them, which aligns with the findings of Dutch et al. (2023). Implementing the Sturm et al. (1997) K_{eff} parameterisation increased the sensitivity of modelled carbon emissions to Ψ_{min} and Q10 compared with the default K_{eff} parameterisation.