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 reviewer for taking the time to read and review the revised 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 reviewer 2 comments:

The revised manuscript is much improved but I'm still a bit surprised at the choice of rcp 8.5 given that it's been widely derided as unrealistic and I feel that the manuscript in many places reads like these dynamics are likely to happen rather than just model realizations. Or perhaps this is just my perception.

We much appreciate the reviewer's opinion that the manuscript is much improved. In terms of inference in the manuscript that we suggest the RCP 8.5 simulation will happen, we found it a little surprising that this was not an issue raised in the initial review. We have tried hard to illustrate uncertainties in all projections by inclusion of both RCP 4.5 and 8.5 throughout the manuscript. While RCP 8.5 may not be attained, the future is likely to be closer to RCP 8.5 than 4.5 towards the end of the century. On re-reading the manuscript to look for unintended messages that model projections (particularly RCP 8.5) were actual realizations, we struggled to find any. Instead, the thrust of our message that CO_2/CH_4 projections from the representation of snow is as large as the climatic variability in the NA-CORDEX datasets remains quantitatively explicit in the description of uncertainty in simulations.

I like how the revised snow physics module introduces numerous improvements, but because CO2 and methane flux are largely dependent on labile inputs from vegetation growth, even during the shoulder and winter seasons, the lack of focus on how the models treat these processes, especially with respect to future changes, diminishes confidence in the results. This is not to say that the model is in any way bad, it certainly represents an improvement, but the focal areas should be more on model improvements rather than overconfident statements like 'This alignment between observations and simulations provides confidence in the model's ability to simulate future Arctic soil processes through to 2100' on line 318. Keeping the message on the importance of snow parameterizations would improve the flow and help inspire further model improvements.

Correct model process representation of microbial processing of labile carbon is indeed important. And how in the shoulder season this impacts temporally aggregated fluxes to and from the atmosphere would benefit from greater consideration. However, as the reviewer states, our improvements to snow physics are a very welcome development and push forward our capacity to provide plausible simulations of future environmental change. This will only benefit future, more explicit model representation of microbial processing of labile carbon.

We in no way wished to suggest our model improvements for carbon fluxes under tundra snow were an end game, so we welcome the reviewer's opinion that this may have been an unintended consequence of our revised text. Consequently, we have 'softened' the tone of the statement designed to reaffirm to the reader that the Q10 and ψ_{min} parameter values of Dutch et al. 2024 are much more appropriate for Arctic tundra soils than CLM5.0 default values. Consequently, we have changed "This alignment between observations and simulations provides confidence in the model's ability to simulate future Arctic soil processes through to 2100" to "This alignment between observations and simulations increases confidence in the model's ability to plausibly simulate future Arctic soil processes through to 2100"

87: units? Should be MPa

These missing units have now been added.

104 and elsewhere: use a non-breaking space between numbers and units like between all the degree Celsius symbols. Line 235 for example does this more or less correctly.

Spaces between numbers and units are now non-breaking spaces.

The discussion could be reorganized a bit for readability, at the moment it is 3 massive paragraphs.

The discussion is edited and restructured to be more concise and to contain 4 paragraphs for readability, as follows:

1. **We remove the following text to emphasise that this paragraph discusses the future:**

"Winter snow cover has a significant influence on the ground thermal regime (Zhang, 2005) and it's representation within ESMs is critical for simulated soil temperatures. The more realistic Keff parameterisation in the CORDEX-Sturm simulations results in reduced soil temperature biases in CLM5.0 (Dutch et al., 2023) and elevates simulated winter soil temperatures to between -10 and 0 °C . Within this range, respiration rates begin to increase rapidly (Natali et al., 2019). Cumulative winter CO2 simulations (Figure 5) under present day conditions are in line with contemporary (2016-2019) NEE simulations, generated using in-situ meteorological data at TVC (Dutch et al., 2024) for both Jordan (~15-35 gCO2 m-2) and Sturm (~25-55 gCO2 m-2) Keff parameterisations."

And add:

"Soil temperatures are linked to changes in the atmosphere by the thermal conductivity of the snow layer"

2. **We remove the following text:**

"Natali et al. (2019) estimated that winter CO2 emissions would increase by 41% by 2100 (from 'present', i.e. 2003-2017 conditions; Natali et al. (2019); this study 2016-2046) under RCP 8.5 whereas CLM5.0 simulations of CO2 emissions under CORDEX-Sturm more than triple under RCP 8.5 which demonstrates the impact of snow representation on simulated soil carbon emissions. Under RCP 8.5 the magnitude of the influence of CORDEX-Sturm on winter carbon fluxes is comparable to the uncertainty in the future climate, reinforcing the importance of snow representation in future projections of Arctic carbon fluxes."

And rework this paragraph to be more concise:

"By comparison, Natali et al. (2019) projected a 41% increase in CO2 emissions by 2100 compared to present. Additionally, under RCP 8.5, the magnitude of the influence of CORDEX-Sturm on winter carbon fluxes is comparable to the uncertainty associated with future climate projections, and snow-related processes - snow cover extent and duration (Natali et al. 2019) and snow thermal conductivity (this study) - emerge as common critical drivers of this uncertainty."

3. **We remove the following text:**

Soil moisture and temperature are critical controls of soil carbon emissions and adjustments to Ψmin, Q10 and Q10ch4 bring CLM5.0 simulations into closer alignment with field measurements (Dutch et al., 2023).”

“Further, the difference in CO2 output between RCP 4.5 and 8.5 shows the possible impacts of climate mitigation efforts on future Arctic winter carbon emissions (Figure 6).”

And more the following text to later in the paragraph:

“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 (Figure E1).”

4. **Finally we remove the following text to better focus on our site specifically (TVC), to be more concise and to keep the focus on future emissions:**

In the recent past (1950 to 2017), both zero-curtain and cold season CO2 emissions have increased, for one site of 0.17 and 0.36 gC m-2 yr-1 at Atqasuk, Alaska (Tao et al., 2021), and CLM5.0 simulations suggest that this is set to continue to 2100. 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.