Summary:

In their study, the authors evaluate the influence of a refined parameterization of snow effective thermal conductivity (Keff) on future wintertime CO2 and CH4 emissions from a shrub-tundra site in the Canadian Arctic. They show that using a Keff parameterization, that has in a previous study been found to better reproduce observed soil temperatures at the site, strongly enhances projections of wintertime CO2 and CH4 emissions for the second half of the 21st century under climate scenarios RCP 4.5 and RCP 8.5.

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 Keff. 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.
One strength of the study its very clear focus – it investigates the effect of using a refined Keff 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 Keff parameterization. For this it would greatly help if the future development of Keff 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 Keff 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 Keff could help to relate previous findings, such as stated in ll. 288-299, to the findings obtained from this study.
More clearly focusing on the influence of Keff 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.

Specific comments:

<u>Abstract:</u>

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

ll. 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.

ll. 22-24: The changes in duration and penetration depth of the zero-curtain period could be more explicitly related to the revised parameterization of Keff.

ll. 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.

Introduction:

The introduction could be streamlined and shortened by introducing future wintertime CO2 and CH4 emissions only once. Currently those are introduced in ll. 36-47 and in ll. 60-65.

ll. 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 Keff and the underlying snow properties.

ll. 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 Keff parameterization better reproduces observed soil temperatures at TVC. In your study, you now investigate the influence of this revised Keff parameterization of future projections of greenhouse gas emissions from TVC.

ll. 90-91: The findings on the sensitivity of CO2 and CH4 fluxes to Ψmin, Q10, and Q10ch4 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?

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.

Results:

ll. 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?

l. 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.

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; ll. 210-243) and one on the simulated CO2 and CH4 emissions (ll. 245 - 279).

l. 216: Either "where" or "because" needs to be removed.

l. 222: Reference error.

l. 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 ll. 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 ll. 240-241, 253-255, and 261-262.

ll. 249-259 & Fig. 5: The results shown here are highly interesting and relevant. However, I find their description in the text a little confusing.
In l. 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.
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.
As you describe in ll. 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 ll. 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 l. 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 Keff parameterization) and that carbon emissions are simulated for the entire 300 days following September 1st instead of for the snow-covered period only?
The findings from Figure 5 should be discussed in the discussion section, referring to the seasonal change in Keff and soil temperatures under the different scenarios and parameterizations.

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 Keff in the future (l. 295)?
Similarly, changes in the zero-curtain period should be discussed with a more explicit relation to the parameterization of snow properties (ll. 320-332).

Conclusions

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

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