Article Review comments for: "Observations of methane net sinks in the Arctic tundra", Biogeosciences, Manuscript ID: egusphere-2024-1440

We thank the Reviewers for their careful assessment of our manuscript and their valuable suggestions. We found them very useful for improving and clarifying some of the information that was unclear in the submitted manuscript. Below, we respond to the comments in turn, and summarise modifications made to the manuscript. Our responses are formatted as follows:

Reviewer comments **- black text (bold)**
Author responses - black text
Revised manuscript text - **blue text (bold)**
Line numbers refer to those in the original submission.

Note: Figures in the manuscript are referred to as "Fig. X", figures included in these review responses, but not in the manuscript are referred to as "Fig. RY".

Reviewer #1: RC1: 'Comment on egusphere-2024-1440' - https://doi.org/10.5194/egusphere-2024-1440-RC1

This paper describes two years of eddy covariance CO_2 and CH_4 flux data from an upland tundra in the Svalbard archipelago. These fluxes are quality controlled, and gap filled using standard methodologies. The paper finds that the system is a sink of both CO_2 and CH_4 but the relevance of this sink to the wider region or global level is not clearly explained. There is also not much discussion of how the magnitude of the sink observed compares to other upland soil measurements in the Arctic.

We agree with the Reviewer, now in the revised version of the manuscript a comparative analysis with other Arctic studies has been included, as follow:

3.1 CO_2 and CH_4 mixing ratio and surface fluxes

Seasonal analysis reveals negative median values for the fluxes of CO_2, peaking in summer with -0.37 µmol m^{-2} s^{-1}. **The CO_2 fluxes showed a slightly positive median value during the dark winter (0.02 µmol m^{-2} s^{-1}), actually, due to respiration phenomena from the snow covered surface due to microbial respiration (Hicks Pries et al., 2013). At a finer time scale (30 min resolution), the**

CO_2 flux trend indicates the presence of positive fluxes (emissions) (Fig. 3a), especially during the dark/light winter and the freezing period (Table 1). **As snowmelt begins, accumulated carbon dioxide may be released and exposed patches of ground with a lower albedo begin to warm, further enhancing respiration rates and CO_2. Further, during thawing season, incoming radiation reaches levels adequate for photosynthesis: the combination of increasing light, along with increases in soil temperatures can result in early photosynthesis. At the CCT site, the CO_2 flux decreased starting from the light winter (-0.84 µmol m^{-2} s^{-1}) and it continues during the thawing season (-0.18 µmol m^{-2} s^{-1}). During the fall, soil temperatures were still adequate for substantial microbial respiration. When the senescence of vascular plants advanced, respiration became the dominant process affecting carbon exchange. In addition, as soils freeze, CO_2 may be forced out of the soil towards the atmosphere. However, in the freezing period, at the CCT site, a median negative CO_2 flux has been measured (-0.79 µmol m^{-2} s^{-1}).**

A similar trend is reported for methane: during the dark and light winter periods, methane fluxes are negative, with a median value of -0.17 and -0.36 nmol m^{-2} s^{-1}, respectively (Fig. 3d). **Treat et al. (2018) investigated methane dynamics across Arctic sites and reported negative methane fluxes during winter, attributed to cold temperatures, which inhibit methanogenesis while promoting methane oxidation in dry tundra soils. However, they also highlight methane uptake in dry tundra during colder periods. Zona et al. 2016 reported that methane emissions during the cold season (September to May) account for ≥ 50% of the annual CH_4 flux, with the highest emissions from upland tundra. In this study (Table 1), evidence of significant emission events during winter temperature fluctuations can be observed at the site.** In contrast, these events diminished in the shoulder seasons, where notable net uptake events dominated, with -0.83 nmol m^{-2} s^{-1} during thawing and -0.69 nmol m^{-2} s^{-1} during freezing period. **Seasonal analysis reveals negative median CH_4 fluxes, peaking in summer at-1.28 nmol m^{-2} s^{-1}. Juncher Jørgensen et al. (2015) field measurements, within the Zackenberg Valley in northeast Greenland over a full growing season, show methane uptake with a seasonal average of -2.3 nmol m^{-2} s^{-1} in dry tundra. Wagner et al. (2019) measured a negative peak during the growing season (2009) of -4.41 ng C-CH_4 m^{-2} s^{-1} in a polar desert area at the Cape Bounty Arctic Watershed Observatory (CBAWO - Melville Island, Canada).**

3.2 CO_2 and CH_4 mass budget

The cumulative mass budgets over the two monitoring years at the CCT site ecosystem are shown in Fig. 4. Based on the budget for the whole measurement period, the study area acts as a net sink for both CO_2 and CH_4. During the study period, a CO_2 balance of almost -257 CO_2 g m^{-2} is found, while the contribution of CH_4 uptake is estimated at approximately -0.36 g CH_4 m^{-2} (Fig. 4, dashed red line). Actually, for the evaluation of the cumulated carbon, the gap filled time series should be considered (both with MDS and RF methodology, see Section 2.3). In this perspective, the total cumulative CO_2 budget over the measurement campaign is -472 g CO_2 m^{-2} with MDS and -650 g CO_2 m^{-2} using the RF procedure, respectively (Fig. 4a). On the other hand, CH_4 cumulative budget is about -0.76 g CH_4 m^{-2} with the RF gap filling procedure (Fig. 4b). The mean annual cumulative CO_2 budget is -131 g CO_2 m^{-2} with MDS and -164 g CO_2 m^{-2} with RF. **Oechel et al. (2014) reported a net CO_2 uptake during the summer season of -24.3 g C m^{-2}, while the no growing seasons released 37.9 g C m^{-2}, showing that these periods comprise a significant source of carbon to the atmosphere. In Treat et al. (2024) is reported for 2002–2014, a smaller CO_2 sink in Alaska, Canadian tundra, and Siberian tundra (medians: -5 to -9 g C m^{-2} $year^{-1}$). Euskirchen et al. (2012) established eddy covariance flux towers in an Alaska heath tundra ecosystem to collect CO_2 flux data continuously for over three years. They measured a peak CO_2 uptake, during July, with an accumulation of -51 -95 g C m^{-2} during June–August. On average, the mean annual cumulative budget for CH_4 is -0.18 g CH_4 m^{-2} $year^{-1}$, calculated using gap-filled data (Table 2). This outcome lies within the same order of magnitude estimated by Dutaur et al. (2007) at the global level, reporting a net CH_4 uptake for the non-forested arctic environments (defined as "boreal other") of -0.14 g CH_4 m^{-2} $year^{-1}$. Treat et al. (2018) found that tundra upland varies from CH_4 sink to CH_4 source with a median annual value of 0.0 ± 0.20 g C m^{-2} $year^{-1}$. Lau et al., (2015) found that the CH_4 uptake rate was in the range between −0.1 to −0.8 mg CH_4-C m^{-2} day^{-1} at AHI site (Nunavut, Canada). In this work it was suggested that mineral cryosols act as a constant active atmospheric CH_4 sink (Emmerton et al., 2014) in part because of their low soil organic carbon availability, low vegetation cover and low moisture content.**

The annual budget can be further split into the five seasons considered in this study. Specifically, the CCT area acted as a CO_2 sink during the thawing and summer period with an average value of -0.79 and -1.1 g CO2 m^{-2} day^{-1}, respectively. **During the freezing period the quantity of absorbed CO_2 per day decreased down to almost null value (-0.01 g CO_2 m^{-2} day^{-1}), and slightly increased to a positive value during the dark winter period (0.04 g CO_2 m^{-2} day^{-1}). With the increasing amount of the solar radiation, the mass cumulative CO_2 per day decreased again (-0.25 g CO_2 m^{-2} day^{-1} for light winter). Ueyama et al. (2014) analysed seasonal CO_2 budgets across several tundra ecosystems in Alaska, reporting peak CO_2 uptake during summer with an average value of -46 g C m^{-2} due to maximum photosynthesis rates.** The same pattern was followed by the CH_4 absorbed carbon mass: in this case during the thawing period was observed a value on average of -0.55 mg CH_4 m^{-2} day^{-1}, peaking its negative maximum during the summer period (-1.29 mg CH_4 m^{-2} day^{-1}).

Also, in this case the absorbed carbon mass decreases in the freezing period down to -0.63 mg CH_4 m^{-2} day^{-1}. It was reduced to very low values during the winter season with -0.26 mg CH_4 m^{-2} day^{-1} in dark winter and -0.40 mg CH_4 m^{-2} day^{-1} in light winter.

Dutaur, L., and Verchot, L.V.: A global inventory of the soil CH_4 sink. Global Biogeochem. Cycles, 21, 4013. https://doi.org/10.1029/2006GB002734, 2007.

Emmerton, C. A., St Louis, V. L., Lehnherr, I., Humphreys, E. R., Rydz, E., and Kosolofski, H. R.: The net exchange of methane with high Arctic landscapes during the summer growing season, Biogeosciences, 11, 3095–3106, https://doi.org/10.5194/bg-11-3095-2014, 2014.

Euskirchen, E. S., Bret-Harte, M. S., Scott, G. J., Edgar, C., and Shaver, G. R.: Seasonal patterns of carbon dioxide and water fluxes in three representative tundra ecosystems in northern Alaska, Ecosphere, 3(1):4, http://dx.doi.org/10.1890/ES11-00202.1, 2012.

Hicks Pries, C.E., Schuur, E.A.G. and Crummer, K.G.: Thawing permafrost increases old soil and autotrophic respiration in tundra: Partitioning ecosystem respiration using d13C and Δ14C. Glob. Change Biol., 19, 649–661, doi: 10.1111/gcb.12058, 2013

Juncher Jørgensen, C., Lund Johansen, K. M.,Westergaard-Nielsen, A., and Elberling, B.: Net regional methane sink in High Arctic soils of northeast Greenland, Nat. Geosci., 8, 20–23, https://doi.org/10.1038/ngeo2305, 2015.

Lau, M. C. Y., Stackhouse, B. T., Layton, A. C., Chauhan, A., Vishnivetskaya, T. A., Chourey, K., Ronholm, J., Mykytczuk, N. C. S., Bennett, P. C., Lamarche-Gagnon, G., Burton, N., Pollard, W. H., Omelon, C. R., Medvigy, D. M., Hettich, R. L., Pfiffner, S. M., Whyte, L. G., and Onstott, T. C.: An active atmospheric methane sink in high Arctic mineral cryosols, ISME J., 9, 1880-1891, 2015.

Oechel, W. C., Laskowski, C. A., Burba, G., Gioli, B. , and Kalhori, A. A. M.: Annual patterns and budget of CO_2 flux in an Arctic tussock tundra ecosystem. J. Geophys. Res. Biogeosci., 119, 323–339, doi:10.1002/2013JG002431, 2014.

Treat, C. C., Virkkala, A.-M., Burke, E., Bruhwiler, L., Chatterjee, A., Fisher, J. B., et al.: Permafrost carbon: Progress on understanding stocks and fluxes across northern terrestrial ecosystems, J. Geophys. Res.-Biogeo., 129, e2023JG007638, https://doi.org/10.1029/2023JG007638, 2024.

Treat, C.C, Bloom, A.A, Marushchak, M.E.: Nongrowing season methane emissions—a significant component of annual emissions across northern ecosystems. Glob. Change Biol.,24:3331–3343, https://doi.org/10.1111/gcb.14137, 2018

Ueyama, M., Iwata, H., Harazono, Y., Euskirchen, E. S., Oechel, W. C., & Zona, D. (2014). *Growing season and spatial variations of carbon fluxes of Arctic and boreal ecosystems in Alaska (USA)*. *Ecological Applications*, **24**(8), 1798–1816. doi:10.1890/13-0725.1

Wagner, I., Hung, J. K. Y., Neil, A., and Scott, N. A.: Net greenhouse gas fluxes from three High Arctic plant communities along a moisture gradient, Arct. Sci., 5, 185–201, https://doi.org/10.1139/as-2018-0018, 2019.

Zona, D., Gioli, B., Commane, R., Lindaas, J., Wofsy, S. C., Miller, C. E., Dinardo, S. J., Dengel, S., Sweeney, C., Karion, A., Chang, R.-W., Henderson, J. M., Murphy, P. C., Goodrich, J. P., Moreaux, V., Liljedahl, A., Watts, J. D., Kimball, J. S., Lipson, D. A., and Oechel, W. C.: Cold season emissions dominate the Arctic tundra methane budget, P. Natl. Acad. Sci. USA, 113(1), 40–45, https://doi.org/10.1073/pnas.15160 17113, 2016.

The authors also perform some correlational analysis of the fluxes against potential driving variables and find that higher CO_2 fluxes are correlated with high wind speeds and high temperature anomalies. The CH_4 fluxes in contrast are not found to correlate with expected driving variables like soil temperature and the authors propose that a mismatch in the depth of

the microbial community and the soil temperature may explain this but do not explore if they can recover the expected correlation with lag analysis.

Authors wish to thank the Reviewer for this interesting and valuable suggestion. Please, see the specific question point below.

The authors also describe a seasonal cycle in both fluxes with a maximal sink in the summer and near 0 fluxes in the winter. Other relationships (including null relations) with potential driving variables are not reported and the diel cycles in the flux data are not discussed.

Authors thank the Reviewer for his/her valuable suggestion. Please note that daily patterns for different seasons for both CO_2 and CH_4 have now been included here. A diurnal variability in both fluxes can be observed in the summer period. On the other hand, in winter (especially in the dark winter but also during freezing and thawing periods) such diurnal cycles cannot be so clearly distinguished. In particular the diel pattern for CH_4 is almost absent. We think that such analysis doesn't add any particular improvement to the work. At the CCT site there is not a definite diel cycle as shown in figure R1.

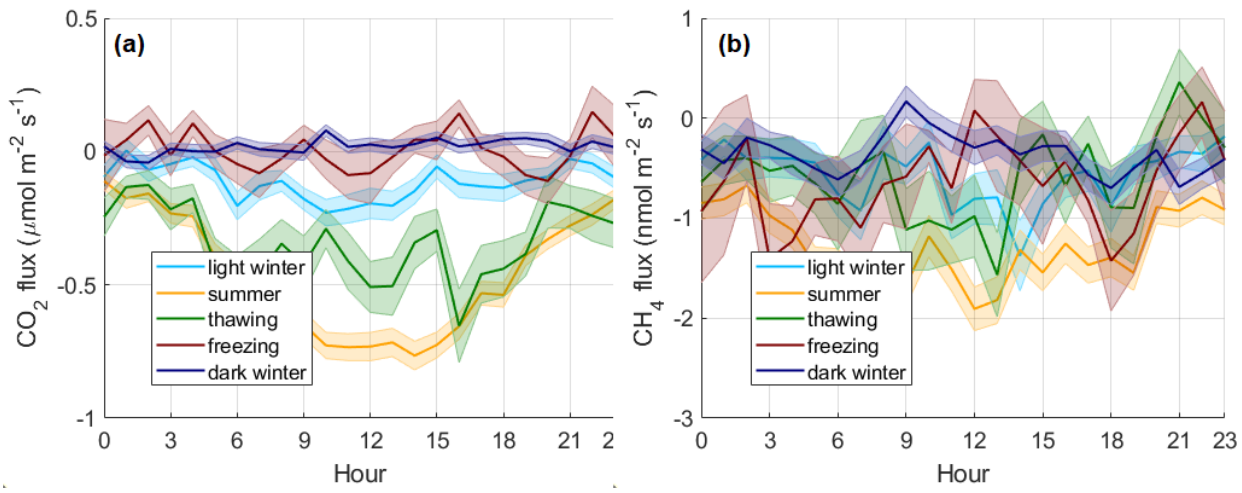

Figure R1 Diurnal pattern for the a) CO_2 and b) CH_4 flux at our measurement site. The patterns were reported for the different seasons considered in this work. Continuous line represents the mean flux values, while the colour shadow area represents the standard error of the measurements.

The authors also propose explanations for the flux correlations and seasonality, but they do not seem to be strongly supported by other lines of evidence. Additionally, although the authors discuss that the fluxes and changes they observe may be the result of microbial respiration or CO_2 uptake by plants they also do not report partitioned CO_2 fluxes which would allow them to more directly attribute the correlations and seasonal changes they see.

Authors acknowledge the Reviewer's suggestion regarding the estimation of Gross Primary Production (GPP) and Respiration components partitioning. Please, see the specific question point below.

Additionally, open path CO_2 sensors (including the LI7500a) have been reported to show an artefact that results in a negative correlation between H and CO_2 flux during cold conditions (https://doi.org/10.1175/JTECH-D-17-0085.1). The correlation observed by the authors may be related to this rather than a real biogeochemical effect and they should discuss how the presence of this artifact may affect their seasonal interpretation and if using the correction term proposed in the above paper affects their results. I also am unsure if the difference in how the authors treat the friction velocity threshold filter for their CO_2 and CH_4 fluxes is appropriate.

We would like to thank the Reviewer for his/her very valuable suggestion. In the revised version of the work the turbulent CO_2 flux has been corrected according to Wang et al, 2017. Please, see the specific question below.

Wang, L., Lee, X., Wang, W., Wang, X., Wei, Z., W., C., Fu, C., Gao., Y., Lu, L., Song, W., Su, P. and Lin, G.: 2017. A Meta-Analysis of open-path eddy covariance observations of apparent CO_2 flux in cold conditions in FLUXNET. J. Atmos. Oceanic Technol., 34, 2475–2487, https://doi.org/10.1175/JTECH-D-17-0085.1, 2017

I think that the data reported in this paper are of interest to the arctic biogeochemistry and eddy covariance community. However, I think that the analysis of the data and the discussion of its significance could be refined and expanded and that doing so would improve the manuscript and its significance.

37: I feel like this sentence repeats information given in 34 and that the information given in the first paragraph could flow better

Thanks for your valuable suggestion. The two sentences are now merged to ensure a more fluent reading of the text

The Arctic region is experiencing rapid climate change in response to the increase in anthropogenic greenhouse gases (GHGs) and short-lived climate forcers (Stjern et al., 2019), such as methane, tropospheric ozone, and aerosols (Howarth et al., 2011; Arnold et al., 2016;

Law et al., 2014; Sand et al., 2015). This phenomenon is known as Arctic amplification (Serreze and Barry, 2011; Schmale et al., 2021).

45: Given your focus on Arctic soils, is this reference relevant?

The suggestion was accepted, so the sentence was erased from the text.

54: This isn't very clear, and your sentences can be restructured to flow better, in the previous sentence you mention the permafrost becoming a source because of more accessible OM and then mention that the driver of the net uptake is vegetation? It might be helpful to clarify how despite there being net uptake, permafrost thaw allows for more emissions

Thanks for your suggestion. The original sentence was unclear. Now, in the revised version, it was changed.

In the Arctic, methane and carbon dioxide fluxes are influenced by a variety of environmental factors, including permafrost thawing, changes in vegetation cover (especially for uptake phenomena), and in soil hydrology. As permafrost thaws, the organic matter it contains becomes more accessible for microbial decomposition, leading to increased methane, carbon dioxide and other greenhouse gas emissions due to microbial mediated degradation activity (Knoblauch et al., 2018).

Knoblauch, C., Beer, C., Liebner, S., Grigoriev, M. N., and Pfeiffer, E.: Methane production as key to the greenhouse gas budget of thawing permafrost, Nature Clim. Change, 8, 309–312, https://doi.org/10.1038/s41558-018-0095-z, 2018.

68: Is this effect referring to the effect in wetlands?

Yes, it refers to wetlands. In the revised sentence an explicit reference to wetlands has been added.

The projections of future emissions in the Arctic are complicated by the multiple effects of changes in temperature and precipitation regimes in the individual ecosystems (i.e. wetlands): while a wetter, warmer climate is generally associated with an increase in natural methane emissions, drier summers can lead to increased respiration rates in soils and reduced releases of methane.

112: I would change the phrasing to "The measurement campaign ran from"

The sentence has been changed according to the suggestion.

Measurement campaign ran from 9th April 2021 to 31st March 2023

194: In this case does your sensor report CO_2 uptake during the winter months? How do you deal with this?

Applying the correction method proposed by Burba et al, (2008), as said in the manuscript at line 194, the fluxes assume unrealistic values. The CO_2 fluxes seem to be affected by a large positive bias not physically justified. For this reason, the Authors prefer to not apply this correction, as done also in other works (Lüers et al., 2014). However, a clarification has been added in brackets in the revision.

The correction methods proposed by Burba et al. (2008) yield unrealistic flux values (with a large positive bias) for this data set, especially during winter season, so that we chose not to apply this correction (Lüers et al., 2014).

Burba, G., McDermitt, D. K., Grelle, A., Anderson, D., and Xu, L.: Addressing the influence of instrument surface heat exchange on the measurements of CO_2 flux from open-path gas analyzers, Global Change Biol., 14, 1854–1876, https://doi.org/10.1111/j.1365-2486.2008.01606.x, 2008.

Lüers, J., Westermann, S., Piel, K., and Boike, J.: Annual CO_2 budget and seasonal CO_2 exchange signals at a high Arctic permafrost site on Spitsbergen, Svalbard archipelago, Biogeosciences, 11, 6307–6322, https://doi.org/10.5194/bg-11-6307-2014, 2014.

211: Since the friction velocity threshold represents turbulence being underdeveloped, when it is below the threshold, wouldn't all the fluxes including the CH_4 fluxes be incorrect as they are also affected by the low turbulence?

The Reviewer is absolutely right. In the original version of the manuscript, we applied the u* filtering also to CH_4 fluxes, using the same u* threshold from CO_2. At a first draft we had decided to not apply the u* filtering to CH_4 fluxes, thus an old wrong sentence left there. In the revised version of the manuscript this sentence has been deleted. Note that the different value of the u* threshold is related to the correction applied to the CO_2 flux.

In our case, it provided u*= 0.0497 m s^{-1} and it was used to filter the CO_2 and CH_4 fluxes dataset, discarding all data corresponding to friction velocities lower than the threshold (0.8 % of the data).

249: Since you discuss results from other seasons, I think it would be good to mention the footprint coverage in them as well and if they differ from the summer? If they are different, it may complicate your interpretation of seasonality.

As can be seen from the Fig.R2, no differences emerge from the footprint analysis between the different seasons considered in this work. The footprints are very similar in dimension and distribution. The two shoulder seasons (thawing and freezing) present intermediate surface characteristics with the presence of snow and tundra at the same time. The noisier behaviour of the two intermediate seasons is due to the smaller dataset.

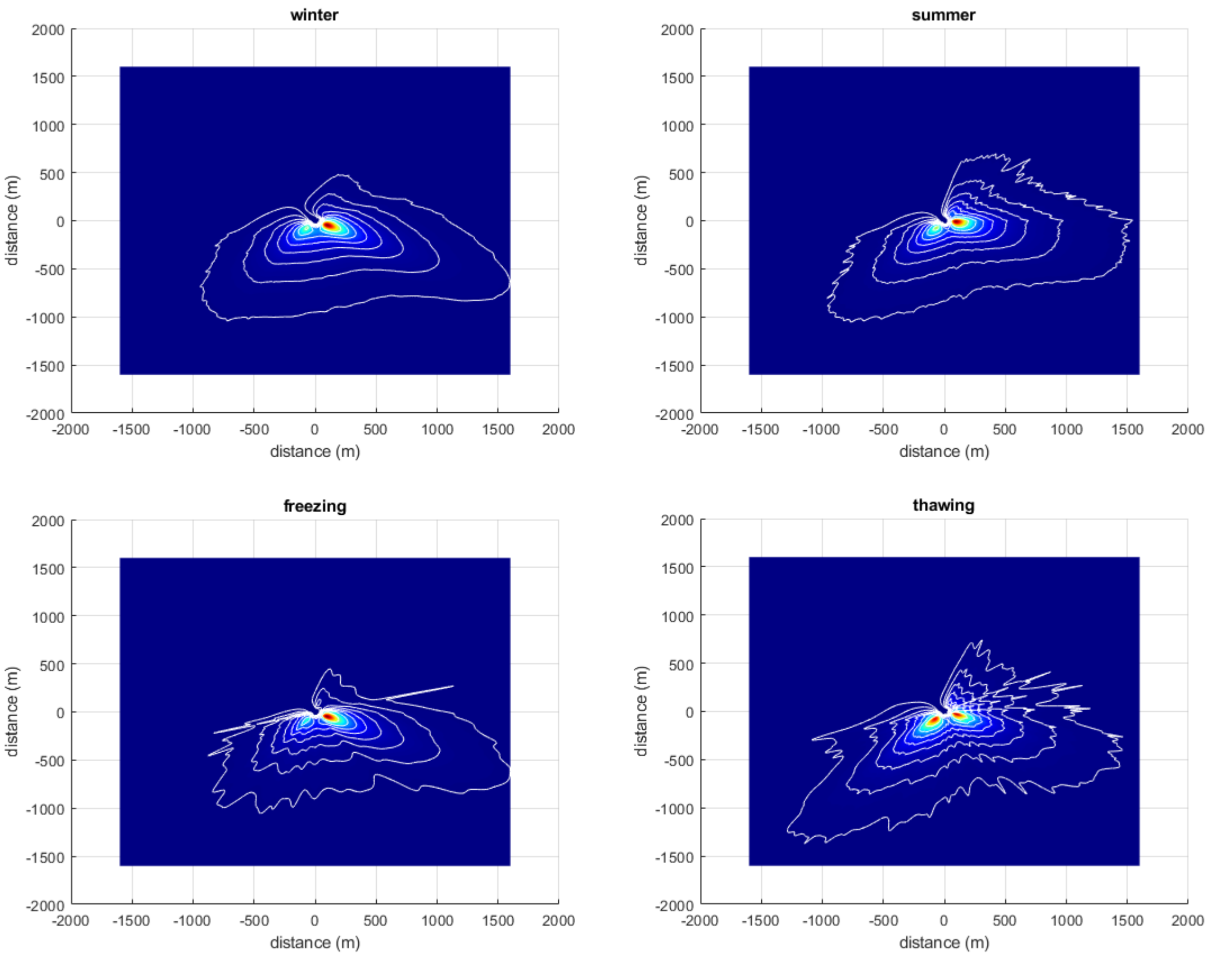

Figure R2 Footprint analysis for the winter, summer, freezing and thawing period considered in this work as reported by the relative title.

255: It is a bit unclear to me how the end of the thaw and freeze up periods are defined. The text only mentions the start.

In the sentence at 258-259, where we define the summer season, at the same time we gave a definition of the thawing season as: … the end of thawing (with a snow depth lower than 1 cm) … In the revised version, as shown below, we also add the definition for the freezing period end. Now, the definition of the seasons should be clarified.

The winter season is between the end of the freezing period (being the solar radiation < 10 W m^{-2}) and the beginning of the thawing period. At the same time the summer season was defined as the period between the end of thawing (being the snow depth lower than 1 cm) and the beginning of the freezing period.

273: The definite article "the" seems to be missing at the start of this sentence and in a few other places

We have checked the manuscript to find other missing definite articles. All of them should be resolved.

309: Is the paper you reference in comparison in a similar ecosystem and location?

No, actually, methane flux measurements in Wang et al, 2013 were carried out at a temperate forest (Haliburton Forest and Wildlife Reserve) in central Ontario from June to October 2011. In the revised version of the manuscript this reference has been disregarded. New references have been added and discussed for a better comparison

318: Since the CO_2 fluxes are used to gap fill the CH_4 fluxes, how can you be sure this similarity is not a result of that?

The Authors point out that the gap filling process is based on 12 variable drivers, among these only one is related to the CO_2 turbulent flux. Besides, the gap filling process only concerns the missing data and not the entire time series. We, therefore, do not believe that the gap filling process led to a same trend in the two timeseries. In Fig.3 the time series are not gap filled. Now, in the revised version of the manuscript, the CO_2 flux has been corrected according to Wang et al., 2017 and the general trend of the gap filled CH_4 time series did not change.

324: I'm not sure if reporting the mass budget without gap filling is meaningful. If the gaps are not randomly distributed, then the periods where gaps are less common will be overrepresented in the budget if you don't gap fill so it's not as directly relevant to the ecosystem fluxes.

We completely agree with the Reviewer opinion, indeed we reported it in line 326-328: "Actually, for the best evaluation of the cumulated carbon quantity, it should be better to consider the gap filled time series (both with MDS and RF methodology)". However, as done also in other works (Lüers et al, 2014), we also represent on Fig. 4 the cumulated carbon quantity for the not gap filled time series as a reference for a comparison. To better explicit our reason, we changed slightly the sentence as reported in the following:

Actually, for the best evaluation of the cumulated carbon quantity, it should consider the gap filled time series (both with MDS and RF methodology) as seen in Section 2.3.

352: It has previously been found that there may be an artifact that causes a correlation between H and CO_2 flux in open path sensors during the cold season so the correlation you find may also be related to that. Without further discussion or analysis of this effect, I wonder if it is justified to say that this is strictly a real effect?

We would like to thank the Reviewer for his/her very valuable suggestion. In the revised version of the work the turbulent CO_2 flux has been corrected according to Wang et al, 2017. Reporting in Fig.R3 a scatter plot of the CO_2 flux vs the sensible heat flux (H), we obtained a linear fit of the aggregated data (with 20 W m^{-2} bins) of the data. The linear fit coefficients are reported in the figure itself. After this correction the CO_2 flux during the dark winter season (with no solar radiation, T<0 °C and snow covered surface) is on average positive.

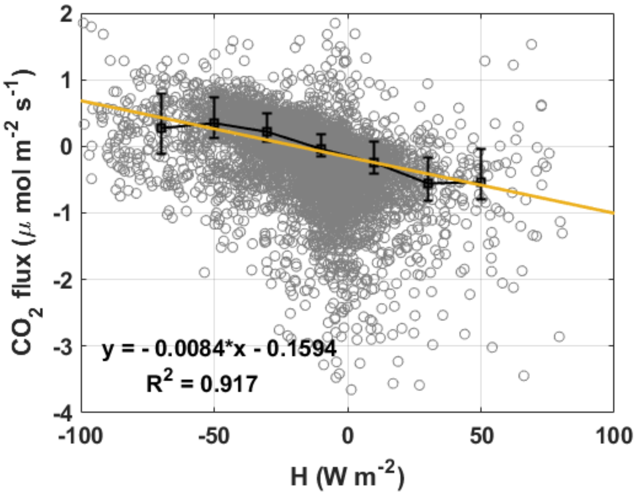

Figure R3 The relationship between wintertime CO_2 flux and the sensible heat flux H. Shown are half-hourly data (grey circles), bin-average values (black squares), and standard errors (error bars).

In the revised version of the manuscript, a sentence was added to take this correction into account. CO_2 flux values throughout the manuscript have been corrected and updated according to this new correction procedure.

Finally, a negative CO_2 flux in the cold season can result from errors propagated through the density correction, because the CO_2 density (ρ_c) can be affected by systematic biases caused by dirt contamination on the transducers and by ageing of the optical components (Fratini et al., 2012). The bias in the CO_2 flux scales linearly with the sensible heat flux H if the CO_2 density is underestimated by a constant amount, causing the CO_2 flux to be too negative (Serrano-Ortiz et al., 2008). In theory, these two fluxes (CO_2 and H) should be independent of each other in cold conditions (T air < 0° C) when photosynthesis is suppressed (Wang et al, 2017). Thus, the correction procedure reported in Wang et al. (2017) was applied to the CO_2 flux (with a mean slope of -0.0084 μmol m^{-2} s^{-1} per W m^{-2}, $R^2 = 0.92$).

Fratini, G., McDermitt, D. K., and Papale, D.: Eddy-covariance flux errors due to biases in gas concentration measurements: origins, quantification and correction, Biogeosciences, 11, 1037–1051, https://doi.org/10.5194/bg-11-1037-2014, 2014.

Serrano-Ortiz, P., Kowalski, A. S., Domingo, F., Ruiz, B. and Alados-Arboledas, L.: 2008: Consequences of uncertainties in CO_2 density for estimating net ecosystem CO_2 exchange by open-path eddy covariance. Bound.-Layer Meteor., 126, 209-218, https://doi.org/10.1007/s10546-007-9234-1.

Wang, L., Lee, X., Wang, W., Wang, X., Wei, Z., W., C., Fu, C., Gao., Y., Lu, L., Song, W., Su, P. and Lin, G.: 2017. A Meta-Analysis of open-path eddy covariance observations of apparent CO_2 flux in cold conditions in FLUXNET. J. Atmos. Oceanic Technol., 34, 2475–2487, https://doi.org/10.1175/JTECH-D-17-0085.1, 2017

365: I wonder if a lot or most of the correlation you see with wind speed is just due to the correlation with wind speed? It seems like most of the data on the at high wind speed are also at low H.

We thank the Reviewer for this comment. After applying the Wang et al. (2017) correction at the CO_2 flux, the correlation between this flux and H has completely disappeared. In the revised version of the manuscript the original Fig.5b has been eliminated.

Wang, L., Lee, X., Wang, W., Wang, X., Wei, Z., W., C., Fu, C., Gao., Y., Lu, L., Song, W., Su, P. and Lin, G.: 2017. A Meta-Analysis of open-path eddy covariance observations of apparent CO_2 flux in cold conditions in FLUXNET. J. Atmos. Oceanic Technol., 34, 2475–2487, https://doi.org/10.1175/JTECH-D-17-0085.1, 2017

366: Which methane concentration gradient are you referring to here? I don't recall you mentioning soil methane measurements or a vertical profile in the atmosphere in your methods

The Reviewer is right, a methane concentration gradient was not measured in this work: the original statement was misleading, and we modified it. In the revised version of the paper, this aspect was clarified and the sentence rewritten.

At the CCT site, where uptake seems to outweigh emission within the flux footprint, the soil layer would be relatively depleted in methane compared to the atmospheric boundary layer.

369: I don't follow how the concentration gradient implies aeration rather than methanotrophic rates.

Please note that in the revised version of the manuscript, this aspect has been clarified.

379: In a section further up, you mention that the soil temperature in the summer (line 321) is the driver of the increased methane uptake in that season. How do you reconcile this with the lack of correlation here?

The Reviewer is right. The Authors agree that the statement, at line 321 in the original form, can be misleading. This aspect is now addressed more clearly in the revised version, indicating explicitly that the statement is referring to a general research work and not specifically regarding this study.

Significantly negative fluxes of CO_2 are driven by photosynthesis, while CH_4 uptake fluxes increase coinciding with a positive peak in ground temperatures (Mastepanov et al., 2013; Howard et al., 2020). While prior research demonstrated the influence of soil temperature on methanotrophic activity (Reay et al., 2007), CH_4 fluxes at CCT site showed limited response to soil temperature, as reported later.

Howard, D., Agnan, Y., Helmig, D., Yang, Y., and Obrist, D.: Environmental controls on ecosystem-scale cold-season methane and carbon dioxide fluxes in an Arctic tundra ecosystem. Biogeosciences, 17, 4025–4042, https://doi.org/10.5194/bg-17-4025-2020, 2020.

Mastepanov, M., Sigsgaard, C., Tagesson, T., Ström, L., Tamstorf, M. P., Lund, M., and Christensen, T. R.: Revisiting factors controlling methane emissions from high-Arctic tundra, Biogeosciences, 10, 5139–5158, https://doi.org/10.5194/bg-10-5139-2013, 2013.

Reay, D., Hewitt, C. N., Smith, K., and Grace, J.: Greenhouse Gas Sinks, CABI, Oxfordshire, ISBN 978-1-84593-189-6, 2007.

383: I assume that soil temperature in the near surface layers is lagged (ie the soil near the surface heats up before the deeper layers) If there is a question of the soil depth of the methanotroph community, would a time lagged version of the 10cm soil temperature data show a better correlation with the methane fluxes?

Authors wish to thank the Reviewer for this interesting and valuable suggestion. We applied a cross-correlation function between methane flux (F_{CH4}) and deeper soil temperature (10 cm) with the aim of determining whether a time lag existed between the two signals. In Fig.R4, we plotted the normalised cross-correlation ([-1, 1]) on the y-axis and the corresponding time lag (in 30-minute intervals) on the x-axis. As can be seen from the figure, the maximum correlation (0.11) is reached at a time lag of approximately 3343, which corresponds to about 69 days. Therefore, we must assume that the lack of correlation between F_{CH4} and Ts is physically justified. Further we report on Fig.R4b, the cross-correlation function between the deeper soil temperature (10 cm) and the shallower one (5 cm). As represented in Fig.R4b, they result almost perfectly correlated at time zero.

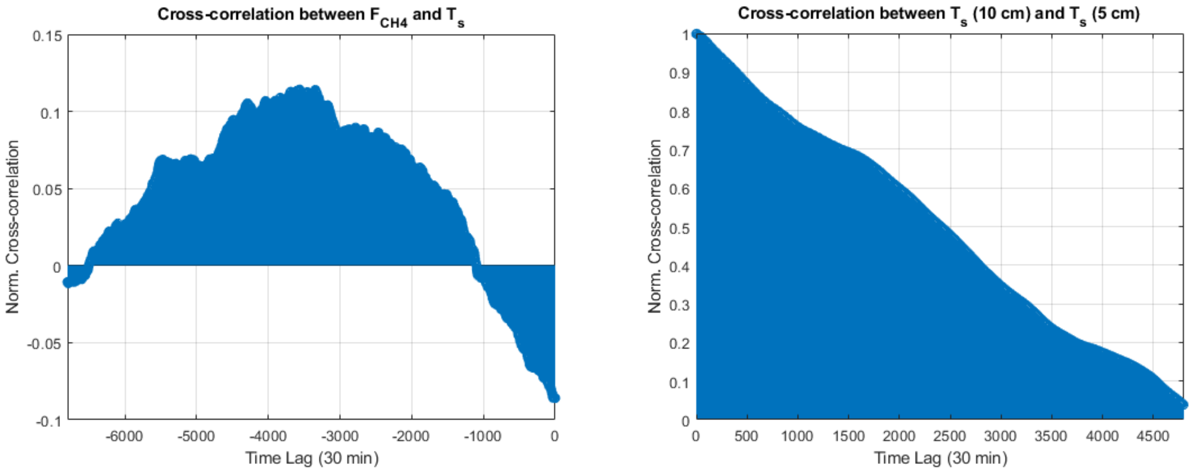

Figure R4 a) The normalised cross-correlation between methane flux (F_{CH4}) and deeper soil temperature (10 cm). b) The normalised cross-correlation between the deeper soil temperature (10 cm) and the shallower one (5 cm).

386: I'm not sure what psychrophilic means coming from an eddy flux background. It may be helpful to define this?

Psychrophilic refers to organisms that thrive in cold environments. These organisms, often bacteria or archaea, are adapted to temperatures below about 15 °C. They have unique biochemical adaptations that allow them to survive and reproduce in icy conditions. However, in the revised version of the manuscript, according to the suggestions of Reviewer#2 (RC2: 'Comment on egusphere-2024-1440' - https://doi.org/10.5194/egusphere-2024-1440-RC2) the sentence has been deleted.

390: Are these anomalies over the mean annual temperature in this period or over the day of year averages? It is not clear from the text what these are and I think you should clarify them.

The temperature anomalies have been estimated with respect to the day of the year average temperature. This has now been clarified in the revised version of the manuscript.

In this study, the temperature anomalies were calculated with respect to the day of the year average values taking the period 1991-2020 as a baseline.

400: Can you quantitatively assess the strength of these trends? It is hard to tell how significant some of the trends are especially as some seasons have small variations in the x axis? Additionally, does this mean that on days where the temperature on a given day is above the long-term seasonal mean for that day the fluxes are higher?

In response to the Reviewer's suggestion, the trends relative to the different seasons were carried out separately as displayed in Fig.R5 and Fig.R6. In each panel is reported also the equation of the best linear fit for the binned data. Flux data (black square) are binned for the ΔT bins, each 5 °C. The results of this analysis show that during days with a high temperature anomaly relative to the mean (of the day of the year), fluxes magnitude is higher. From Fig.R5, it can be noted that only during summer, CO_2 flux shows a significant trend versus the thermal anomaly. While for the other season CO_2 flux shows no significant variation with the thermal anomaly (with a very low Pearson coefficient R^2). Specifically, for the freezing period, there is a very low number of cases, so that it is not possible to make a statistically significant fit. In Fig.R5 has been reported a linear fit also for the union of dark winter and light winter datasets, taken together to increase the statistical significance. Finally, we decided to insert in the revised version of the manuscript only some panels of Fig.R5 and Fig.R6. Specifically, we created only one figure, both for CO_2 and CH_4, inserting “Winter Snow”, “Summer” and “Thawing” for each gas in a 3x2 frame. All the cases have been well described in the text.

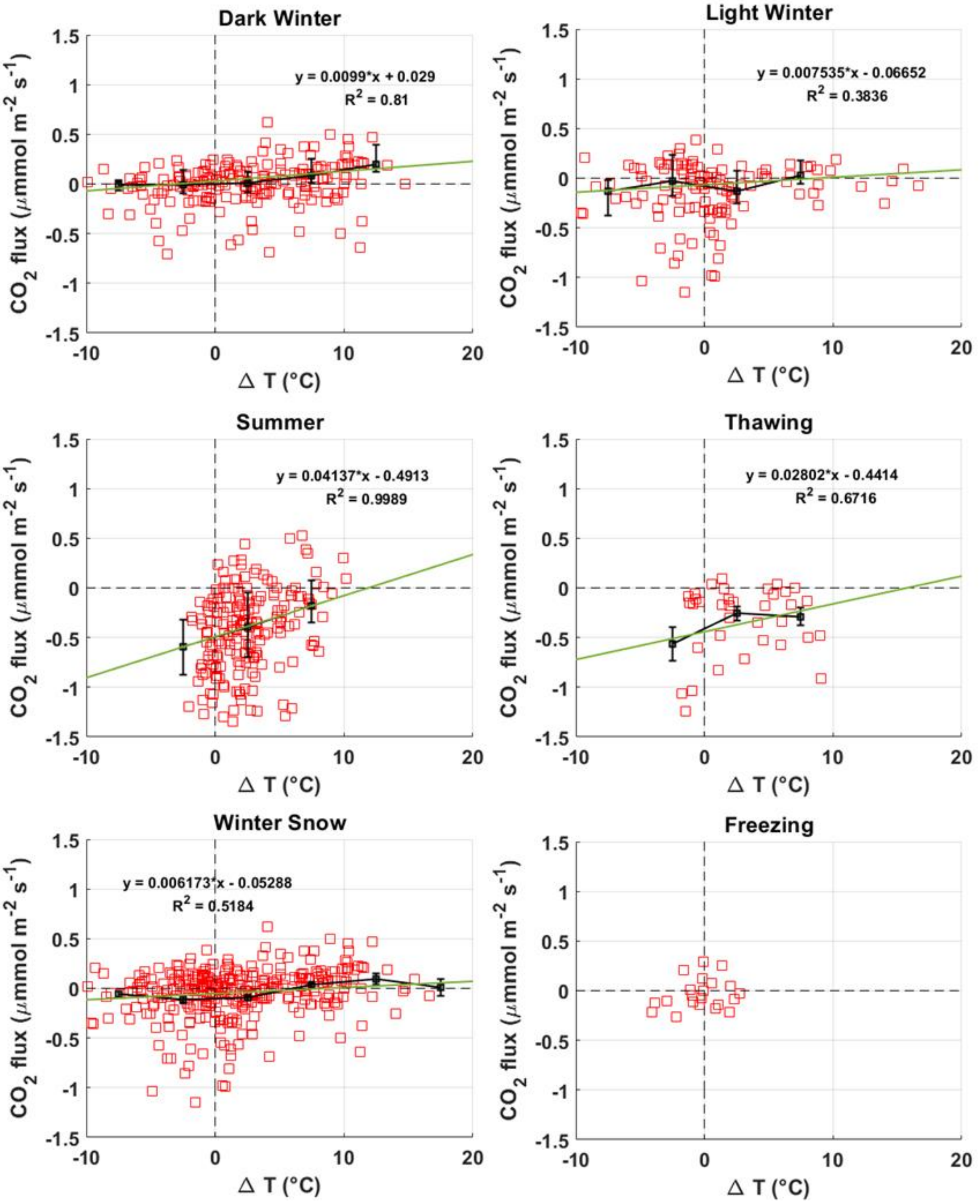

Figure R5 CO_2 vertical fluxes vs temperature anomalies for the different seasons (as reported in the title panel). A linear fit equation and the respective Pearson coefficient (R^2) are reported for each panel.

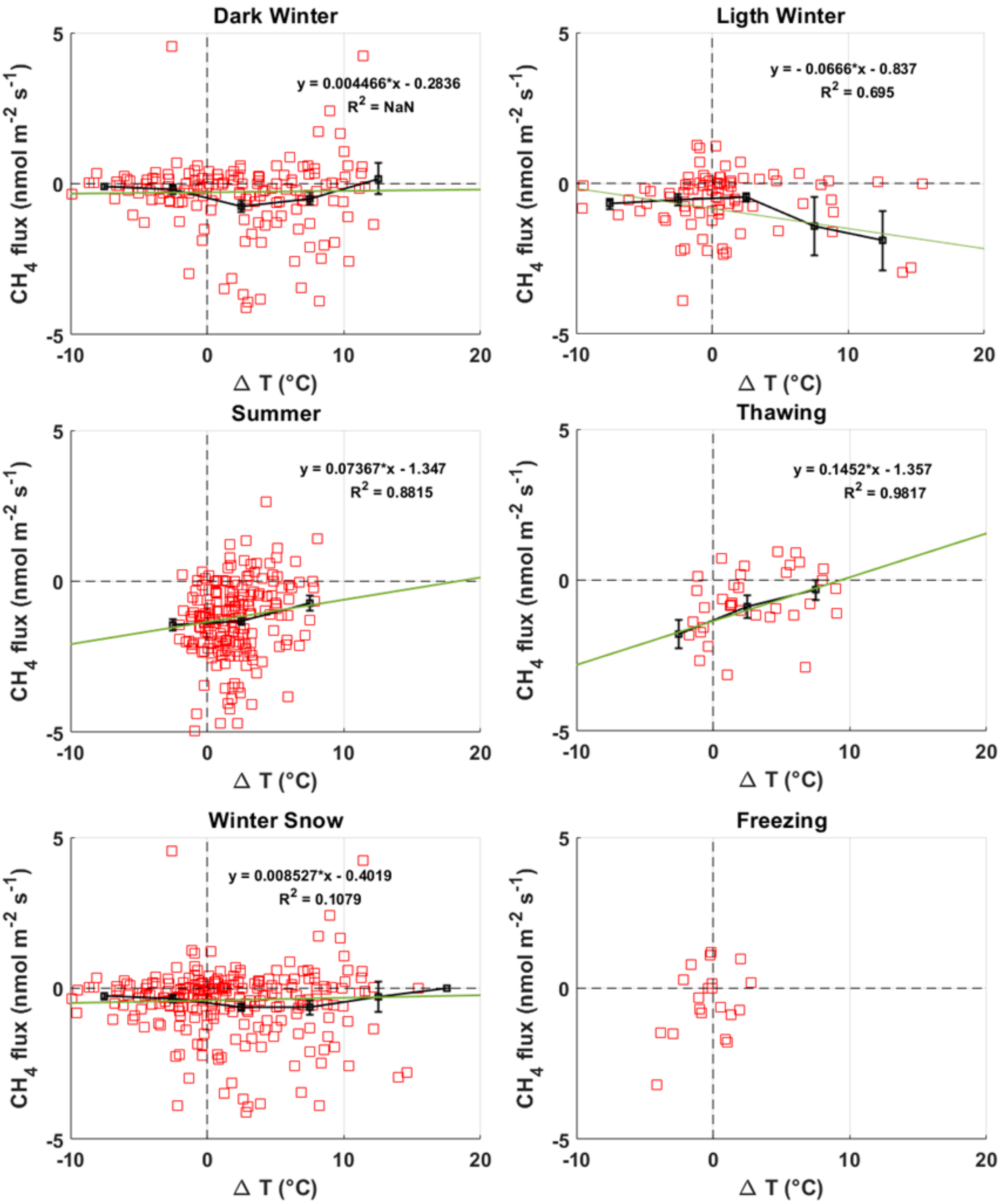

Figure R6 CH_4 vertical fluxes vs temperature anomalies for the different seasons (as reported in the title panel). A linear fit equation and the respective Pearson coefficient (R^2) are reported for each panel.

420: Regarding CO_2 in terrestrial systems, the flux is often partitioned into productivity and respiration. It might be interesting and clarify what drives changes you observe to consider the factors driving each of these separately.

We appreciate the Reviewer's suggestion concerning the estimation of Gross Primary Production (GPP) and the partitioning of respiration components. Unfortunately, we were unable to perform these estimations due to the lack of necessary measurements in our dataset. Additionally, conducting such estimations would require a detailed respiratory surface modelling component, which is beyond the current scope of our study, as our primary focus is on methane fluxes dynamic. However, we will consider this valuable suggestion to guide measurements in the next experimental campaign.

424: I'm not sure how you measured soil aeration

We did not measure soil aeration in this study. Instead, we used the term "aeration" to refer to the wind air pump effect on gas fluxes, with an increasing of oxygenation of the topsoil. In the new form of the sentence, we specified this concept.

… and correlates with the increasing aeration (wind effect) of the topsoil and its decreasing albedo.

427: It is not clear to me why you would see a negative CO_2 flux in the winter. Is this flux below your measurement error and detection limit?

Please note that this phenomenon seriously reduced after the application of the suggested correction (Wang et al., 2017). However, the CO_2 flux continues to be negative also during the winter on a 30 min basis, with very low magnitudes (but greater than the LOD threshold), due basically to the weak uptake of the carbon dioxide by the snow.

Wang, L., Lee, X., Wang, W., Wang, X., Wei, Z., W., C., Fu, C., Gao., Y., Lu, L., Song, W., Su, P. and Lin, G.: 2017. A Meta-Analysis of open-path eddy covariance observations of apparent CO_2 flux in cold conditions in FLUXNET. J. Atmos. Oceanic Technol., 34, 2475–2487, https://doi.org/10.1175/JTECH-D-17-0085.1, 2017

431: Is it correct to say this since you find only a very small relation with soil temperature?

The Reviewer is right. In the original form of the sentence, it is not very clear the cause-effect process. The negative soil temperature brings to a freezing of the water content of the active layer, which in turn reduces the methanotrophs activity. In the revised version of the manuscript, we have rewritten the sentence as follow:

nearly stopped by negative soil temperature, which triggers the freezing process of the active layer water content.

455: Is it a typo that the summer shortwave radiation is lower than the winter one?

We thank the Reviewer for pointing out the error in the graph. We have now corrected it and updated the graph to show total radiation (shortwave downward radiation).

Reviewer #2: RC2: 'Comment on egusphere-2024-1440' - https://doi.org/10.5194/egusphere-2024-1440-RC2

General comments

The dataset presented in this manuscript is of high quality and is a unique time series of net CO_2 and CH_4 fluxes from an understudied ecosystem type in the Arctic, that nonetheless comprise the majority of the Arctic area. Thus, understanding the magnitude of CO_2 and CH_4 exchange with the atmosphere is relevant in the context of the Arctic carbon budget and how it responds to environmental change. The authors present and discuss the data in a concise and structured manner with good interpretation, although I recommend more careful interpretation of the relation between wind and net CH_4 uptake by including the interaction with soil hydrology. Also, the authors do not show this correlation, which I suspect is very variable and not better than the one for temperature.

We strongly thank the Reviewer for the helpful and constructive review, which allowed us to make significant improvements, especially in the biogeochemical aspects of the work. Despite the Reviewer's valid observations that rightly point to soil hydrology measurements for understanding these processes, we unfortunately do not have any measurements available that can support such analyses. We use this recommendation to plan installations that support the existing infrastructure and adapt it for measurements that account for soil hydrology. In the revised version of the manuscript, we add a figure with the scatter plot of CH_4 flux vs wind velocity (as suggested by the Reviewer). Also, the text within the manuscript was changed accordingly.

There is a general switching between present and past tense in the entire manuscript which makes it confusing at times to read and halts the flow. Language itself is good but I strongly recommend you to make it either present or past tense throughout.

In the new version of the manuscript, the past tense is used.

Perhaps I am missing a little more discussion on the annual sums of CO_2 fluxes compared to other studies in the Arctic.

We agree with the Reviewer, now in the revised version of the manuscript a comparative analysis with other Arctic studies has been included. Please, see the specific question below.

I also suggest to add an analysis of the diurnal patterns for the different seasons as this would support the overall purpose of the manuscript.

Thank you for the valuable suggestion. A daily cycle analysis was carried out for both CO_2 and CH_4 on a seasonal basis. This analysis and related figures have now been added below to answer your specific question.

Abstract

Line 25-27: This formulation "CH_4 fluxes…" is not very clear, because how is the reader supposed to understand how wind velocity is related to electron acceptors in the soil. There seems to be missing some information in between the wind and the soil, so please detail this

Thank you for the suggestion. In the revised text of the manuscript the Abstract section was heavily rewritten. This sentence was deleted from the text.

Abstract. This study focuses on direct measurements of CO_2 and CH_4 turbulent eddy covariance fluxes in tundra ecosystems in the Svalbard Islands over a two-year period. Our results reveal dynamic interactions between climatic conditions and ecosystem activities such as photosynthesis and microbial activity. During summer, pronounced carbon uptake fluxes indicate increased photosynthesis and microbial methane consumption, while during the freezing seasons very little exchange was recorded, signifying reduced activity. The observed net summertime methane uptake is correlated with the activation and aeration of soil microorganisms, and it declines in winter due to the presence of snow cover and because of the negative soil temperature **which triggers the freezing process of the active layer water content**, but then rebounds during the melting period. The CH_4 fluxes are not significantly correlated with soil and air temperature, but are instead associated with wind velocity, **which plays a role in the speed of soil drying. Nongrowing season emissions accounted for about 58% of the annual CH_4 budget, characterised by large pulse emissions.** The analysis of the impact of thermal anomalies on CO_2 and CH_4 exchange fluxes, underscores that high positive (> 5 °C) thermal anomalies may contribute to an increased positive flux **both in summer and winter periods, effectively reducing the net annual uptake.** These findings contribute valuable insights to our understanding of the dynamics of greenhouse gases in tundra ecosystems in the face of evolving climatic conditions. Further research is required to **constrain** the sources and sinks of greenhouse gases in dry upland tundra ecosystems**, to develop an effective reference for models in response to climate change.**

Line 27-28: "High temperature anomalies…" Do they occur in winter/autumn/spring? Please clarify in text. Also, how does this respiration inhibit productivity? Do you mean that these anomalies decrease the annual net sink?

The Authors agree that the statement can be misleading. This aspect is now addressed more clearly in the revised version.

The analysis of the impact of thermal anomalies on CO_2 and CH_4 exchange fluxes, underscores that high positive (> 5 °C) thermal anomalies may contribute to an increased positive flux both in summer and winter periods, effectively reducing the net annual uptake.

Line 28-29: How much of the annual budget does the winter CH_4 emission constitute? I think you should add that number here

This quantity has now been added as suggested by the Reviewer, as follow:

Nongrowing season emissions accounted for about 58% of the annual CH_4 budget, characterised by large pulse emissions.

Line 29: replace "comprehending" with "understanding" or "measuring"

Thanks, suggested corrections have been implemented in the paper

Line 30: replace "elucidate" with "constrain"

Thanks, suggested corrections have been implemented in the paper

Introduction

Line 37: delete "affect the…"

Done, thanks for the suggestion.

Line 47: "absorption" Do you mean "net uptake"? If so, I suggest to write this. Merge this sentence with the next by deleting "This is" and replace "that season" with "growing season".

The sentence has been rewritten according to the Reviewer's suggestions.

Line 51: I would here use "soil hydrology" instead of "water levels"

Thanks for your suggestion. We replaced "water levels" with "soil hydrology".

Line 53: I do not think the Kleber et al. 2023 citation fits in here as this relates to glacier retreat and release of thermogenic methane. So I suggest to remove it

Thanks for your valuable suggestion. In the revised version of the manuscript this reference has been removed.

Line 55-64: I suggest to delete this entire paragraph. It is kind of trivial for the interested reader for your paper. No need to use space on this and in the next paragraph you get to the primary knowledge gap which is the dry tundra ecosystems.

The Reviewer's observation is appreciated. The paragraph has been shortened, retaining the most significant parts of the text, as follows:

Methane uptake occurs in the atmosphere through chemical and/or photochemical oxidation, or biologically in soil and in water, through methane-oxidising bacteria and archaea (hereafter methanotrophy) that use methane as a source of energy and carbon (Serrano-Silva et al., 2014).

Line 76-90: Overall a good wrap up of existing papers on net CH_4 uptake in dry tundra soils. A few updated papers came out recently that might be of interest for you as well:

- **Juncher Jørgensen, C., Schlaikjær Mariager, T., & Riis Christiansen, J. (2024). Spatial variation of net methane uptake in Arctic and subarctic drylands of Canada and Greenland. *Geoderma*, *443*, 116815. https://doi.org/10.1016/j.geoderma.2024.116815**
- **D'Imperio, L., Li, B.-B., Tiedje, J. M., Oh, Y., Christiansen, J. R., Kepfer-Rojas, S., Westergaard-Nielsen, A., Brandt, K. K., Holm, P. E., Wang, P., Ambus, P., & Elberling,**

B. (2023). Spatial controls of methane uptake in upland soils across climatic and geological regions in Greenland. ***Communications Earth & Environment*****,** ***4*****(1), 461. https://doi.org/10.1038/s43247-023-01143-3**

We thank the Reviewer for these very interesting works. In the revised version of the manuscript these recent works have been added to the references.

Line 96: I do not understand the phrase "equilibrium between CO_2 and CH_4 in dry tundra environments". Do you mean the balance between the net flux of the two gases? I suggest to rephrase to make it clear what you mean

The Authors agree that the statement can be misleading. This aspect is now addressed more clearly in the revised version.

Bridging the gap between the balance of CO_2 and CH_4 net flux, in dry tundra environments, with the increasing frequency and intensity of extreme events is essential for understanding the role of these ecosystems in the context of climate change.

Line 97: You have to mention in the very top of the introduction that one of the predicted changes with the Arctic Amplification is "increasing frequency…". In this way you tie the introduction better together

Thank you for the suggestion, now this statement has been added in the revised manuscript.

Line 100: This sentence is a little off in relation to the text above and below, so I suggest to delete

Thank you for this suggestion. In the revised version of the manuscript the sentence was deleted.

Line 103: Write how many years

This information has now been added in the revised manuscript.

In particular, the objective is to understand the duration and magnitude of the exchange mechanisms and environmental drivers for CO_2 and CH_4 **for two year-rounds** (including the shoulder seasons) and their relative importance.

Line 105-107: When you write "assess impact on…greenhouse gas fluxes" do you then mean the mechanisms in the soil or the impact on the budget? I think it is important to distinguish as most of your introduction is focused on budgets, which essentially your study design by using eddy is best suited for. So for the reader it is important that you upfront outline whether you focus on mechanistic processes or budgets.

This aspect is now addressed more clearly in the revised version.

This study aims to evaluate how seasonal temperature anomalies (1990-2020) affect the GHG budget. These anomalies are used as key indicators to understand how changes in temperature trends influence the overall greenhouse gas balance in the studied ecosystem.

Methods

Measurement site

Line 137-140: I guess you mentioning this as it might be affecting measurements occasionally? I think you just have write why you mention this.

We wish to thank the Reviewer for her/his suggestion. We add a clarification in the sentence, as follow:

On the other hand, there are few combustion engine cars on the roads and some electric vehicles **that might affect measurements occasionally.** The village lacks specific combustion sources, relying entirely on electric facilities. The airport has only two flights per week, and ship arrivals are uncommon, occurring 1-2 times a month, however, cargo handling involves heavy-duty vehicles, and it is moderately active. **All these activities are out of the measurement system footprint.**

Eddy covariance data analysis

Line 224: You develop a random forest model to account for the complex biogeochemical variables using 12 drivers, but only one is directly related to the soil. Thus, your random forest model is less of a direct model but rather an indirect based on meteorological variables. I would

therefore be hesitant to call this a model that can handle complex biogeochemical interactions as you state.

The authors agree with the Reviewer that this statement is misleading, so this has been clarified in the revised version of the manuscript.

However, to take in consideration a large range of meteorological interactions and some biogeochemical variables, a random forest regression model of the fluxes was also developed (Kim et al., 2020, Knox et al., 2021) with 12 environmental drivers: sensible and latent heat fluxes, air temperature, soil temperature at 10 cm depth, relative humidity, vapour pressure deficit, air pressure, shortwave incoming and longwave outcoming radiation, the snow depth, the friction velocity and, finally, the boundary layer height.

Results and discussion

Line 251 – 270: I think all this text belongs in Methods section, perhaps as a sub chapter to the eddy covariance data analysis section.

As recommended by the Reviewer, this section has been moved to the previous Section 2.3 "Eddy Covariance". In the revised version of the paper a new subsection was inserted: **2.4 Seasonality**.

3.1 CO_2 and CH_4 mixing ratio

Line 300-301: The Wang et al. 2013 is hardly referring to High Arctic conditions and I would not cite this paper here and suggest to use a more suitable one that represents Arctic conditions

The Reviewer is absolutely right. In this new revised version of the paper we add more references. Wang et al., 2013 refers to a snow covered surface, actually a snow covered temperate forest in central Ontario (Haliburton Forest and Wildlife Reserve). For sure it is not the most appropriate reference for a comparison in this work. In the revised version of this work a series of more suitable references have been added and discussed.

Line 307: replace "absorption" with "net uptake". Absorption is a word used in chemistry

Many thanks for the suggestion. Now the term "absorption" has been changed with the more appropriate "net uptake" throughout the paper.

Line 297 – 309: In this text you mostly present the median values, but I think you neglect to address the sizable variation of instantaneous fluxes around this median for both CO_2 and CH_4. Your box plots off course show that most of the fluxes are within the 25th and 75th percentiles, but regardless of season you have very high variation of fluxes within very short times. For CH_4, for example, you fluxes range from +10 to -10 nmol m^{-2} s^{-1}, in what seems to be hours or even shorter (difficult to see on figure 3). Hence, what is behind this large variation in flux estimates. Is it purely stochastic related to the measurement principle due to the high noise-to-signal ratio for CH_4, at least? I doubt that it can be related to a process that can switch the flux that fast from strong net uptake to strong net emission. Please comment on this in the text.

Thank you for your insightful question. The eddy covariance method can result in significant variability in turbulent flux measurements, even within short time intervals (< 1 h). This variability is partly due to the intrinsic nature of the eddy covariance technique, where turbulent fluxes are derived from high-frequency measurements that can exhibit substantial instantaneous variation. Our data processing includes filtering based on the limit of detection of 0.9 nmol m^{-2} s^{-1} (as reported in the text at line 198), ensuring that the reported values are robust and reflective of the actual flux dynamics. The Authors would like to point out that CO_2 fluxes also show a similar temporal variation, with a higher magnitude than methane.

Also, I missing an analysis of the diurnal variation in CO_2 and CH_4 fluxes for the different seasons. One would expect higher variability in summer than in winter. With your data set you are able to make some robust estimates of diurnality. This also feeds in to your overall aim of investigating temporal patterns and drivers of CO_2 and CH_4 fluxes. So I suggest you include this in the manuscript. If there is no clear patterns then you can choose to leave the data out of the paper and merely mention that no differences in diurnal patterns were detected and leave it at that. However, if there are some differences it might serve the overall purpose of your manuscript very well.

Authors thank the Reviewer for her/his valuable suggestion. A response has been provided to a similar question by the Reviewer RC1 in this Biogeosciences open discussion (RC1: 'Comment on egusphere-2024-1440' - https://doi.org/10.5194/egusphere-2024-1440-RC1). Please note that daily patterns for different seasons for both CO_2 and CH_4 have now been included here. As referenced by the Reviewer, a diurnal variability in both fluxes can be observed in the summer period. On the other hand, in winter (especially in the dark winter but also during freezing and thawing periods) such diurnal cycles cannot be so clearly distinguished. In particular, the diel pattern for CH_4 is almost absent. Given that no distinct diel cycle is evident at the CCT site, as illustrated in figure R1, we believe this analysis does not significantly enhance the work.

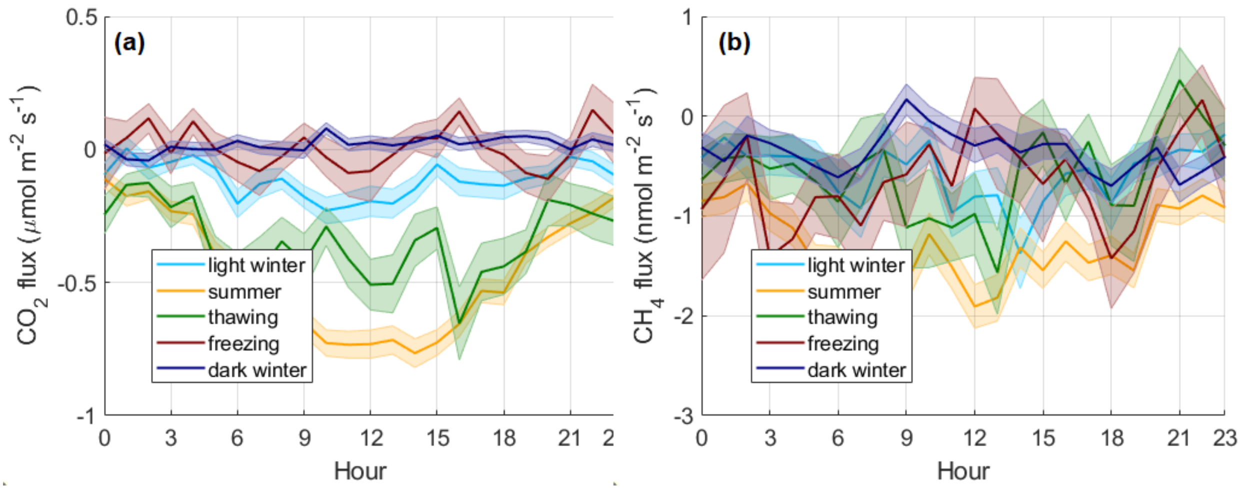

Figure R1 Diurnal pattern for the a) CO_2 and b) CH_4 flux at our measurement site. The patterns were reported for the different seasons considered in this work. Continuous line represents the mean flux values, while the colour shadow area represents the standard error of the measurements.

3.2 CO_2 and CH_4 mass budget

Line 332-333: Unclear what number you refer to in Treat et al. 2016. Please specify whether it is CH_4. Also there is no comparison to other Arctic CO_2 budgets although there have been measured a lot, so I suggest you compare the CO_2 budgets with other studies.

In the original version of the paper the wrong reference by Treat was reported. In the new version we reported the correct one: Treat et al., 2018, which was added correctly in the references section. We agree with the Reviewer, now in the revised version of the manuscript a comparative analysis with other Arctic studies has been included.

3.1 CO_2 and CH_4 mixing ratio **and surface fluxes**

Seasonal analysis reveals negative median values for the fluxes of CO_2, peaking in summer with -0.37 µmol m^{-2} s^{-1}. **The CO_2 fluxes showed a slightly positive median value during the dark winter (0.02 µmol m^{-2} s^{-1}), actually, due to respiration phenomena from the snow covered surface due to microbial respiration (Hicks Pries et al., 2013). At a finer time scale (30 min resolution), the CO_2 flux trend indicates the presence of positive fluxes (emissions) (Fig. 3a),** especially during the dark/light winter and the freezing period (Table 1). **As snowmelt begins, accumulated carbon dioxide may be released and exposed patches of ground with a lower albedo begin to warm, further enhancing respiration rates and CO_2. Further, during thawing season, incoming**

radiation reaches levels adequate for photosynthesis: the combination of increasing light, along with increases in soil temperatures can result in early photosynthesis. At the CCT site, the CO_2 flux decreased starting from the light winter (-0.84 µmol m^{-2} s^{-1}) and it continues during the thawing season (-0.18 µmol m^{-2} s^{-1}). During the fall, soil temperatures were still adequate for substantial microbial respiration. When the senescence of vascular plants advanced, respiration became the dominant process affecting carbon exchange. In addition, as soils freeze, CO_2 may be forced out of the soil towards the atmosphere. However, in the freezing period, at the CCT site, a median negative CO_2 flux has been measured (-0.79 µmol m^{-2} s^{-1}).

A similar trend is reported for methane: during the dark and light winter periods, methane fluxes are negative, with a median value of -0.17 and -0.36 nmol m^{-2} s^{-1}, respectively (Fig. 3d). **Treat et al. (2018) investigated methane dynamics across Arctic sites and reported negative methane fluxes during winter, attributed to cold temperatures, which inhibit methanogenesis while promoting methane oxidation in dry tundra soils. However, they also highlight methane uptake in dry tundra during colder periods. Zona et al. 2016 reported that methane emissions during the cold season (September to May) account for ≥ 50% of the annual CH_4 flux, with the highest emissions from upland tundra. In this study (Table 1), evidence of significant emission events during winter temperature fluctuations can be observed at the site.** In contrast, these events diminished in the shoulder seasons, where notable net uptake events dominated, with -0.83 nmol m^{-2} s^{-1} during thawing and -0.69 nmol m^{-2} s^{-1} during freezing period. **Seasonal analysis reveals negative median CH_4 fluxes, peaking in summer at-1.28 nmol m^{-2} s^{-1}. Juncher Jørgensen et al. (2015) field measurements, within the Zackenberg Valley in northeast Greenland over a full growing season, show methane uptake with a seasonal average of -2.3 nmol m^{-2} s^{-1} in dry tundra. Wagner et al. (2019) measured a negative peak during the growing season (2009) of -4.41 ng C-CH_4 m^{-2} s^{-1} in a polar desert area at the Cape Bounty Arctic Watershed Observatory (CBAWO - Melville Island, Canada).**

3.2 CO_2 and CH_4 mass budget

The cumulative mass budgets over the two monitoring years at the CCT site ecosystem are shown in Fig. 4. Based on the budget for the whole measurement period, the study area acts as a net sink for both CO_2 and CH_4. During the study period, a CO_2 balance of almost -257 CO_2 g m^{-2} is found, while the contribution of CH_4 uptake is estimated at approximately -0.36 g CH_4 m^{-2} (Fig. 4, dashed red line). Actually, for the evaluation of the cumulated carbon, the gap filled time series should be considered (both with MDS and RF methodology, see Section 2.3). In this perspective, the total cumulative CO_2 budget over the measurement campaign is -472 g CO_2 m^{-2} with MDS and -650 g

CO_2 m^{-2} using the RF procedure, respectively (Fig. 4a). On the other hand, CH_4 cumulative budget is about -0.76 g CH_4 m^{-2} with the RF gap filling procedure (Fig. 4b). The mean annual cumulative CO_2 budget is -131 g CO_2 m^{-2} with MDS and -164 g CO_2 m^{-2} with RF. **Oechel et al. (2014) reported a net CO_2 uptake during the summer season of -24.3 g C m^{-2}, while the no growing seasons released 37.9 g C m^{-2}, showing that these periods comprise a significant source of carbon to the atmosphere. In Treat et al. (2024) is reported for 2002–2014, a smaller CO_2 sink in Alaska, Canadian tundra, and Siberian tundra (medians: -5 to -9 g C m^{-2} $year^{-1}$). Euskirchen et al. (2012) established eddy covariance flux towers in an Alaska heath tundra ecosystem to collect CO_2 flux data continuously for over three years. They measured a peak CO_2 uptake, during July, with an accumulation of -51 -95 g C m^{-2} during June–August. On average, the mean annual cumulative budget for CH_4 is -0.18 g CH_4 m^{-2} $year^{-1}$, calculated using gap-filled data (Table 2). This outcome lies within the same order of magnitude estimated by Dutaur et al. (2007) at the global level, reporting a net CH_4 uptake for the non-forested arctic environments (defined as "boreal other") of -0.14 g CH_4 m^{-2} $year^{-1}$. Treat et al. (2018) found that tundra upland varies from CH_4 sink to CH_4 source with a median annual value of 0.0 ± 0.20 g C m^{-2} $year^{-1}$. Lau et al., (2015) found that the CH_4 uptake rate was in the range between −0.1 to −0.8 mg CH_4-C m^{-2} day^{-1} at AHI site (Nunavut, Canada). In this work it was suggested that mineral cryosols act as a constant active atmospheric CH_4 sink (Emmerton et al., 2014) in part because of their low soil organic carbon availability, low vegetation cover and low moisture content.**

The annual budget can be further split into the five seasons considered in this study. Specifically, the CCT area acted as a CO_2 sink during the thawing and summer period with an average value of -0.79 and -1.1 g CO2 m^{-2} day^{-1}, respectively. **During the freezing period the quantity of absorbed CO_2 per day decreased down to almost null value (-0.01 g CO_2 m^{-2} day^{-1}), and slightly increased to a positive value during the dark winter period (0.04 g CO_2 m^{-2} day^{-1}). With the increasing amount of the solar radiation, the mass cumulative CO_2 per day decreased again (-0.25 g CO_2 m^{-2} day^{-1} for light winter). Ueyama et al. (2014) analysed seasonal CO_2 budgets across several tundra ecosystems in Alaska, reporting peak CO_2 uptake during summer with an average value of -46 g C m^{-2} due to maximum photosynthesis rates.** The same pattern was followed by the CH_4 absorbed carbon mass: in this case during the thawing period was observed a value on average of -0.55 mg CH_4 m^{-2} day^{-1}, peaking its negative maximum during the summer period (-1.29 mg CH_4 m^{-2} day^{-1}). Also, in this case the absorbed carbon mass decreases in the freezing period down to -0.63 mg CH_4 m^{-2} day^{-1}. It was reduced to very low values during the winter season with -0.26 mg CH_4 m^{-2} day^{-1} in dark winter and -0.40 mg CH_4 m^{-2} day^{-1} in light winter.

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3.3 Physical drivers on GHGs surface fluxes

Line 357: I think you refer to Fig. 5b and not "9b"

Ok, many thanks for the suggestion.

Line 372-375: I think the discussion on methanotrophy in Type I and implicitly Type II is off here and not really relevant as you have to assume that it is aerobic methanotrophy that is responsible for the net uptake, but whether it is one type of methanotrophs or the other is irrelevant in your case as you cannot really evaluate this. If you were to say anything then you

would have to assume that it is type II (high affinity MOB's) that do the oxidation as there are no wetlands in the CCT footprint.

The paragraph indicated by the Reviewer has been deleted from the revised text.

Line 375-377: This is more a conclusive statement and I would remove from here and add to conclusions if needed

We agree that this statement is more appropriate for the conclusions. It has been removed from its original position and incorporated into the conclusion section as recommended.

Line 386-388: But on the other hand windspeed is higher in winter with the lowest fluxes. And given the low range of wind speeds I doubt that you will find a strong link between net CH_4 uptake rates and wind speed. You are correct that oxygen addition to deeper layers is likely stimulating methane oxidation, but this is as much related to the drying out of the soil during the summer. Since you say the CCT is also a semi-desert my best interpretation is that the CH_4 flux regulation is most directly related to the soil hydrology, indirectly affected by the wind that can dry the soil, rather than it is actually mechanical mixing of oxygen into the soil. Remember also, that methane oxidation requires one O_2 molecule. Thus, the oxygen requirement is very low compared to how much O_2 there is in the air, it is several orders of magnitude. So I would also assume that even at atmospheric stability or inversion and when the soil diffusion was not restricted by water (summer and freezing) O_2 supply would not be limiting CH_4 oxidation. I therefore have difficulty in attributing turbulent vertical atmospheric O_2 mixing as the primary stimulant of soil profile CH_4 oxidation. Research points to that this is regulated by soil hydrology and porosity. I therefore suggest you to moderate this claim and include how wind may act to dry the soil and hence increase diffusivity for O_2 and atmospheric CH_4. However, the problem is that you do not have direct soil moisture measurements to support this claim, but still I think it is a more feasible explanation that has been shown in other studies.

In the revised version of the manuscript, we add a figure (Fig.5b) with the scatter plot of CH_4 flux vs wind velocity (as suggested by the Reviewer). Also, the text within the manuscript was heavily changed accordingly.

High temporal resolution measurements of CO_2 and CH_4 facilitate looking at the underlying causes of emissions, looking, for example, at the relationship between meteorological/flux variables and CH_4 fluxes (Taylor et al., 2018). Further, the importance of soil net CH_4 uptake is poorly constrained, but it is widely recognised that soil temperature, soil moisture, and substrate availability (CH_4 and O_2) are the main drivers of the temporal variations of observed and predicted net CH_4 fluxes (D'Imperio et al., 2024). Juncher Jørgensen et al. (2024) incubation studies revealed that subsurface CH_4 oxidation is the main driver of net surface-atmosphere exchange, and it responds clearly to changes to soil moisture in these dry upland environments. The production, consumption, and transport processes of CH_4 are primarily related to hydrology, vegetation, and microbial activities (Vaughn et al., 2016; Wang et al., 2022). In this work any soil hydrology measurements were available for understanding these processes, however the measured wind velocity and soil temperature have been used as proxies for soil moisture and water table depth. Previous works have shown that advection, forced by wind pumping related to atmospheric turbulence, can increase turbulent fluxes from/to the snowpack (Sievers et al., 2015). Typically, the wind pumping effect led to increased emissions flux in CO_2 resulting from ebullition and/or ventilation. This correlation is analysed for the snow-covered periods (dark/light winter) in our measurement site (Fig.5a). **The scatter plot in Fig. 5a shows a quadratic relationship (the equation of the fit is reported in the figure, R^2=0.91) between wind speed and vertical turbulent CO_2 flux, with a clear increasing trend indicating positive fluxes for wind speed above 3 m s^{-1}. From a similar analysis, but in this case for the whole measurement period, for the CH_4 fluxes (Fig.5b), it can be observed, in this case too, a quadratic relationship with the wind velocity (R^2 = 0.98). In the range of low wind velocity CH_4 exchange balance is on median values very close to zero but going to greater wind speed (>10 m s^{-1}) the negative CH_4 flux (uptake) increases.**

Despite the Reviewer's valid observations that rightly point to soil hydrology measurements for understanding these processes, we unfortunately do not have any measurements available that can support such analyses. In the revised manuscript the Reviewer's explanation of the process has been inserted, as follow:

Overall, the observed correlation in the ecosystem uptake of methane with wind velocity suggests that the methanotrophic communities in the Svalbard soils might be stimulated by soil aeration, strongly related to its drying out during the summer. Since the CCT is also a semi-desert surface, the CH_4 uptake regulation is most directly related to the porosity and soil

hydrology (not measured in this study), indirectly affected by the wind that can dry the soil and increase diffusivity for atmospheric oxygen.

3.4 GHGs fluxes response to seasonal temperature anomalies

Line 400 Do you mean net annual CO_2 uptake?

Yes, we mean the net annual CO_2 uptake

Line 401-402: This statement would be easier to interpret if the temp-anomaly vs CO_2 plot were split into seasons. Perhaps do this as a supplementary figure?

The Reviewer is right. A comprehensive response has been provided to a similar question by the Reviewer RC1 in this Biogeosciences open discussion (RC1: 'Comment on egusphere-2024-1440' - https://doi.org/10.5194/egusphere-2024-1440-RC1). In response to the Reviewer's suggestion, we produced a new figure where the trends relative to the different seasons, taken in consideration in this work, were carried out separately (Fig. R2 and Fig.R3). In each panel is reported also the equation of the best fit for the binned data. Black squares represent the flux data binned for ΔT bins (5 °C large). Error bars represent the standard errors. In Fig.R2 and in Fig.R3 has been reported a linear fit also for the union of dark winter and light winter datasets, taken together to increase the statistical significance. Finally, we decided to insert in the revised version of the manuscript only some panels of Fig.R2 and Fig.R3. Specifically, we created only one figure, both for CO_2 and CH_4, inserting "Winter Snow", "Summer" and "Thawing" for each gas in a 3x2 frame. All the cases have been well described in the text.

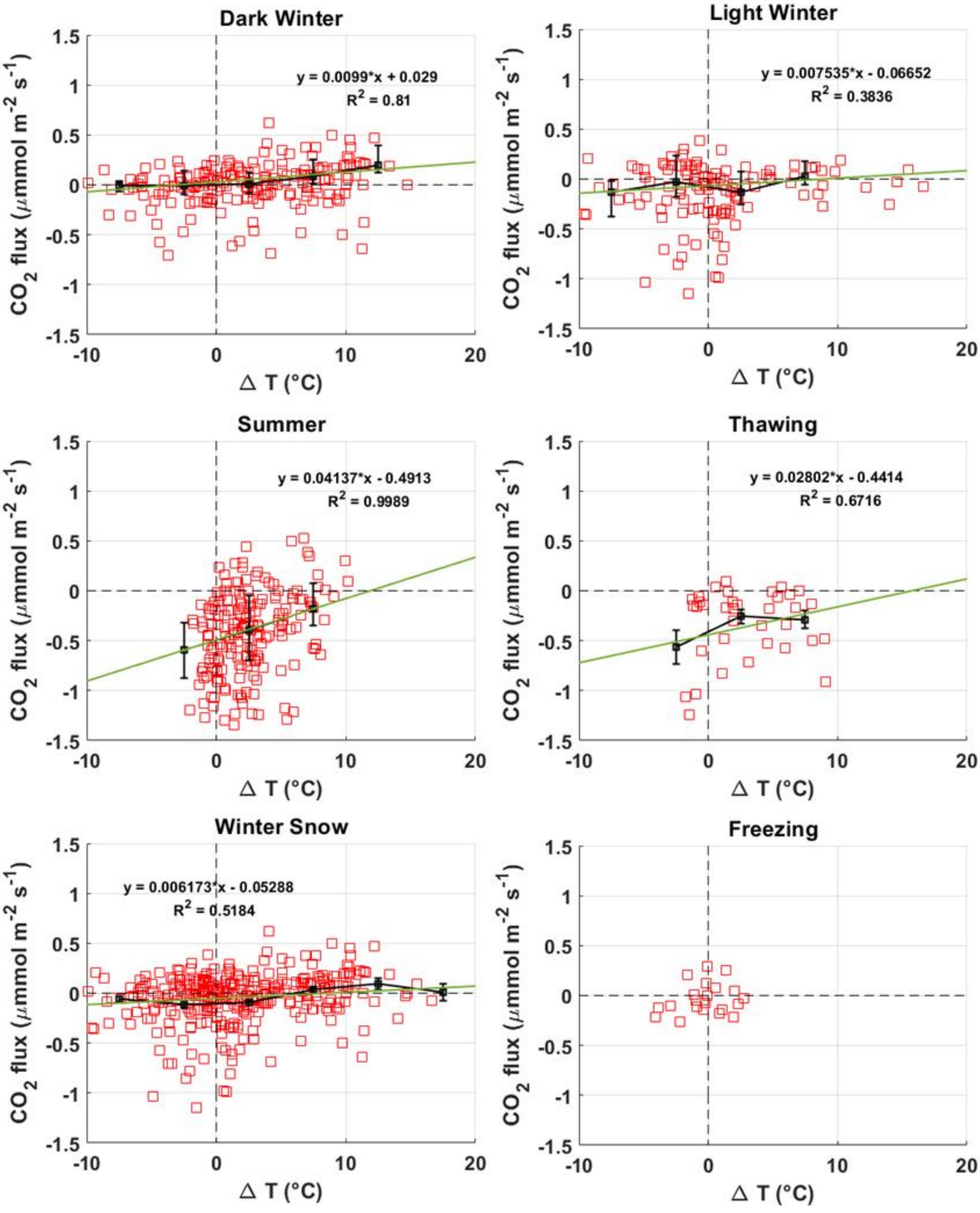

Figure R2 CO_2 vertical fluxes vs temperature anomalies for the different seasons (as reported in the title panel). A linear fit equation and the respective Pearson coefficient (R^2) are reported for each panel.

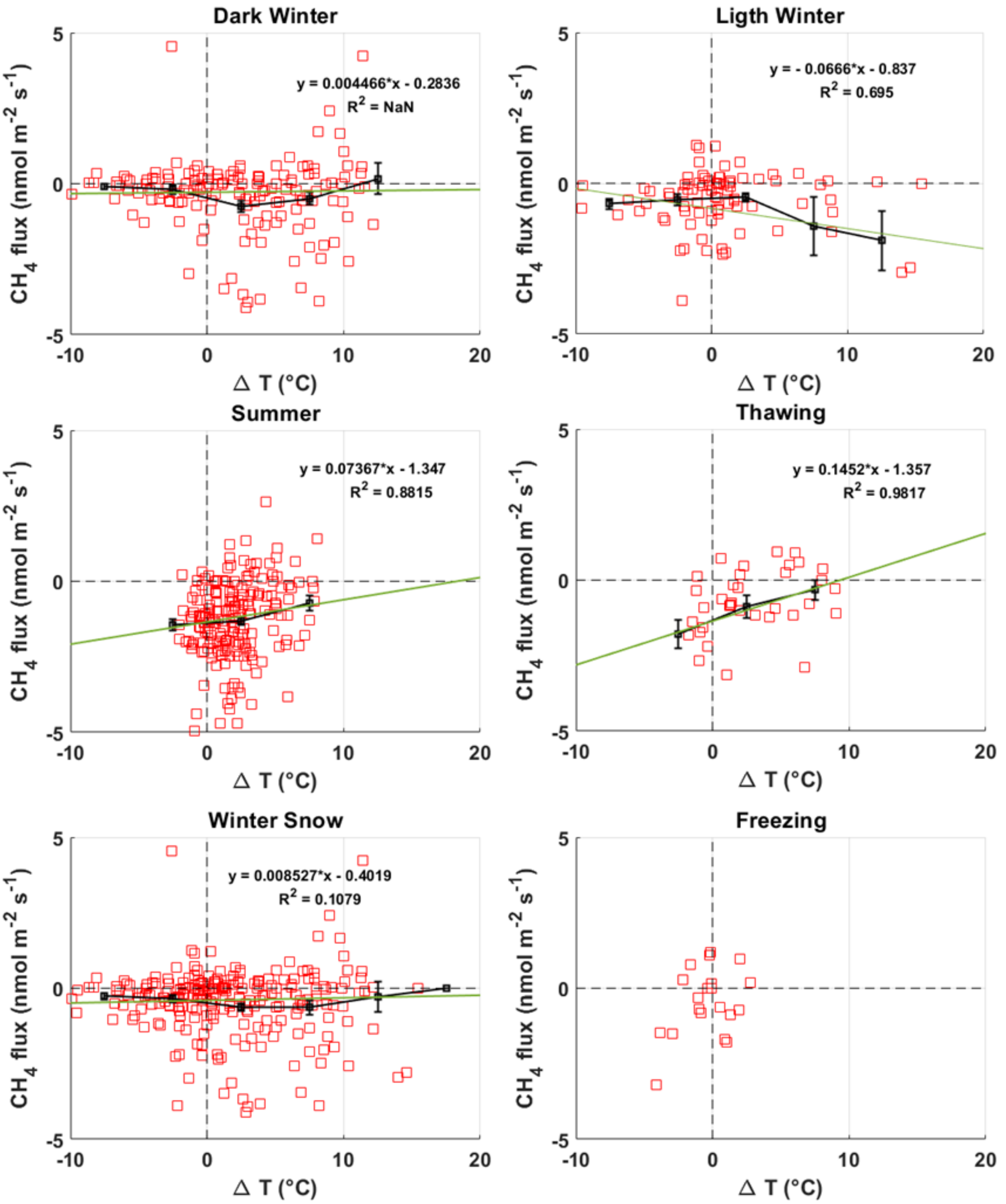

Figure R3 CH_4 vertical fluxes vs temperature anomalies for the different seasons (as reported in the title panel). A linear fit equation and the respective Pearson coefficient (R^2) are reported for each panel.

Line 411-412: Difficult formulation. I do not understand what you mean. I suggest to rephrase. Is this transition in the same direction in summer or winter or in opposite directions and hence what is the impact of the annual net CO_2 sink? If the transition to higher net CO_2 emissions with temp anomaly is the same for summer and winter then the net annual CO_2 uptake decreases, but if the transition is opposite in winter and summer then they may cancel out. I think this is what you mean by the sentence, but I am not sure. Sorry for the confusion.

In the revised version of the paragraph, the text was intensively modified. The sentence which the Reviewer refers to was rephrased as follow:

Overall, the results suggest a transition of CO_2 and CH_4 flux regimes to an emissive scenario (reduced net uptake) for thermal anomalies above 10°C for all the periods considered, especially for the winter, where the thermal anomalies have a greater relative magnitude.

Conclusions

Line 424: "increasing aeration" In my opinion and from knowledge of these soil types, they dry out fast in the spring if not snow covered. This is maybe because of wind, but likely also because of a relatively low albedo

The Reviewer is absolutely right. In the new form of the sentence, we put in evidence the albedo effect

… and correlates with the increasing aeration (wind effect) of the topsoil and its decreasing albedo.

Line 428: "reducing any further biological activity." I suggest to delete this part of the sentence as it does not really add meaning to this conclusion

Thanks a lot for the suggestion. Now, this sentence has been deleted.

Line 431-433: A weakness here of the conclusion that "other environmental variables" control CH_4 uptake is that you have not measured soil moisture content which is at the core of this increase. Solar radiation and wind plays a role in the speed of drying, but the soil material and structure ultimately determines how much it dries under the given climatic conclusion. I suggest you attempt to include more reflections on the role of soil moisture and that you may have a missing link here in your study.

Despite the Reviewer's valid observations that rightly point to soil hydrology measurements for understanding these processes, we unfortunately do not have any measurements available that can support such analyses. In the Conclusion Section, now, we include a sentence which involves more reflections on the role of soil moisture and the lack of this type of measurements in our work.

The CH_4 fluxes at CCT exhibited a limited association with both soil and ambient temperature in contrast to other environmental factors, such as the soil moisture and water table depth. Solar radiation and wind play a role in the speed of drying, but the soil material and structure ultimately determine how much it dries under the given climatic conditions. Overall, the observed correlation in the ecosystem uptake of methane with wind velocity suggests that the methanotrophic communities in the Svalbard soils are stimulated by oxygen uptake, strongly related to its drying out during the summer.

Line 433-434: I do not think this is the case. For example, Jørgensen et al. 2015 that you also cite shows that methanotrophs in dry tundra has a Q_{10} of 2, which does not indicate a lesser temperature dependency. Rather it is likely that the variation in CH_4 uptake is not limited by temperature, but by other factors.

In the new version of the manuscript this sentence has been deleted.

Line 434-435: I think you have an indirect effect of the wind, but via the soil hydrology as mentioned above. Furthermore, this correlation is not presented and the reader cannot assess if it a strong or as weak a correlation with the soil temperature. So I would be careful in concluding like this here and rather moderate the discussion in throughout the text.

Ok, we wish to thank the Reviewer again, in the new form of the manuscript all these issues should be resolved.

Line 438: Maybe add here after "…CO_2" "both in summer and winter periods, effectively reducing the net annual uptake." I think this is an important finding.

Many thanks for the suggestion. In the new form of the paper, we added the suggested sentence.

Line 438-439: Rather it is the opposite. Higher temperatures would stimulate plant growth if not limited by water and hence higher GPP. But if higher GPP is counterbalanced or even exceeded by more frequent temp-anomaly driven CO_2 emissions in summer and winter the annual net effect may actually be an overall decrease. The way you write it here indicates that

CO_2 respiration from increasing temp inhibits plant productivity, but this is not the case. So rephrase to avoid this mistake.

The Reviewer is right. Now, in the new form of the paper, the sentence was rephrased as follow:

The analysis of the impact of thermal anomalies on CO_2 and CH_4 exchange fluxes, underscores that high positive (> 5 °C) thermal anomalies may contribute to an increased positive flux both in summer and winter periods, effectively reducing the net annual uptake. Warming in permafrost ecosystems leads to increased plant and soil respiration that is initially compensated by an increased net primary productivity.

Figures
Really nice figures 1 – 6

Thanks a lot for your comment.

Figure 4 – lower panel for CH_4. Check y-axis title. There seems to be an "m" too much

Thanks for your suggestion. The y-axis label now is corrected.

Figure 6 – In the caption the black line is not explained. Also, I would suggest to show this figure split into the different seasons, so in order to more clearly see if seasons behave similarly or different.

In response to the Reviewer's suggestion, we produced a new figure (Fig. 6) where the trends relative to the different seasons, taken in consideration in this work, were carried out separately.