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

We thank the Reviewer for his/her careful assessment of our manuscript and his/her 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.

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.

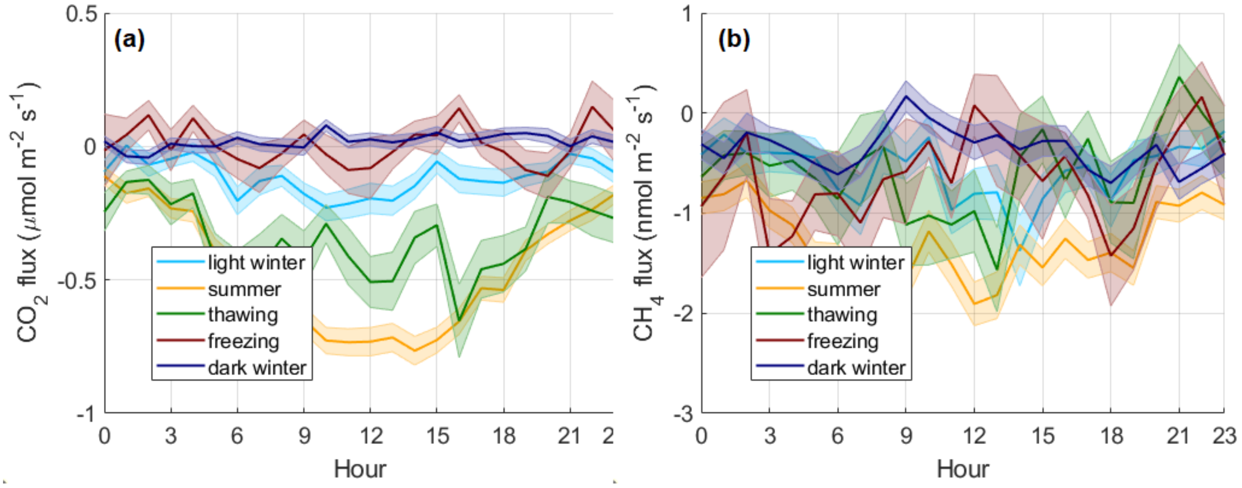

Figure R1 Diurnal pattern for the a) CO_2 and b) CH_4 flux at our measurement site. The patterns were reported for the different seasons considered in this work. Continuous line represents the mean flux values, while the colour shadow area represents the standard error of the measurements.

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.

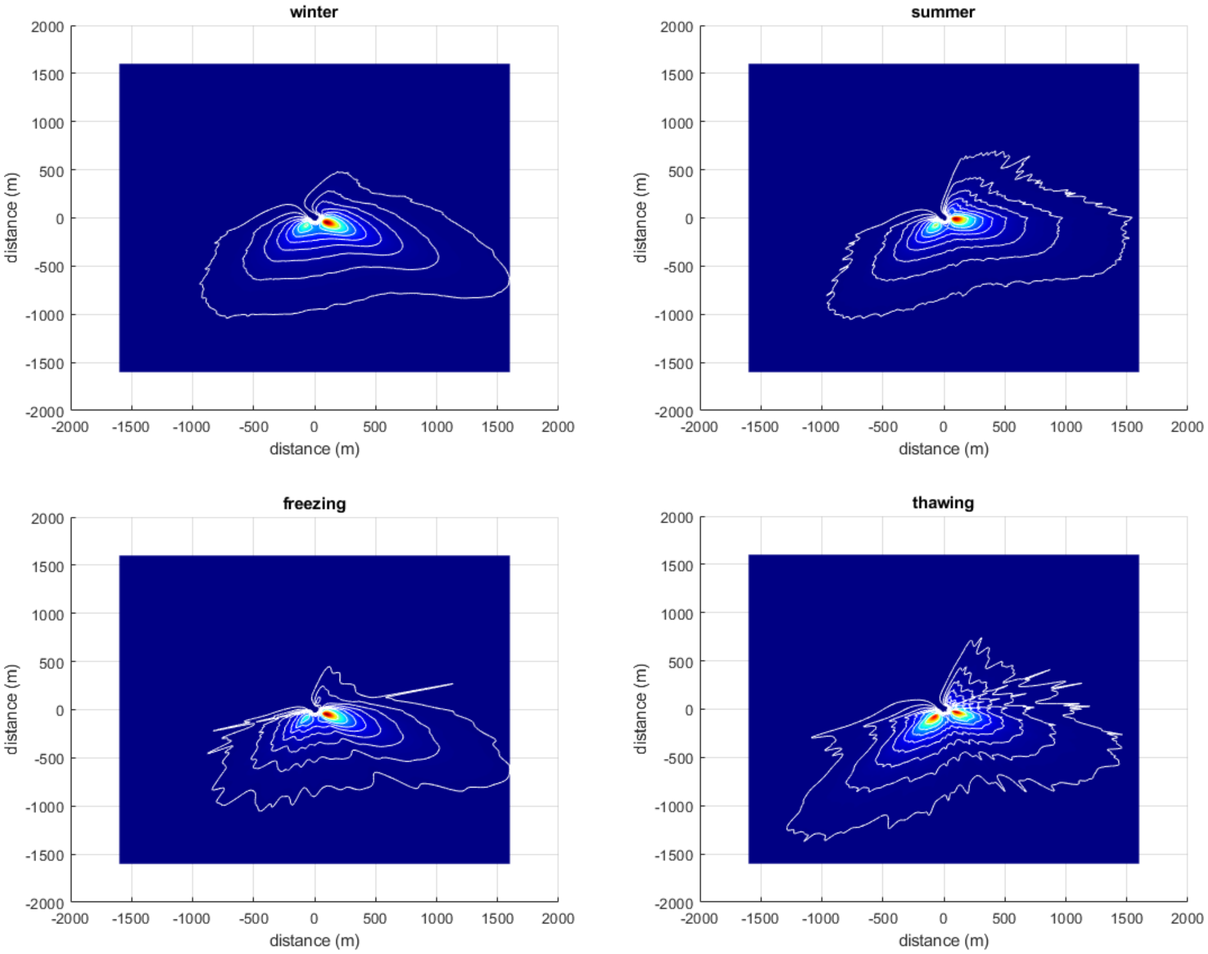

Figure R2 Footprint analysis for the winter, summer, freezing and thawing period considered in this work as reported by the relative title.

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 time series. 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.

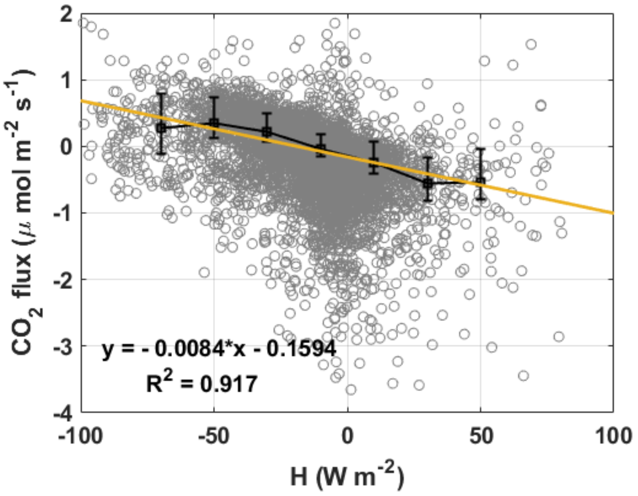

Figure R3 The relationship between wintertime CO_2 flux and the sensible heat flux H. Shown are half-hourly data (grey circles), bin-average values (black squares), and standard errors (error bars).

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.

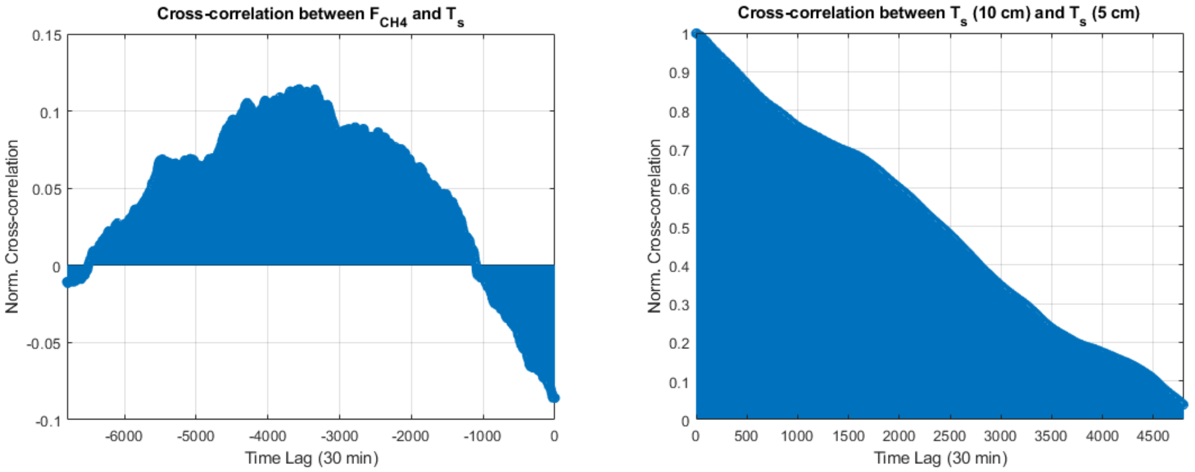

Figure R4 a) The normalised cross-correlation between methane flux (F_{CH4}) and deeper soil temperature (10 cm). b) The normalised cross-correlation between the deeper soil temperature (10 cm) and the shallower one (5 cm).

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.

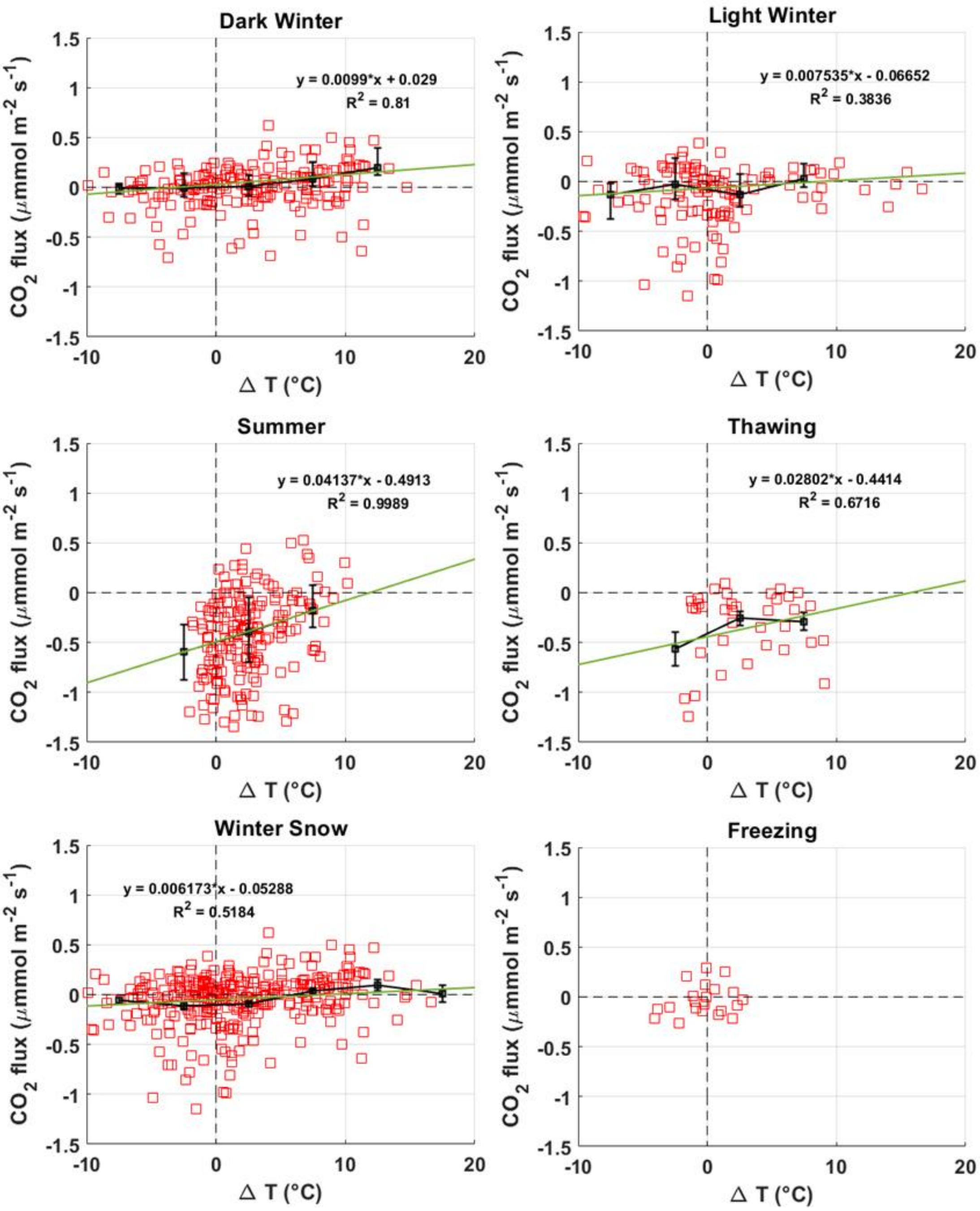

Figure R5 CO_2 vertical fluxes vs temperature anomalies for the different seasons (as reported in the title panel). A linear fit equation and the respective Pearson coefficient (R^2) are reported for each panel.

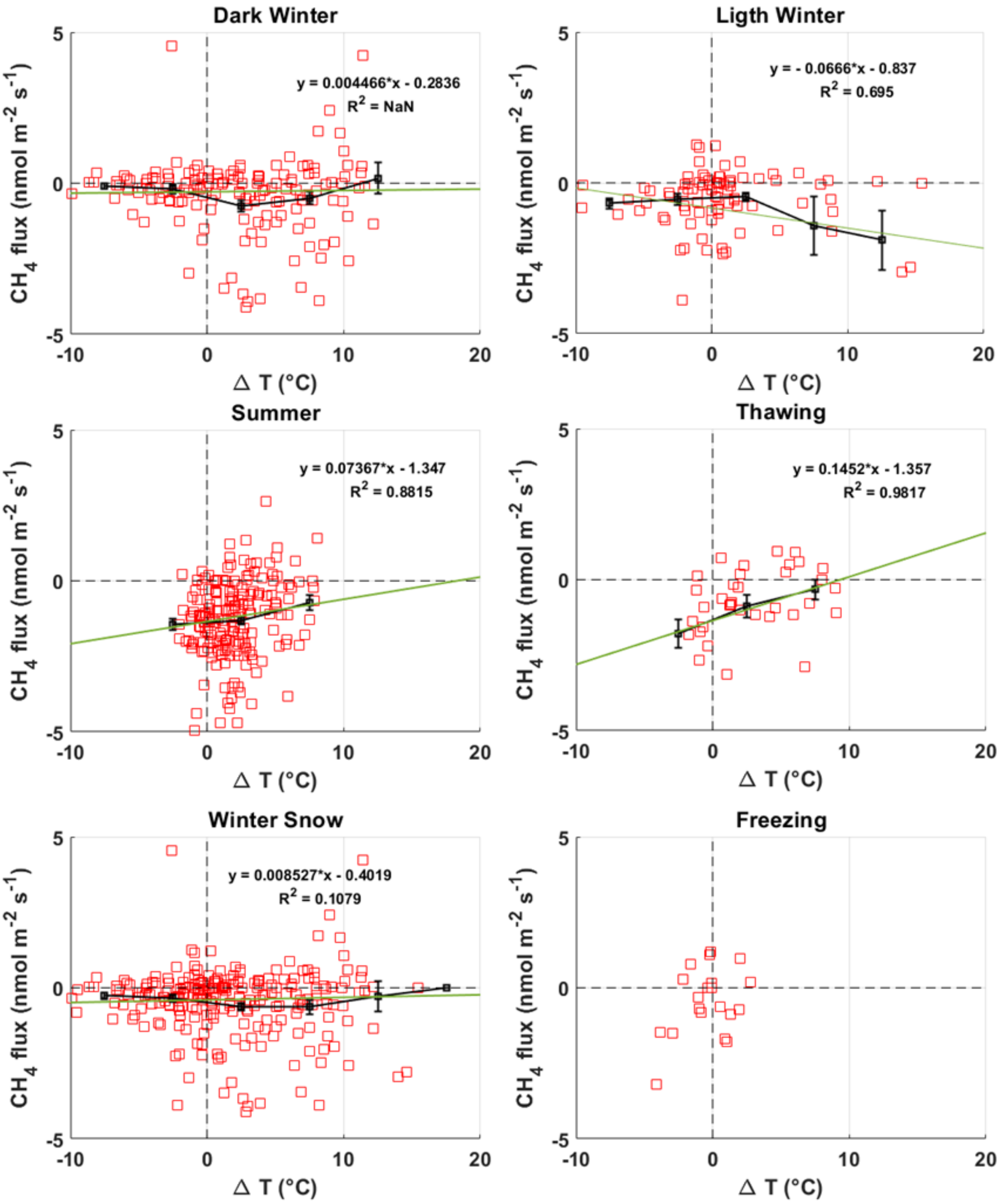

Figure R6 CH_4 vertical fluxes vs temperature anomalies for the different seasons (as reported in the title panel). A linear fit equation and the respective Pearson coefficient (R^2) are reported for each panel.

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 + longwave incoming radiation).