Dear Editor and Referees,

The following is our response to the two anonymous referees for our paper titled "Environmental correlates of peatland carbon fluxes in a thawing landscape: do transitional thaw stages matter?"

We wish to thank the two referees for their time and insightful comments on our manuscript. We believe that their constructive criticism and suggestions significantly improved our manuscript.

We have included all of the suggestions from the reviewers and have modified the manuscript accordingly. Several revisions have been made in the text including the addition of a subsection and slight modification of figure 5. Revisions are described in detail here and can also be seen in the track changes version of the manuscript.

The original referee comments are pasted below in black font. In a purple font we respond to each of the comments and in a green font, we detail the associated changes made in the manuscript.

Thank you,

A. Malhotra and N.T. Roulet

Referee #1

The manuscript shows that the spatial variation is an important control of C gas exchange processes during permafrost thaw. While this is not a novel idea as it has been shown for different microforms/vegetation communities of other type boreal peatlands, it is still important to prove that this also holds for permafrost, whose thawing is likely to have large consequences for climate in future. As authors say, this should be handled also when building process based models for these ecosystems. The methods and approach are valid to most part, but see the specific comments. The presentation is clear and concise throughout the MS.

We thank the referee for their general support of the manuscript and constructive suggestions on how to improve the manuscript. Based on the referee comments, we have improved our description and interpretation of some methods and analyses, respectively. Each specific comment is addressed below.

Specific comments:

pg450 l23: quite small plot to capture a vegetation community

We based our collar size on a vegetation survey of the sites where we found that the minimum distance where vegetation was relatively homogeneous was approximately 30 cm. At some sites the distance was larger but on the palsa and thawing sites the distances were small. Therefore, we selected collars of 26 cm diameter to be able to capture a homogenous plant community within a collar that would not overlap with a different community.

We have revised the wording in the manuscript to make it clear that each collar covered a surface area of 0.05 m^2.

Original text: Within each of the 10 selected communities 3 collars of 0.05 m^2 area were inserted in the peat surface and served as a seal for the manual gas flux measurements.

Revised text: Within each of the 10 selected communities 3 collars of 0.05 m^2 area each were inserted in the peat surface and served as a seal for the manual gas flux measurements.

pg451 l5: how large were your samples? your chamber is rather small, so sample collection may cause pressure. or did you use some sort of vents?

We collected 5 samples of 20 ml and the chamber headspace was either 9 L or 18 L (larger volume to capture taller vegetation types). Therefore each collected sample was either 0.2 % or 0.1% of the total headspace and in total either 1% or 0.5% of the total headspace volume was extracted as sample. Vents were not used but we believe that the pressure created during sampling was negligible because each sample was only a small fraction (0.2% or 0.1%) of the total headspace.

We have revised pg451 l4 to provide more details on volume of sample and total number of samples. We also corrected a typo in the manuscript where we said that samples were collected over 25 minutes rather than 20 minutes.

Original text: Headspace gas samples were collected every 5 min over 25 min.
Revised text: Five headspace gas samples of 20 ml each were collected every 5 min over 20 min.

pg451 l20: with such a small chamber, how did you manage with increasing temperature and condensation during light measurements?

We had a fan in the chamber and did not have considerable change in temperature over the short measurement period of 3 minutes (average change in temperature during measurement period was 1.9 ^{o}C).

Condensation was only observed on very hot days, when air temperature was greater than 20 ^{o}C, which was rare at Stordalen mire. Of the 10 days on which we sampled CO_2 fluxes, only 5 hours had an average air temperature above 20 ^{o}C. See figure A below for distribution of average hourly air temperature for the 10 sampled days.

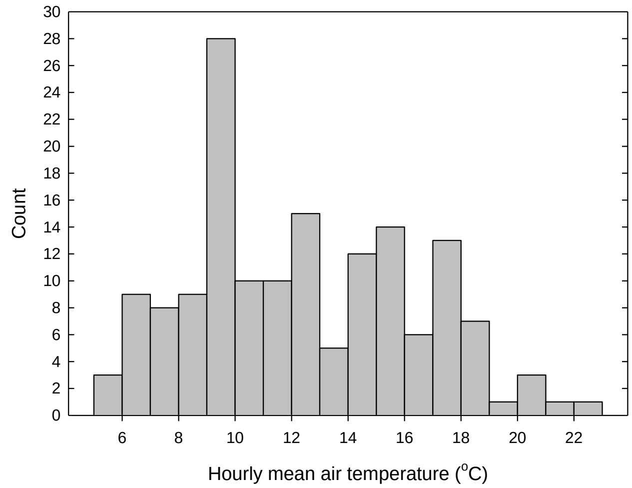

Figure A. Distribution of average hourly air temperature during the 10 days when CO_2 flux was sampled.

We have modified the text to clarify this.

Text added on p451l23: Over the 3 minute measurement period, on average, temperature in the chamber only increased by 1.9 ^oC.

pg452 l12. how did you manage with the VGA modelling with only 4 points?

VGA was measured at 4 time points x 28 spatial points (collars). A Gaussian best fit model was used for interpolation of seasonality based on previous studies (Lai, 2012; Wilson et al., 2006). We found that elevation explained the spatial variability of VGA, using a quadratic function. Thus we were able to combine the two models and fill in missing data for VGA accounting for the spatial and temporal variability.

pg452 l23. what was the need for this transformation?

The raw methane data were highly skewed and ranged over several orders of magnitude. The transformation decreased this skew. The transformation also improved the linear fit between methane and various abiotic and biotic variables (helpful for the use of multiple linear regressions).

We have added the following text to explain why this transformation was performed.

Added following text at P452l24: Log_{10} transformation decreased the skew in the raw data and improved the linear relationship between methane and other variables, allowing for the use of multiple linear regressions.

pg453 l13: why did you choose this approach as these relationships are seldom linear? or what are you aiming with this? does this procedure capture for example the seasonality in the NEE that is lacking in eq 1?

We expected PAR to have the strongest relationship with NEE, but we wanted to further assess which abiotic or biotic variables were linked with NEE (including, as the reviewer points out, influence of seasonality via VGA, soil temperature and thaw depth as well as influence of WTD). We had assessed these variables for non-linear relationships but did not find any significant non-linear models. We did however find weak linear relationships, and reported correlations since data were non-parametric (Table 3). Since these correlations are weak, they are not a major component of the discussion and we focus on the dominant control of NEE (PAR). We think that due to the spatial heterogeneity of the site, it was difficult to see relationships between NEE and WTD, thaw depth, soil temperature and VGA.

We have modified the text to clarify the aim of this exercise and mention that we did try non-linear regressions as per theory but did not find significant trends. We have also corrected that the analyses used were non-parametric correlations rather than linear regressions.

Original text: Linear regressions were performed between the CO_2 flux data as well as WTD, thaw depth, soil temperature and VGA.
Revised text: Other than PAR, we expected to see non-linear relationships between CO_2 flux and WTD, thaw depth, soil temperature and VGA, but we did not find significant relationships. Instead we found linear relationships to be significant. Since our data were non-parametric, we used Spearman's correlation coefficients to quantify the link between CO_2 flux with abiotic and biotic variables.

pg 457 l4: you do not discuss VGA, although it was significant in your model and many previous studies have indicated the importance of its components as well. such as change from shrubs to sedges (other aerenchymatoes species). I assume this is the case in your study as well. if you would include only VGA of those species, you might get even higher significance for VGA. in addition, seasonal development of VGA is likely a better indicator of seasonality than Julian day.

We agree that VGA could be discussed further and have added text at pg 457 l2 to address this.

Text added at pg 457 l2 (after additions from referee#2 comment on removing elevation from the model): VGA is likely a strong effect as it is linked with spatial and seasonal changes in substrate availability, litter input and root exudates and thus relates to both spatial and temporal variability in CH4 flux (Whiting and Chanton 1993).

Regarding the VGA of shrubs vs sedges, we leave this out of section 4.1 because it is discussed in the section 4.3 on CH_4: CO_2 ratios and in newly added to the methods and results as per the last comment of reviewer#2 (regarding P 460, Line 15-23). In these new sections and in section 4.3 we discuss that sedge VGA is related to both CH_4 and CO_2 fluxes, while shrub and herbaceous VGA is not. We also found that *Sphagnum* abundance is related to CH_4 and CO_2 fluxes.

pg457 l10-14: you might like to take a look at paper Laine et al. 2009. Ecological modelling 220 (2009) 2646–2655

We are unsure if the paper is closely related to our discussion as our objectives do not include providing spatially explicit CO_2 balance for the site. We suspect that the reviewer suggested it to include a discussion that using a site level model is inappropriate in a heterogeneous site and therefore our reported light use efficiency model for the site level pooled data is likely biased. If so, we agree with the reviewer and have modified our discussion to further emphasize that site level model results may be related to the spatial heterogeneity of the site.

Original text: Comparatively our across peatland lumped data fit to the rectangular hyperbola model explain a lower percent of the variance (52 %) in NEE, likely due to the structural heterogeneity on our site.
Revised text: Comparatively our across peatland lumped data fit to the rectangular hyperbola model explain a lower percent of the variance (52 %) in NEE, likely due to biases introduced by the high spatial heterogeneity on our site (Laine et al., 2009).

pg457 l16 delete 'was' from, which was makes.

We have modified this text as per the comment.

pg457 l25-26: sedge VGA an explanatory here?

We agree with the reviewer that sedge VGA would indeed be a strong correlate of CH_4 (Fig. 1) and sedge VGA and overall VGA are higher later in the growing season and in the later stages of thaw. We have modified the text to include this aspect. We discuss VGA in detail in section 4.3.

Original text: This trend of increasing correlation could be partly due to the increasing magnitude and variance of not only CH_4 fluxes but also the environmental variables with thawing permafrost.
Revised text: This trend of increasing correlation could be partly due to the increasing magnitude and variance of not only CH_4 fluxes but also the environmental variables with thawing permafrost. Additionally, higher VGA later in the growing season could also be result in a stronger seasonality effect (Fig. 4c) in the later stages of thaw, especially as these stages had the highest sedge VGA.

pg459 l11: it is still not clear to me how you use VGA in the modelling. do you use some average value per plot for all measurements or do you use the modeled VGA so that seasonality is included?

Throughout the paper, we always used modeled VGA (includes the spatial and temporal variability) in our analyses, so seasonality of VGA is included.

To make this clear in the text, we have modified pg 452 l13.

Original text: The seasonality of VGA was modeled using a Gaussian fit and combined with a quadratic fit with elevation to extrapolate a spatially and temporally higher resolution dataset for VGA, referred to as modeled VGA in the text.

Revised text: The seasonality of VGA was modeled using a Gaussian fit and combined with a quadratic fit with elevation to extrapolate a spatially and temporally higher resolution dataset for VGA. Throughout the manuscript we only use the modeled VGA.

pg460 l20-23: why do you ignore the impact of graminoids here?

We agree with the reviewer that the effect of graminoid VGA on CH_4:CO_2 ratio is important and has been emphasized in previous studies. We did find a strong effect of VGA of graminoid species on the CH_4:CO_2 ratio but were surprised that the effect of *Sphagnum* was stronger and had interactive effects with soil temperature that graminoids did not have. Therefore, we had a few additional sentences on *Sphagnum.* We have clarified this in our revised discussion (see the last comment of referee#2 for details).

Figure 5. rather than an increase in R2 along thaw gradient, I see two groups defined by existence of permafrost and maybe cover of vegetation. the linear fit just doesn't work.

The review makes a good point regarding the linear fit not being appropriate and we have removed it from the figure and figure caption. However, we cannot say that there are two groups defined by the existence of permafrost because only stages 1-3 have permafrost while the groupings of R^2 are 1-4 and 5-10. There are no clear differences in vegetation cover to explain the two groups either.

Fig 6. I am not sure if I am reading this figure correctly. is it so that VGA is included only for stages 6, 8 and 9? and for stage 6 the estimate is negative?

Yes, the reviewer is reading the figure correctly. The results regarding VGA suggest that within stages 6, 8 and 9 there is enough spatial or temporal heterogeneity in VGA that it is a significant predictor of methane. In the other stages, this variability is better captured by elevation, thaw depth and temperature. We are unsure why VGA has a negative contribution in stage 6. We think it might be because late in the growing season, while the VGA beings to decline, the CH_4 flux continues to increase, likely because soil temperature is still relatively high (between 8 to 12 ^oC).

Fig 6. what does the models of stages 2 and 3 include, as nothing gets any values?

The model fits for stages 2 and 3 were not significant and therefore were excluded from the figure. We have added this information to make it clear.

Text added on p455l19: Model fit was non-significant for stages 2 and 3, and therefore their slope coefficients are not reported in Fig 6.

Literature cited

Lai, Y. F.: Spatial and Temporal Variations of Carbon Dioxide and Methane Fluxes Measured by Autochambers at the Mer Bleue Bog, PhD thesis. McGill University, Montreal, Canada., 2012.

Wilson, D., Alm, J., Riutta, T., Laine, J., Byrne, K. A., Farrell, E. P. and Tuittila, E.-S.: A high resolution green area index for modelling the seasonal dynamics of CO2 exchange in peatland vascular plant communities, Plant Ecol., 190(1), 37–51, doi:10.1007/s11258-006-9189-1, 2006.

Referee #2

The ms explores how permafrost thaw in (sub) artic peatlands may change gaseous carbon exchange dynamics as the system moves from a frozen to fully thawed state, including several transitional stages occurring along the way. Chamber measurements of CO2 and CH4 for each transitional stage are correlated with several environmental variables to explore how the importance of these factors as controls of C exchange processes change as the system thaws. Given the potential warming of high latitudes the topic of the study is timely and important for attempts to e.g. identify and quantify feedback processes associated with ecosystem transition. It also emphasizes the complexity involved in doing so due to spatial heterogeneity. The ms is well written and, for most parts, clearly structured. Methodological approaches are generally sound, clearly conveyed and motivated. However, I have some concern on the data evaluation and the statistical approach.

We thank the referee for their general support of the manuscript and excellent suggestions to improve the statistical approach and interpretation as well as our discussion of CO_2 and CH_4 ratio. Each specific comment is addressed below.

Expanding from the simple bivariate correlations the authors use MSLR in order revel more complex interrelations of their variables. However, the analysis appears to be limited to additive effects while it is well known that interactions are seldom only additive. Why were other interaction terms (e.g. products) not included in the analysis? This could potentially shed more process level insights on the transition dynamics.

We thank the reviewer for this excellent suggestion and agree that interactive effects could be useful. We reproduced our site level analyses with interactive effects to explore these. We added an interactive effect between soil temperature and VGA and found that this was insignificant to the overall model. We also investigated a version of the model with an interactive term between VGA and thaw depth, which was significant (p value = 0.01) but only improved the adjusted R^2 of the model by 1%. VGAxThaw depth also had a very low contribution to the model (lowest beta weight of 0.06, compared to the highest of 0.46). We are unsure how to interpret these weak interactive effects given that most of the variables used are already proxies for multiple controls on methane production and might already be including some interactive effects. Given the low contribution of the interactive effects to our model as well as difficulty in interpreting these interactions, we decided to include additive effects in the model, though we do clarify that interactive effects were explored.

We have modified the text on pg 452 l27 to explain that we attempted to explore interactive effects but did not find any major effect.

Original text: To explore the relationship between environmental correlates and CH_4 flux, we used stepwise multiple linear regression.

Revised text: To explore the relationship between environmental correlates and CH_4 flux, we used stepwise multiple linear regression. We used both additive and interactive effects to explore a best fit model, but found that interactive effects were either insignificant or had a weak contribution to the overall model. For ease of interpretation, given that our variables are already proxies for several interacting controls on methane fluxes, we only included additive effects in our final model.

The study finds that “elevation” is a main factor for explaining CH4 fluxes, but from a process level perspective this variable makes less sense. The authors do acknowledge that “elevation” likely integrates for other variables like WTD, nutrients etc. that are important in driving CH4 production and flux, but is there a risk that inclusion of this variable obscures correlations with other, more meaningful variables, that could be important for explaining the flux dynamics? If elevation was omitted from the MLSR the WTD would probably correlate most strongly, and it is probable from Fig 1 that the following residuals could correlate differently. Was this tested? There could be risk of strong collinear influence on potential X-variables, but this could be solved by e.g. principal component extractions and concomitant MLSR.

Several combinations of variables were explored for MLSR and elevation improved model fit considerably in each case. We also tested for multicollinearity and ensured that there were no problems with highly correlated variables in our final model. The reviewer, however, brings up a good point, that elevation might be obscuring the effect of the other variables.

We agree with the reviewer that removing elevation makes sense theoretically, and have added a model that excludes elevation. We also keep the original model that includes elevation and our discussion that elevation incorporates several controls of methane. For example, since there is no water table in the palsa thaw stages, elevation serves as a better proxy for moisture than the water table depth.

Added text on P454l14: An alternative model that excluded elevation wherein the adjusted R^2 drops to 0.62, is also reported as it better isolated the effects of VGA, soil temperature and thaw depth. The contribution (beta weights reported in brackets) of soil temperature (0.16) and thaw depth (-0.27) are similar in the model with or without elevation. The contribution of VGA increases from 0.26 to 0.58 when elevation is removed from the model.

Added text on P457l2: Rerunning the best fit model without elevation decreases the overall model fit by 10% but increases the contribution of VGA to the model, while the contribution of thaw depth and soil temperature remain the same. Removal of elevation from the model better isolates the relative effects of thaw depth, temperature and VGA on methane fluxes and suggests that the strongest contribution is from VGA, followed by thaw depth and soil temperature.

Specific comments: P 457, L 16: strange sentence; reword.

We have modified this text as per the comment and have deleted ‘was’ from the text on pg457 l16 ‘..which was makes sense as..’.

P 458, L1-10: Expand this discussion to also address the specific influence of temperature on methanogensis and methanotrophy, respectively, and the net influence on CH4 fluxes. Several studies have reported different temperature sensitivities for the two processes which are in accordance with the observations.

Since we only have measurements of net CH_4 flux, we are unable to isolate the effect of temperature on methanogenesis or methanotrophy. To avoid speculating about which process likely dominates in each of the thaw stages, we simply added a sentence mentioning the importance of the two processes and that we cannot distinguish their respective influence on our measurements.

Added text on P458l20: Our estimated temperature sensitivity for each thaw stage is the net effect of temperature on methanogenesis and methanotrophy and since we only measure the net CH_4 flux we cannot isolate the relative temperature sensitivities for the two processes.

P459, L8-11: Confusing; how can elevation/thaw depth better account for thermal regime than temperature itself?

Elevation and thaw depth might be representing the thermal regime over a longer time scale and are also likely related to other controls (eg. moisture) of methane flux. We intended to discuss that for these two reasons, elevation and thaw depth are stronger model effects than soil temperature. However, we agree with the reviewer that the sentence is confusing.

We have changed the sentence to reflect the above.

Original text: Soil Temperature was not a statistically significant estimate for any of the thaw stages, possibly because elevation and thaw depth (significant for stages 1, 4, 5, 7, 8 and 10) better accounted for thermal regimes.
Revised text: Soil Temperature was not a statistically significant estimate for any of the thaw stages, possibly because elevation and thaw depth are better proxies for the long term thermal regime and also relate to several other controls of CH_4 flux, as previously mentioned.

P 460, Line 15-23: Why is this observation not in the results section? As it reads it comes across as a somewhat awkward add-on. Suggest moving it to the Results and also give adequate background info in methods. You can then expand the discussion around partitioning and what controls it.

We fully agree with the reviewer and have made the suggested changes to the manuscript. Specifically, we have added the following paragraph to the Data Analysis subsection in methods.

Text added on P453l26: Lastly, we evaluated the relationship between CH_4 and CO_2 fluxes using a simple CH_4: CO_2 flux ratio. To use a standardized measure of CO_2 flux we use the GP_{MAX} from each thaw stage.

We also added a new section in the Results.

Text added on P455l25: 3.3 The relationship between CO_2 and CH_4 GP_{MAX} and CH_4 were positively correlated (ρ=0.56, p=0.0021; Fig. 7). We found that the best explanatory variables for CH_4: GP_{MAX} ratio were *Sphagnum* percent cover (ρ =-0.72, p=0.008; and graminoid VGA correlated (ρ =0.63, p=0.0004). While graminoid VGA did not have any interactive effects with abiotic variables in explaining CH_4: GP_{MAX} ratio, *Sphagnum* cover and soil temperature had a significant interactive effect (Table 5).

Lastly, we made necessary changes to section 4.3, to remove repetition. These modifications also include the revisions for referee#1 comment: "pg460 l20-23: why do you ignore the impact of graminoids here?"

Original text: Interestingly, thaw stages 8 to 10 (graminoid dominated) have a different relationship of GP_{MAX} and CH_4 compared with thaw stages 1 to 7 (moss dominated) suggesting a shift in the partitioning of C loss from the system as CO_2 or CH_4 with increasing thaw and changing vegetation. We further investigated whether this shift is related to loss of *Sphagnum* (increase in pH and decrease in organic matter lability) or increase in graminoid species (increase in lability and CH_4 emission via aerenchyma). Both percent cover of *Sphagnum* ($\rho = -0.72$, $p = 0.008$) as well as VGA of graminoid species ($\rho = 0.63$, $p = 0.0004$) in the collar were significantly related to $CH_4 : CO_2$. Additionally, there was a significant interaction between soil temperature and *Sphagnum* cover in a linear model explaining $CH_4 : CO_2$, suggesting that the relationship of CH4 and CO2 depends on *Sphagnum* abundance but the effect of *Sphagnum* varies by temperature (Table 5).

Revised text: Interestingly, thaw stages 8 to 10 (graminoid dominated) have a different relationship of GP_{MAX} and CH_4 compared with thaw stages 1 to 7 (moss dominated) suggesting a shift in the partitioning of C loss from the system as CO_2 or CH_4 with increasing thaw and changing vegetation. We expected this shift to be related to an increase in graminoid VGA (increase in lability and CH_4 emission via aerenchyma), which was supported by our data. Surprisingly, we also found the shift to be related to a loss of *Sphagnum* cover, perhaps due to an increase in pH and decrease in organic matter lability. Furthermore, there was a significant interaction between soil temperature and *Sphagnum* cover in a linear model explaining $CH_4 : CO_2$, suggesting that the relationship of CH_4 and CO_2 depends on *Sphagnum* abundance but the effect of *Sphagnum* varies by temperature (Table 5).