Response to referee's comments on "Investigating the sensitivity of soil respiration to recent snow cover changes in Alaska using a satellite-based permafrost carbon model"

Dear Editor,

We appreciate the constructive comments from the two reviewers, and have carefully revised the paper based on those comments. Specifically, we added a flowchart and a brief model description to make the paper easier to follow; we performed attribution analysis to investigate main climate controls on annual carbon fluxes. We also paid particular attention on the definition of soil respiration and removed "redundant" discussion throughout the results and discussion section. Our responses to the comments are provided in the following text, and the revised manuscript is enclosed as a supplement with changes highlighted.

Thank you very much for considering our manuscript.

Yonghong Yi, on behalf of all authors

Review 2#:

1) General comments: "In this study, Yi et al used a satellite-based permafrost carbon model to analyze the response of soil respiration to changes in snow coverage and temperature in the Alaska ecosystems. They concluded that for the time period from 2001 to 2017, soil respiration has overall increased with the warming. While I can sense the study was well attempted and carefully written, I feel some additional analyses may further improve the quantitative strength of some of the currently too colloquial conclusions. For instance, a time series plot showing how the carbon fluxes over Alaska have changed through the whole time period will give readers a more direct visual impression. In addition, in the trend analysis presented in Fig. 7, it is unclear how such trend change should be put into the context of changes in snow cover and warming. Perhaps an attribution analysis of these carbon flux trends to changes in snow cover, temperature, ALT, etc. will be helpful? Finally, maybe the authors could think of beginning the paper with a diagram (or flow chart) of how soil respiration is related to the variables they are investigating in this study? Such a diagram will put the attribution analysis (if the authors decide to do it) or the analysis in the result section into a better mental perspective."

Response:

Thank you for the suggestion. In response to your comments, we have: 1) added a time series plot (Fig. S10), and performed additional attribution analysis (Fig. 9) to support our conclusion; and 2) added a diagram of the modelling framework (Fig. 1). We also added description on the permafrost soil model that we used and a few figures in the supplementary materials to address the reviewer's concerns. Please see our response below for more details.

2) Model description: the hydrological module is not well described. It took me quite a while to figure out the soil moisture is not simulated but rather is model input (am I right?). Moreover, in order to understand the model, I also read a number of other papers about the model, but was never clear how the whole model was assembled. So, if I may request, can the authors present a model description as supplemental material? Or at least give a list of what major variables are simulated, and what are prescribed as input.

Response:

Yes, the permafrost soil model (RS-PM) does not simulate the soil water movement directly; rather it uses the total soil water content from SMAP L4SM product as the inputs, and then simulates the changes in the unfrozen liquid water fraction due to soil freeze/thaw activity. We have added a short paragraph in the beginning of Section 2.1 to more clearly illustrate the modeling process and the link between the permafrost soil model and the carbon model:

Line 103-112: "The Remote Sensing driven Permafrost Model (RS-PM) developed in Yi et al (2018; 2019), was coupled with a terrestrial carbon flux (TCF) model (Yi et al., 2015) to investigate the climate sensitivity of carbon fluxes across Alaska (Fig. 1), with a particular focus on the shoulder season. The soil decomposition model in the original TCF model was revised in this study to account for vertical soil carbon transport in order to better simulate the depth-dependent soil carbon distribution and respiration fluxes. The RS-PM model simulates the soil temperature and changes in soil liquid water content due to soil freeze/thaw along the soil profile, using remote sensing datasets including land surface temperature (LST), snow cover information and total soil moisture content. The RS-PM outputs were then used as inputs to the TCF model, as constraints on both the vegetation productivity and soil respiration. A brief description of the modeling framework was described here, with a focus on the revised soil decomposition model, while a detailed description on the RS-PM model was provided in the supplementary material."

The flow diagram was presented as the new Figure 1. We also provided description on the permafrost soil model in the supplementary materials. Please refer to the manuscript for more details.

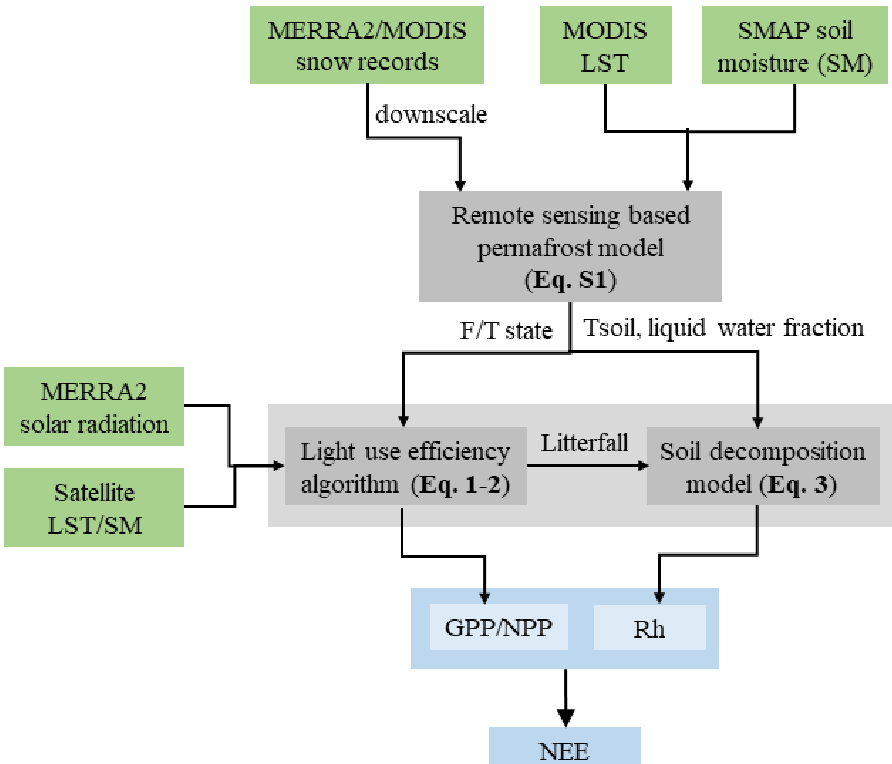

Fig. 1 Flow diagram describing the modelling procedure and main input datasets used in this study. The terrestrial carbon flux model has two components, including the light use efficiency algorithm for vegetation productivity estimates and a soil decomposition model for soil heterotrophic respiration estimates. The main equations used for each modelling component was also included in the modelling box.

3) Fig 2, it is not easy to compare model with observations, even though I can see the model ball-park agrees with the response curve derived in Slate et al. (2017). The authors may consider interpolate the model results to the observations and present a scatter-plot as an addition to help analyzing the model performance.

Response:

There is a generally large discrepancy between downscaled MERRA2 (1-km) and in-situ effective snow depth data at the Snotel sites (Fig. S1a), so we chose not to directly compare the model simulated and in-situ soil temperature data at the Snotel sites. But we do see an overall consistency between model simulated soil temperature and in-situ data at 20 cm depth as shown in Fig. S1b. Soil temperature data at 5 and 50 cm show similar performance. We chose not to include this figure in the main text but in the supplementary material to make the paper more concise.

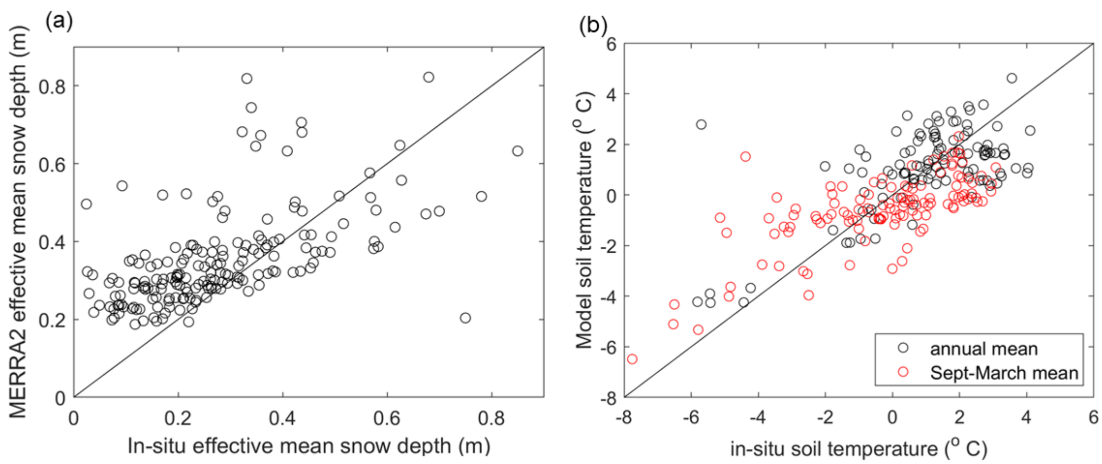

Fig. S1 Comparison between (a) effective snow depth derived from in-situ observations and downscaled MERRA2 data, and (b) observed and model simulated monthly soil temperature at 20 cm at the Snotel sites. Note that the sites compared for snow depth and soil temperature are not the same due to inconsistency between the snow depth and soil temperature measurements at the Snotel sites. There are generally more snow depth measurements than soil temperature measurements at the Snotel sites.

4) Fig 3, it will be helpful to present a scatter-plot of modeled vs measured NEE.

Response:

The scatter-plots between modeled and measured NEE fluxes are now added as panel (d) in Fig. 4 (the original Fig. 3). The temperature sensitivity of ecosystem respiration at US-Atq in the original panel (d) was now presented as Fig. S2.

5) Fig 6. Panel c and d are hard to compare, maybe the authors can consider contrasting two depths each panel in two panels, so readers can compare the time series more straightforwardly.

Response:

According to the reviewer's suggestion, we now combined panel (c) and (d) in Fig. 7 (originally as Fig. 6) as a single panel, and compared the depth-dependent Rh fraction for the two permafrost zones. We combined the two intermediate soil depths (13-33 cm, 33-55 cm) as a single depth (13-55 cm), to be more concise. Please refer to the new Figure 7 for more details.

6) Fig. 7, like in my major comments, if a quantitative attribution analysis can be done here, it will be very helpful.

Response:

We added two figures to support quantitative analysis of our results as requested by the reviewer: 1) Fig. S10 shows the time series plot of the annual carbon fluxes; 2) Fig. 9 shows the relative importance of selected climate variables to the annual carbon fluxes. The original Fig. 9 that provides results on the correlation analysis between Rh fraction and seasonal LST was now moved to the supplementary material (Fig. S13) to make the paper more concise.

The attribution analysis was conducted using the gradient boosting regression method, and was described in Section 2.4 (Line 289-302):

"Finally, we used the gradient boosting regression (GBR) method to quantify the contribution of climate variables to the annual carbon fluxes. The GBR method consists of a sequence of models, and each consecutive model is developed based on the errors of previously added models (Friedman, 2000). The above model simulated annual carbon fluxes from 2002 to 2017 were used to train and evaluate the GBR models. We chose the following nine contributing factors or predictors to annual carbon fluxes during the model fitting, including summer (June-August) NDVI, annual freezing and thawing index, mean annual downward solar radiation, rootzone soil moisture during the thaw season, snow offset and onset, mean snow depth averaged from January to March (representing annual maximum snow depth), and snow depth during the early snow season (from October to November). The GBR method was implemented using the sklearn package of Python 2.7. The following method was used to determine the relative importance of each predictor to the GBR model's predictive performance. We first run the GBR model using all nine predictors, and the model results were referred as baseline simulation ($GBR_{baseline}$). We then ran the fitted model with one randomized variable but with other variables remained intact, and the results were referred as $GBR_{one\_variable\_randomized}$. The variable importance was then computed and normalized based on the Person's correlation coefficient between the two runs using the following equations (Karjalainen et al., 2019; Zheng et al., 2020):

$$\mathrm{I_x} = 1 - \mathrm{corr}(\mathrm{GBR_{baseline}} - \mathrm{GBR_{one\_variable\_randomized}})$$

$$\mathrm{RI_x} = \frac{\mathrm{I_x}}{\sum_{\mathrm{x}=1,9} \mathrm{I_x}} \quad (6)$$

"

The attribution analysis results were added in section 3.2.1 (Line 413-430):

"…At the regional scale, the time series of annual carbon fluxes also showed non-significant ($p>0.1$) positive trends, with values of 2.58, 1.86, 0.38 Tg C yr^{-1} for GPP, Rh and NEE fluxes respectively (Fig. S10).

The attribution analysis results using the GBR method also indicate that summer NDVI and annual thawing index are the two most important variables affecting the annual carbon fluxes, which was generally consistent across different vegetation types (Fig. 9). For annual GPP flux, NDVI was the most important variable followed by annual thawing index and downward solar radiation, while for annual Rh fluxes, annual thawing index was the most important variable, followed by NDVI, with other variables playing a very minor role. Despite the importance of annual thawing index controlling annual GPP and Rh fluxes, the snow offset showed little importance to both fluxes. This was likely due to the low temporal resolution of the MODIS snow cover data used for the snow offset calculation, which was calculated as the center date of the 8-day composite period with snow disappearance. The low temporal resolution of snow offset (i.e. discrete variables) and a strong correlation ($R>0.7$, $p<0.1$) between annual thawing index and snow offset may limit its use in the regression model. As for annual NEE flux, thawing index, NDVI, downward solar radiation, and annual freezing index are among the most important factors. However, the effects of different variables on annual NEE flux varied throughout the period due to their compensating effects on GPP and NEE, and NEE being a small residual flux; therefore, none of the variables played a dominant role throughout the entire period. The GBR model also showed a relatively poor performance in prediction of annual NEE fluxes ($R \geq 0.7$) comparing with the other two fluxes ($R > 0.9$)."

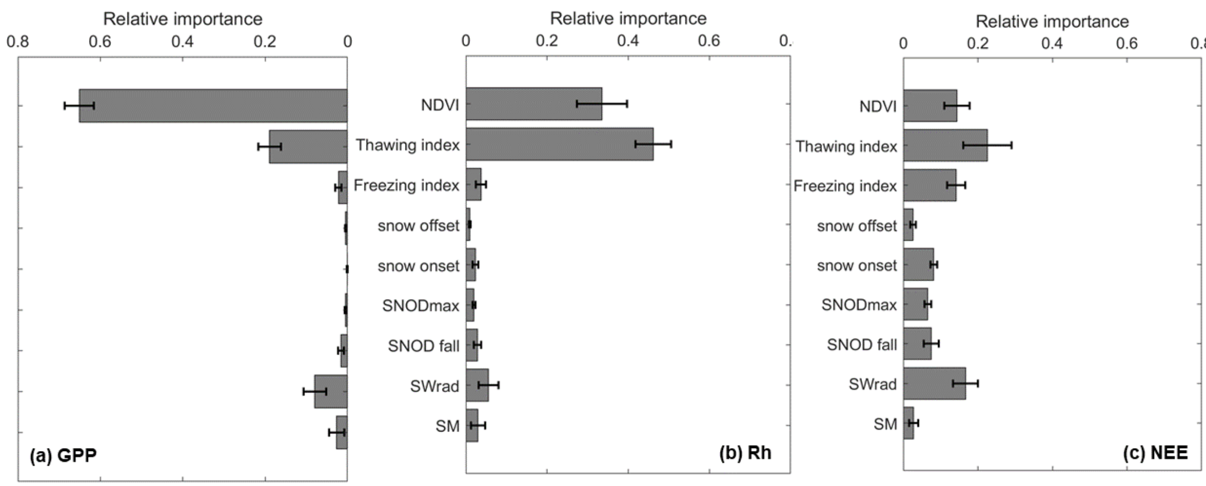

Fig. 9 Mean relative importance values of climate variables in controlling annual carbon fluxes in Alaska (a: GPP; b: Rh; c: NEE). The importance values were averaged for four major vegetation types (Forest, Shrub, Herbaceous, and Wetlands, Fig. 2), and the error bar represents their standard deviation across different vegetation types. The nine variables are: summer (June-August) NDVI, annual thawing and freezing index, snow offset and onset, mean snow depth averaged from January to March (representing annual maximum snow depth, SNODmax), and snow depth averaged during the early snow season (from October to November, SNOD_fall), mean annual downward solar radiation, and rootzone soil moisture during the thaw season. The annual thawing and freezing index are the sum of MODIS LST above 0 °C and below 0 °C throughout the year respectively.

7) Other minor comments: L 204 "soil moisture" is unclear, maybe "liquid water" should be used.

Response:

We now use "liquid water content" instead of "soil moisture".