RC2

I reviewed this manuscript for a previous submission. This remains an extremely impressive and comprehensive model- and observation- based analysis of tundra carbon cycling. The authors go through a fairly exhaustive list of modeling scenarios in a valiant attempt to explain a very limited set of observed growing season and cold season emissions. The results provide a very nice analysis of different model representations of seasonal dco2 timing and magnitude.

We thank the reviewer for their helpful comments and suggestions. Specific responses to each comment follow in red, with proposed edits to the manuscript in blue. Line numbers refer to the original manuscript.

The discussion section hasn't changed much. It could still use more qualitative discussion of results, with more references to the literature (here are several paragraphs with no references) to help explain/support findings.

We have rearranged and expanded the discussion section as noted below and through response to Reviewer 1.

Given the large ensemble of model scenarios, I was hoping to see a more focused discussion of how these difference scenarios (ecosystem parameterization, vegetation distribution, meteorological inputs) affect regional carbon balance, as a way to characterize uncertain and inform future modeling efforts. These scenarios are discussed sporadically throughout, but I think it would help to add separate section to the Discussion summarizing these effects.

We agree that this discussion was lacking in the previous version.

We have added a summary of the scenarios and how they could be used to inform modeling studies to end of discussion in Sect. 3.4.2:

"The large initial range of potential regional net CO_2 flux values we found for the Alaska North Slope indicates a large sensitivity to choices and assumptions made when scaling eddy flux observations from the site- to regional- scale. The most important of these choices are the representation of the upland tundra, particularly for the response of R_{soil} to T_s during the cold season, and the distribution of vegetation types throughout the domain. Future tundra CO_2 modeling efforts should focus on using site-level data that is the most consistent with regional-scale fluxes, rather than incorporating data from all available sites. Consistency and accuracy in classification schemes used in vegetation maps must also be addressed. As we have shown with the atmospheric observations, not all model scenarios have equal likelihood to be true, and the mean of the model ensemble is not necessarily the most likely or most consistent with the atmosphere. Using these atmospheric observations is uncertain, however, due to potential errors in the transport modeling, which are difficult to quantify. Atmospheric modeling of remote areas such as the Alaska North Slope requires further evaluation and improvement. Further, increasing model temporal resolution should be considered as the importance of the zero-curtain and snow cover to the net CO_2 flux of tundra ecosystems is recognized, both of which vary on the order of days and weeks, rather than months."

L363-368: It's not clear why a "PF-Model Derived Soil Temperature" is required to more accurately capture soil freezing processes. Is this process unique to PF affected regions, or are there other factors at play related more generally to soil thermodynamics, hydraulic properties, freeze-thaw dynamics, etc?

The soil temperatures from the Remote Sensing-Permafrost Model (RS-PM) are an Alaska-specific data product developed for permafrost zones to better understand the impact of climate warming on soil carbon loss (Yi et al. (2018, 2019)). RS-PM uses more tailored inputs, derived specifically for Arctic Alaska, to determine soil temperatures than those used by global- and regional-scale reanalysis products such as NARR and ERA5. These input datasets include higher spatial-resolution snow depth and variable soil dielectric constants derived from airborne radar. The configurations and parameterizations in RS-PM were also developed and tested using soil temperature and active layer thickness measurements from the North Slope. Further, RS-PM produces soil temperatures at higher vertical resolution in the near-surface than the reanalysis products, which is important to capture the subsurface heterogeneity in unfrozen soil which may be responsible for continued soil respiration during the zero-curtain throughout the freezing and thawing time periods.

Although we found limited improvement in the TVPRM cold season net CO_2 fluxes compared to the atmospheric observations when we implemented RS-PM soil temperatures, it was important to test this Alaska-specific permafrost soil temperature product. Using soil temperature itself, rather than any specific soil temperature product, seems to be the limiting factor in reproducing the observed cold season net CO_2 fluxes.

We have re-written portions of the text to better reflect the above description of the RS-PM soil temperatures:

in Sect. 2.4: "RS-PM uses tailored input for Alaska permafrost zones, such as downscaled snow depth and aircraft-observed soil dielectric constants and was developed and tested using T_s and active layer thickness measurements from the North Slope. RS-PM also produces T_s at higher vertical resolution in the near-surface than the reanalysis products to capture subsurface heterogeneity in unfrozen soil, which is important to represent the zero-curtain throughout the freezing and thawing periods in Alaska."

in Sect. 3.2: "To test the impact of reanalysis T_s on the early cold season CO_2 fluxes, we implement T_s that are more specifically developed to represent Alaska tundra permafrost soils during freeze-thaw processes than the reanalysis products driving our constrained TPVRM member."

L373-374: Would more SOC, or more labile soil C (e.g., Jeong et al 2018), help to elevate fall soil C emission rates?

Since R_{soil} in TVPRM is derived from the site-level eddy flux measurements, the impact of all forms of soil carbon on the emission rates are implicitly included in the formulation. There is not a way to explicitly add additional SOC or more labile soil C in the current model framework. Should the relationship between soil carbon and emissions change in the future (more carbon available to be respired) in a way not related to T_s, then the parameters calculated would no longer be accurate.

We now refer to this potential scenario in Sect. 4.3, which was added in response to a comment by Reviewer 1:

"TVPRM could be used with projections of meteorology and SIF to calculate the future net CO_2 balance for this region, but we caution against overuse of the model using current parameters, as the flux-driver relationships in the rapidly warming Arctic ecosystems are changing so quickly that we would not assume accuracy into the future."

L449-451: Could you please elaborate on the "expected" response of tundra ecosystems to light and heat/temperature?

The previous wording was unclear.

We have revised this sentence to read as follows:

"The good performance of the TVPRM ensemble against the atmospheric observations during the growing season indicates that the tundra ecosystems of the Alaska North Slope respond to light and heat as quantified by PAR, T_s, and T_a, and that the net CO_2 flux is largely controlled by the simple R_{soil}, $R_{plant,}$ and GPP relationships in the empirical model over this time."

L452-459: It is interesting that coastal ecosystems are more representative of North Slope, due to increased sensitivity to light. Is this a statement of a specific vegetation type, or more general statement that north slope vegetation is more sensitive to light, for example as an adaptation to long dark cold seasons. This discussion really could use some references to the literature to support some of these claims. Also reading ahead to 596-608 suggests that "net flux" could also be affected by respiration due to topography and soil inundation. Could the authors please speculate on the competing roles of vegetation/GPP vs topography/soil water/TER on GS net flux?

We do not say that coastal ecosystems are more representative of the North Slope as a whole, but rather that our analysis suggests that the ecosystem response of the southern North Slope (away from the coast) is consistent with coastal ecosystems (lines 456-457), because vegetation maps with more coastal tundra in the southern North Slope produce more uptake for the same drivers and better match with the atmospheric observations. While the southern North Slope areas are more consistent with coastal tundra, it is possible that these areas are misclassified in either our simplified two-tundra type scheme or in the vegetation maps themselves.

In TVPRM, coastal tundra does take up more CO_2 for a given unit of PAR, which could be evidence for an adaptation to lower light levels. Figure S1 supports this claim, where we show that coastal tundra growing season uptake is very high (panels for IVO, ICS, ICH, ICT) when driven by inland (more southern) tundra site meteorology (T_a, PAR) and SIF. The λ parameter values reported by Luus et al. (2017) also indicate greater uptake at "wetland" sites like Atqasuk and Barrow than at "graminoid tundra" sites like Ivotuk and Imnavait when all driver inputs are constant. Further, Mbufong et al. (2014) found that peak growing season net uptake for constant light is also greater at Barrow than at Ivotuk. However, when considering the ability of coastal tundra to take up CO_2 when moved toward the south, Patankar et al. (2013) saw that tundra plants exposed to additional intense light did not respond with additional uptake.

This section has been modified to read:

"The regional net CO_2 flux is highly sensitive, however, to the distribution of tundra vegetation types (upland v. coastal) throughout the North Slope during the growing season. Coastal tundra takes up more CO_2 for a given unit PAR compared to inland tundra, based on the relationships between observed site-level net CO_2 flux and PAR in this study (TVPRM parameters, Fig. S1), which could be evidence for an adaptation to lower light levels. This difference is consistent with Luus et al. (2017), who calculated greater uptake at "wetland" sites like Atqasuk and Barrow than at "graminoid tundra" sites like Ivotuk and Imnavait when all driver inputs are constant and with Mbufong et al. (2014), who also found that peak growing season net uptake for constant light is greater at Barrow than at Ivotuk. The stronger CO_2 uptake response of coastal tundra to light is important to consider due to the fact that the vegetation distributions assessed here with more coastal tundra to the south (CAVM (Walker et al., 2005), ABoVE LC (Wang et al., 2020)) better agree with the atmospheric observations. When considering the ability of coastal tundra to take up CO_2 when moved toward the south, Patankar et al. (2013) saw that tundra plants exposed to additional intense light did not respond with additional uptake. Therefore, while the ecosystem response of the southern North Slope is more consistent with coastal ecosystems, it seems possible that these areas are misclassified in either our simplified two-tundra type scheme or in the vegetation maps themselves. The large variability in net CO_2 flux calculated by using the different maps supports the importance of accurate ecosystem type locations in upscaling eddy flux measurements and highlights the need for improved vegetation mapping and classification schemes in the Arctic ecology research community."

The section on respiration referred to on lines 473-482 points out the importance of topography and soil inundation as contributing factors to the Rsoil-T_s relationships derived at the individual eddy flux sites. These relationships vary greatly between the eight sites, and we have tested each of them against the atmospheric observations to see which is most consistent with the response of the North Slope. Varying topography and soil inundation throughout the region means that each of the site relationships is likely to be representative of many different locations, but the regional-scale response seems to be most consistent with IVO for inland tundra and CMDL for coastal tundra.

This section has been modified to read:

"The largest differences in the net CO_2 flux between TVPRM ensemble members result from the contrasting site conditions driving the ICS and ICT R_{soil} parameterizations during the cold season. When taken separately by cold season segment, ICS members perform quite well against observations at the NOAA BRW tower for early cold season and ICT members perform well for the late cold season. The contrasting performance between site parameterizations is due to the topographic and hydrologic conditions, which are quite heterogeneous over a short distance and influence the plant communities and carbon storage, at each site. The ecosystems sampled by the ICS tower are seasonally inundated and retain a deep layer of organic soil that can be respired in greater amounts longer into the early cold season, while the well-drained hillslope at ICT does not allow for accumulation of organic matter in the same way (Euskirchen et al., 2017; Larson et al., 2021). While varying topography and soil inundation throughout the North Slope means that each of these site relationships is likely to be representative of many other locations in the region with similar conditions, the early-to-late cold season reduction in CO_2 fluxes at these sites is not consistent with the observed regional atmospheric trend, however, and we remove the members parameterized by them from the ensemble. Individual eddy flux site parameterizations may reproduce regional CO_2 fluxes for a given season, but it is important to consider their response to drivers across multiple seasons when scaling from the site-level to regional domains."

We have also expanded the discussion of competing roles of respiration and GPP on interannual variability in Sect 4.1 in response to this comment and those by Reviewer 1.

The interannual variability discussion now reads as follows:

"The growing season of each year determines the sign of the regional annual net CO_2 flux during our study period, with 2013 and 2015 being strong net sinks and 2014 being the strongest net source. The relative magnitude of each component of the net CO_2 flux during the growing season (i.e., R_{soil}, R_{plant}, GPP) varies from year-to-year (Table S7) and helps explain the interannual variability in the net source or sink status of the North Slope. Growing season 2015 was very warm, dry, and sunny in Alaska and resulted in extreme biomass burning activity outside of the North Slope (Table S1). High regional mean T_a and PAR (Table S8) and low accumulated precipitation (Table S9) in NARR confirm this was the case for North Slope as well, with high T_a and PAR contributing to a very high GPP. The growing season SIF signal from the CSIF product, which determines the seasonal cycle and relative magnitude of photosynthetic activity, is also large in 2015 (Table S8), further enhancing GPP. This year and others with a larger GPP component of NEE correspond to growing seasons with stronger SIF signals, which is an indicator of increased productivity and consistent with previous studies (e.g., Magney et al., 2019; Sun et al., 2017). While fairly high T_a and T_s in 2015 also result in high R_{soil} and R_{plant}, respectively, this elevated respiration is not enough to offset the very high GPP and results in a large net CO_2 sink. In contrast, the summer of 2014 was cool, wet, and cloudy, and the North Slope experienced very low T_a, PAR, and SIF signal, producing very low GPP. Lower-than-normal T_a also results in very low R_{plant}, but as with 2015, this is not enough to offset the extremely low uptake by GPP resulting in a large net CO_2 source for 2014. In 2013, the other growing season with a strong net CO_2 sink, moderately high GPP combines with moderately low R_{plant} and very low R_{soil}. Extremely low T_s causes this very low R_{soil}, which, relative to moderate T_a and PAR, is likely a result of above-average lingering snowpack into May (Table S9). This lingering snowpack is perhaps surprising given that the mean snowpack for the proceeding cold season was not particularly deep. The important impact that snow cover and the timing of snowmelt has on T_s and carbon response in tundra ecosystems has been recently emphasized (e.g., Kim et al., 2021), and is supported by our work which shows that the prevalence of snow in the spring may determine the sign of the regional net CO_2 for an entire year."

The following were added to the Supplement as Tables S7-S9:

Table S7. Alaska North Slope growing season (May–Aug) net CO_2 flux by component for the TVPRM Constrained + ZC and IW scenario for 2012–2017.

Flux Component	2012	2013	2014	2015	2016	2017
R_{soil} [TgC]	18	16	17	18	18	17
R_{plant} [TgC]	33	30	28	33	33	30
GPP [TgC]	69	71	60	77	71	68
NEE [TgC]	-18	-25	-15	-25	-19	-21

Table S8. Alaska North Slope growing season (May-Aug) mean TVPRM drivers used in the TVPRM Constrained + ZC and IW scenario for 2012–2017, where the mean uses model gridboxes where the total ABoVE LC ocean and other land fraction is less than 0.5 (see Fig. S5).

Driver	2012	2013	2014	2015	2016	2017
NARR T_a [°C]	7.4	6.6	6.2	7.5	7.8	6.8
NARR T_{scale}	0.67	0.61	0.58	0.65	0.65	0.58
NARR T_s [°C]	2.6	0.68	1.3	2.4	2.7	1.5
NARR PAR [μmol photon m^{-2} s^{-1}]	484	478	466	495	497	507
CSIF SIF product [mW m^{-2} nm^{-1} sr^{-1}]	0.17	0.18	0.16	0.19	0.18	0.18

Table S9. Alaska North Slope growing season (May-Aug) mean additional select NARR Variables for 2012–2017, where the mean uses model gridboxes where the total ABoVE LC ocean and other land fraction is less than 0.5 (see Fig. S5).

Variable	2012	2013	2014	2015	2016	2017
NARR 3hr accum. precipitation [kg m^{-2}]	0.19	0.21	0.20	0.15	0.16	0.16
NARR soil moisture content [kg m^{-2}]	688	745	755	747	733	734
NARR snow depth [m]	0.046	0.076	0.032	0.030	0.026	0.040
NARR snow cover fraction [0-1]	0.15	0.20	0.16	0.12	0.11	0.17
NARR snow depth [m] during proceeding Sep-Apr	0.42	0.35	0.36	0.38	0.35	0.38
NARR snow cover fraction [0-1] during proceeding Sep-Apr	0.81	0.78	0.79	0.83	0.87	0.78

L460-465: This paragraph basically says that net uptake increases sometimes because of SIF, but we don’t know why. I think more effort is needed to explain why. If its not because of air temperature or PAR, could it be soil temp? soil moisture? longer growing season? Different freeze/thaw dynamics?

We agree that more description was required to explain the net uptake increases.

We have expanded discussion of the variability of drivers leading to interannual variability in net uptake in Sect 4.1 in response to this comment and those by Reviewer 1. The new text of this discussion is copied above.

L493-495: Please elaborate on the processes driving the “physical release of CO2 from soil.” I’m confused what could be the source of carbon if not from microbial activity. Please also comment on the possible role of emissions from permafrost and talik.

CO_2 produced by microbial activity in the soil must be released into the atmosphere before counted as an emissions source. When CO_2 is trapped between frozen/freezing layers or under the snowpack, there will be a disconnect between the microbial production rate of CO_2 and the emission rate of CO_2 into the atmosphere. The addition of the zero-curtain (ZC) emissions accounts for the observed sporadic delayed release of CO_2 produced when T_s was higher.

We have modified this section to read:

“The additional zero-curtain flux represents large-scale emission events not directly timed to microbial activity and root respiration controlled by T_s, but could be related to the delayed physical release of previously produced CO_2 from soil through the snowpack as the soil layers remain unfrozen (Bowling and Massman, 2011).”

L516-528: It’s surprising to see no mention of existing or future satellite datasets, which are getting better at resolving cold season emissions (e.g., Byrne et al., 2022)

Satellite products that rely on reflected sunlight such as XCO_2 from OCO-2 have essentially no coverage on the North Slope from October to March (Byrne et al., 2022). Inversions using only XCO_2 that cover this time period would be influenced by observations from farther south, where CO_2 emissions are more likely to continue into the cold season.

We now mention the limitations of satellite datasets during the cold season in Sect. 4.3.1:

“Satellites that rely on reflected sunlight to detect CO_2 have increasingly been used to constrain CO_2 budgets in the northern latitudes (e.g., Byrne et al., (2022)), but data is very limited in the cold season, especially in far-northern regions like the North Slope.”

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