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Interactive comment on "Detecting the permafrost carbon feedback: Talik formation and increased cold-season respiration as precursors to sink-to-source transitions" *by* Nicholas C. Parazoo et al.

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Reviewer 2

Overall impression

In the current study, Parazoo and colleagues have used the land surface model CLM4.5 to simulate permafrost state and changes from 2010 to 2300 under strong warming following the RCP8.5 scenario. They have investigated how permafrost degradation evolves in space and time, with a special focus on how talik formation affects thaw

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dynamics. Further, the authors have used their model experiment to analyse how future C fluxes in permafrost regions will evolve and when a carbon sink to source transition is likely to occur along different regions of the permafrost domain.

The presented analyses are helpful for increasing our process understanding of how individual factors explain inferred differences in simulated carbon fluxes between cold and warmer permafrost regions. E.g. the authors find that cold permafrost locations become C sources due to altered thaw-season dynamics while transitions of warm permafrost regions are mainly affected by changes in cold season dynamics. Further, the authors discuss how the presented results of this study can help finding an (optimal) design for monitoring the thermal and carbon state and changes in permafrost regions. The paper is well structured and written, and model analyses were performed elaborately. Adding new insights into permafrost degradation and carbon dynamics, this study can be considered of broad interest to the readership of The Cryosphere.

General comments

1) Initial SOC storages The initialized soil C stocks play a key role in affecting simulated future C release and the timing for a sink to source transition. In the study presented, no information is given how these C stocks were initialized for the simulation setting used here (besides referring to two previous CLM4.5 studies). Information should be provided in a sub-section on how SOC stocks were initialized, and on how these stocks compare to observed data (e.g. NCSCD - in terms of total storages and with regard to CLM4.5 inferred high (peaty) SOC storages at northern grid cells). As talik formation down to some meters are analysed in this study, I wonder how deep SOC is initialized in the soil column? Can e.g. soil thaw deeper than 3 meters further increase the pool of thawed carbon available for decomposition? A further key factor not discussed in the manuscript concerns assumptions about SOM lability made in the model. As especially uncertainty in slowly decomposing SOM is very high, I wonder how different settings of a humus timescale parameter (or different partitioning between labile and less labile pools) would affect inferred sink to source transition times? If feasible, this

would be worth exploring by an extra sensitivity run, or at least by discussing qualitatively the impact of uncertainty in assumed SOM decomposition timescales on the findings discussed here.

Response:

We thank the reviewer for the recommendation to include the very important discussion of soil C stocks and decomposition controls in CLM. Deep soil decomposition experiments in CLM have been run in previous studies by the co-authors, to decouple changing dynamics of surface soils from deep soils, to determine the potential contribution from permafrost layers, and to calibrate initial soil C stocks against observations.

We have elaborated on these details in the methods (L139) as follows:

"CLM is spunup to C equilibrium for the year 1850 by repeatedly cycling through 20 years of pre-industrial climate forcing with CO2 and N-deposition set at 1850 levels. C initialization is achieved via slow mixing by cryoturbation between the seasonally thawed active layers and deeper permafrost layers (Koven et al., 2009). Including vertically resolved processes leads to a sign change in the projected high-latitude C response to warming, from net C gains driven by increased vegetation productivity to net C losses from enhanced SOM decomposition (Koven et al., 2011). The soil grid includes 30 vertical levels that has a high-resolution exponential grid in the interval 0–0.5 m and fixed 20-cm layer thickness in the range of 0.5–3.5 m to maintain resolution through the base of the active layer and upper permafrost, and reverts to exponentially increasing layer thickness in the range 3.5–45 m to allow for large thermal inertia at depth. Soil C turnover in CLM4.5 is based on a vertical discretization of first-order multipool SOM dynamics (Koven et al., 2013; Oleson et al., 2013) where decomposition rates as a function of soil depth are controlled by a parameter Z_τ (Koven et al., 2015; Lawrence et al., 2015). This depth control of decomposition represents the net impacts of unresolved depth dependent processes. In this study, we utilize Z_τ=10 m, which yields a weak additional depth dependence of decomposition beyond the environmental controls and, as discussed and evaluated relative to Z_T=1m and Z_T=0.5m in Koven et al (2015), results in CLM permafrost-domain soil C stocks that are in closest agreement (1582 Pg for Z_T=0.5 m, 1331 Pg for Z_T=1m, and 1032 Pg for Z_T=10m) with observed estimates (1060 Pg C to 3 m depth; Hugelius et al 2013). This reduction in initial C is due to higher decomposition rates at depth during the model initialization period. There is no C below 3.5 m, so additional thaw below 3 meters has a small impact on the C cycle. We note that the relationship applied in CLM4.5, which implies multiplicative impacts of limitations to decomposition, is commonly applied in land biogeochemical models, but is quite uncertain."

We also discuss implications of 3.5 m C limit in discussion (Line 626):

"Our estimate of C emissions following talik onset (~20 Pg C) is low compared to the cumulative emissions from all long term C source transitions (120 Pg C), but likely strongly underestimated. Soil C is not permitted below 3.5 m in CLM4.5, or in most analogous models, such that potential decomposition of the ~350 Pg soil organic C in deep permafrost (> 3 m) is not accounted for (Hugelius et al., 2014; Jackson et al., 2017). This is significant for our simulations, which show frequent talik formation and accelerating thaw volumes below 3 m (e.g., Fig. 3). We therefore caution the reader in the interpretation of the timing and magnitude of permafrost C emissions following talik onset in our simulations, which represent a lower bound of potential emissions based on the current formulation of CLM4.5."

Reviewer:

Talik formation

The study focuses on talik formation as a key process which leads to abrupt permafrost degradation. The discussion (and the model simulation) is done for non-lake environments. Talik formation through thermokarst lake initialisation is not considered and mentioned. Yet this process is known to lead to rapid thaw through pronounced sub-lake talik formation, which can strongly affect carbon release from thawed sub-lake sediments. Although it is questionable to which extent future Arctic landscapes will be affected by thermokarst formation, this process should be discussed in the context of future permafrost degradation and permafrost carbon release.

Response:

We agree that thermokarst is an important process which is not considered in our simulations. We added the following discussion of thermokarst effects to the intro (Line 87)

“More abrupt processes such as thermokarst lake initialization can also lead to rapid thaw through pronounced sub-lake talik formation (Jorgenson and Osterkamp, 2005). These processes can initiate formation of a talik zone (perennially thawed sub-surface soils) during active layer adjustment to new thermal regimes (Jorgenson et al., 2010) in lake and non-lake environments.”

And methods (Line 135)

“More abrupt thaw processes affecting permafrost C dynamics and talik formation such as the effect of thermokarst or other thaw related landscape dynamics changes in wetland or lake distribution are not accounted for (see Riley et al (2011) for more discussion).”

and discussion (Line 590):

“Other factors that are necessary for more accurate simulation of soil hydrology and carbon cycling but not considered in CLM4.5 and analogous models include: enhanced spatial resolution in complex topography and in discontinuous permafrost, sophisticated vegetation community definitions including trait based representation, shifts in vegetation community, lateral flow representation, thermokarst activity and other thaw-related changes to the ground surface, surface slope and aspect, soil heterogeneity, and potentially several other factors (see Jorgenson and Osterkamp (2005) for discussion of some of the many complexities to be considered).”

Reviewer:

Vegetation distribution: As discussed extensively in the presented paper, the Arctic land carbon balance is determined by changes in the net flux of vegetation carbon uptake and respiration losses. To what extent is CLM4.5 able capturing high latitude vegetation distribution/patterns? Some short discussion on simulated high latitude vegetation in CLM4.5 would be interesting to include.

Response:

The use of static vegetation distributions and simple vegetation community definitions is a major source of uncertainty in CLM4.5. We have acknowledged this model weakness in the response above.

Reviewer:

Cumulated C fluxes: I guess you want to discuss C source numbers as PgC per year? (L387). Please specify in the text and in Fig.7B y-axis label. How does the cumulative C source from 2010- 2300 of 11.6 PgC relate to shown C release rates in Fig. 7B? If I interpret numbers shown correctly, these suggest much larger cumulative release. Given published work on total C release from future permafrost degradation under RCP8.5 in other studies (suggesting much larger release), this number (total C release) should be discussed in the context of existing estimates.

Response:

We thank the reviewer for correctly pointing out our y-axis error and suggesting to compare our cumulative releases to existing estimates. We corrected the y-axis error by moving the C source numbers from Fig. 7B to Fig. 8 for more in depth analysis (Figures 7 and 8 attached). Our cumulated emission is 120 Pg C which is more in line with existing estimates. We summarize in the discussion as follows (Line 596):

"Our simulations show increasing C emissions over time across the talik region (Fig. 1B), as cumulative NBP becomes increasingly negative (NBP < 0 equals a net C source), reaching a net source of 140 Pg C by 2300 (Fig. 8, crosses), consistent with previous estimates of net C balance across the larger pan-Arctic region from CLM4.5 (∼160 Pg C, Koven et al., 2015; Lawrence et al., 2015). Ecosystems which transition from net C sinks to net C sources represent less than half the total talik area (6.8 of 14.5 Million km2, Fig. 7A), but account for most (∼85%) of the cumulative emissions, reaching 10 Pg C in 2100, 70 Pg C in 2200, and 120 Pg C by 2300 (Fig. 8, solid black). Removing the effect of vegetation C gain (∼20 Pg C in 2100 and 40 Pg C in 2200 and 2300 according Koven et al., 2015), we estimate a cumulative permafrost emission for C source transition regions of 30 Pg C in 2100, 110 Pg C in 2200, and 160 Pg C in 2300. These numbers are on the low end but consistent with estimates of permafrost C emissions summarized by Schuur et al. (2015), which range from 37-174 Pg C by 2100 and 100-400 Pg C by 2300."

Reviewer:

Specific comments

Results presented in this study are inferred for the RCP8.5 scenario. This should be made more clear in the text (when discussing future evolution of permafrost and carbon fluxes), and in some of the figure legends.

Response:

We have added RCP8.5 and ECP8.5 information throughout the text:

L263 Section 3.1:

"Our simulations show widespread talik formation throughout Siberia and northern North America over the period 2010-2300 (Fig. 1B), impacting ∼14.5 million km2 of land in NHLs (55°-80°N) assuming a freeze/thaw threshold of -0.5°C and RCP8.5 and ECP8.5 warming scenarios."

L432 Section 3.3:

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“The cumulative pan-Arctic C source increases slowly over the 21st century, reaching 10 Pg C by 2100 with RCP8.5 warming, then increases more rapidly to 70 Pg C by 2200 and 120 Pg by 2300 with sustained ECP8.5 warming (Fig. 8, solid black).”

We also included information in the first talik figure (Fig. 1, attached) and carbon figure (Fig. 7):

“These results assume a Representative Pathway 8.5 warming scenario through 2100 and an Extended Concentration Pathway 8.5 through 2300.”

Reviewer:

Please check for consistent/correct use of NBP sink/source definition (e.g. L410) Fig.8: Did you intend to put the dashed horizontal NBP threshold line at -25 gCm-2yr-1 - in accordance with your definition?

Response:

The definition of NBP has been corrected in the text and in the figures.

Reviewer:

I wonder whether a discussion of a bi-modal distribution (Fig. 7D) seems more likely than a tri-modal distribution.

Response:

We thank the reviewer for this suggestion and understand the motivation, since 2 clearly defined peaks exist on either side of the talik onset lag = 0 line. However, we argue that a tri-modal distribution is appropriate here since each peak falls into a distinct category associated with a unique process: High SOM (left peak), High Fires (right peak), and low SOM and low fires (middle peak). We have added the following discussion on L507 to justify the trimodal distribution:

“The decadal time lag between talik onset and C source transition is more normally distributed in the remaining region, represented by the residual grey bars visible in Fig. 7D, which occurs predominantly in cold northern permafrost in northwest Siberia where low SOM (< 100 Kg m-2) and fire emission (< 25 g C m-2 yr-1) prevail. This region has a mean lag of 1 decade from talik onset to C source, with high standard deviation of lags ($\pm$ 8 decades) reflecting a skewed distribution of GPP; low productivity in cold permafrost (GPP = 385 g C m-2 yr-1) increases the likelihood that soil thaw will lead to C source transition prior to talik onset, and high productivity in warm permafrost GPP = 1111 g C m-2 yr-1) increasing the likelihood of a transition after talik onset. Cumulative C emissions from this region are on the low end (27 Pg C by 2300; Fig. 8, blue) due to low soil C (SOM = 59 kg C m-2). "

Reviewer:

Maybe a shifting of some figures (e.g. Fig 10., Fig.11) to an appendix section would be good?

Response:

Based on comments from both reviewers that Figures 10 and 11 do not add much to the paper, they have been removed, and replaced with more details describing the results of these figures

Reviewer:

L338/339 you mean positive trends?

Response:

Yes, this has been corrected

Reviewer:

L 365 and following Given the small (statistically insignificant?) trend at Drughina, probably discussing "unchanged" conditions (instead of discussing a "change in sign") is more appropriate.

Response:

Thanks for the excellent suggestions. We have modified the text as follows (L410):

“Thaw projections in northern Siberia indicate an unchanged trend and continued stability of permafrost through the early 22st century, followed by a shift to accelerated soil thaw in the early 2120, marked by onset of deep soil thaw late in the cold season.”

Reviewer:

L 362 and following Please check colour specifications (in my printed version lines are yellow instead of orange, “blue” and “cyan” are used to refer to the same line, ...)

Response:

Color specifications have been corrected.

Reviewer:

L494 define “NF” - or better avoid abbreviation

Response:

NF has been expanded to non-frozen

Reviewer:

Fig.12 legend how were error bars inferred / what do they describe? Spelling

Response:

We have added a statement about error bars in figure 12 (now figure 11), which represent the multi-decadal standard deviation of seasonal and C source transition time series from 2040 – 2270.

“Time series of ecosystem C fluxes showing seasonal and decadal patterns during C source transition. This present mean and standard deviations over the period 2040-2270 for (A-B) Gross Primary Production (GPP),”

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Reviewer:

L29 IS -> is

Response:

Corrected, thank you

Reviewer:

L458 form -> from

Response:

This paragraph has been removed

Reviewer:

L470 = -> -

Response:

Corrected, thank you

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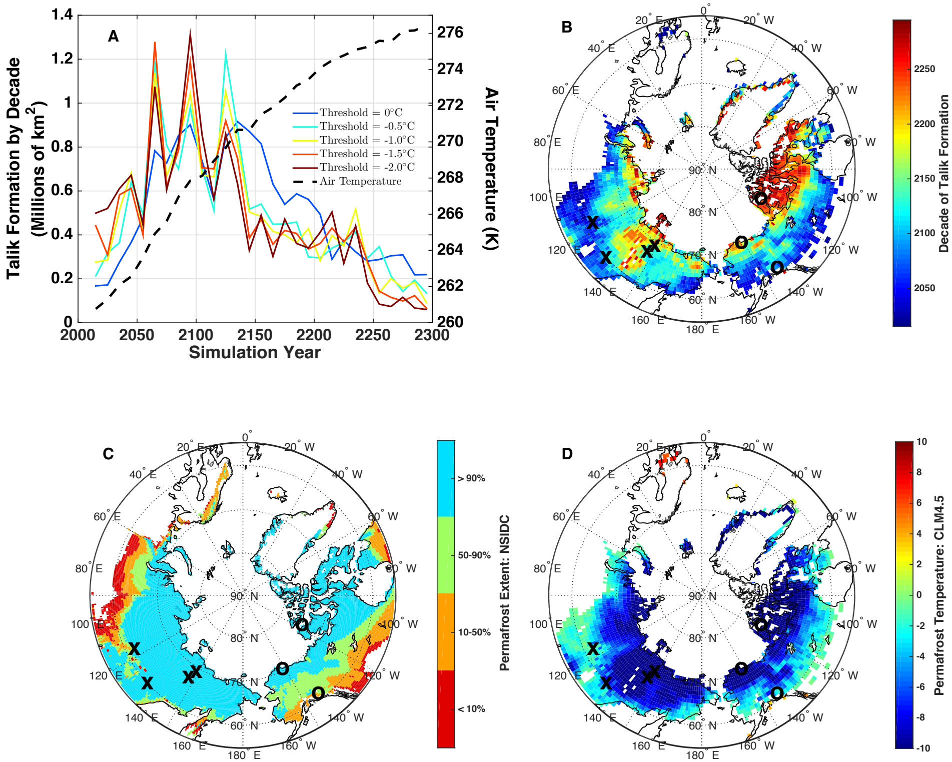

Fig. 1. Figure 1. Decade of projected talik formation and correlation to initial state of simulated permafrost temperature and observed permafrost extent. (A) Time series and (B) map of the simulated decade o

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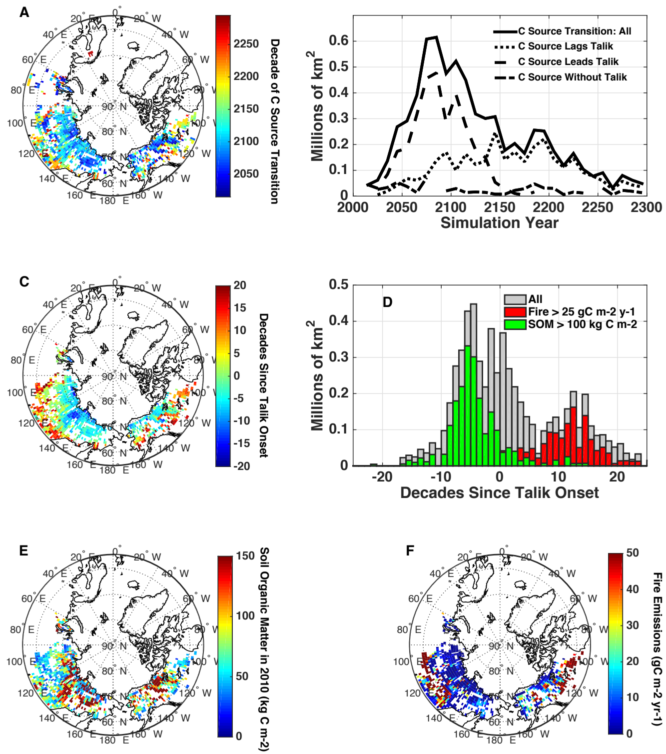

Fig. 2. Figure 7. Projected decade when permafrost regions shift to long-term C sources over the period 2010-2300, and relation to talik onset, soil C, and fire emissions. (A) Map of the decade of transition

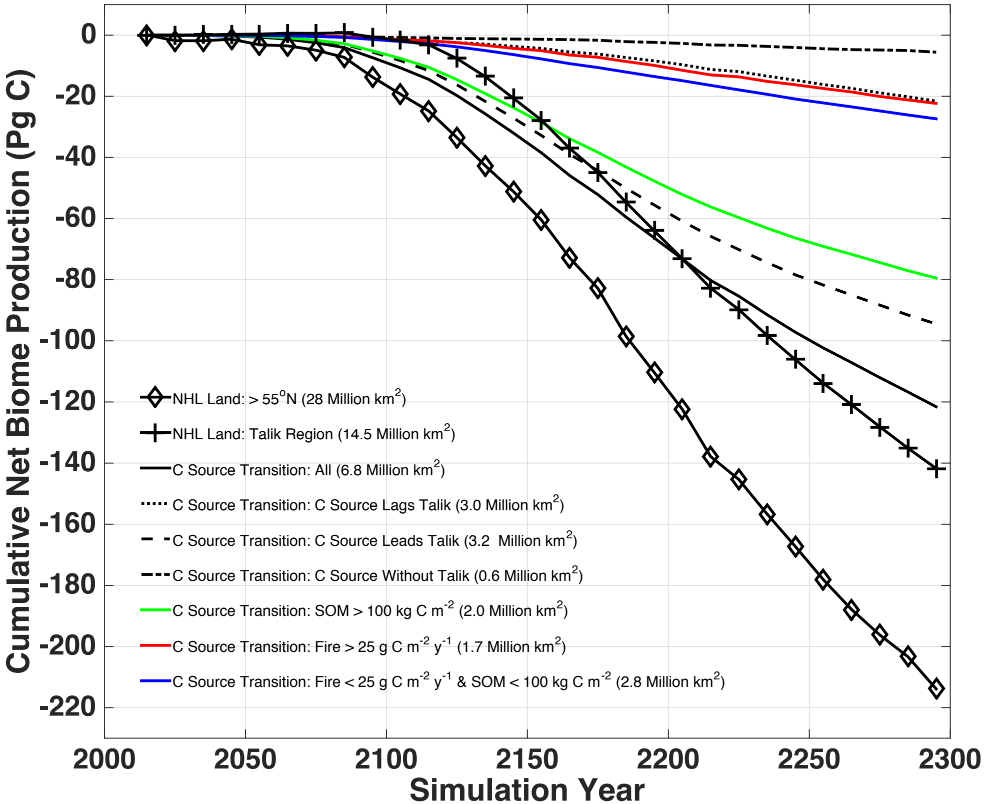

Fig. 3. Figure 8. Cumulative net biome production (NBP) over northern high latitude (NHL) regions (> 55°N) from 2010 to 2300. NBP < 0 represents a net C source. NHL regions are divided into the following cate