Reviewer comments

Author response, ***Changes made in manuscript***

Anonymous Referee #2

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Comments on "Variability of the surface energy balance in permafrost underlain boreal forest" submitted by Simone Maria Stuenzi et al. to Biogeosciences

In this manuscript, the authors developed a biophysical atmosphere-land interaction model (CryoGrid) and examined its performance by comparing with observations at a mixed forest in East Siberia. By coupling with a multi-layer canopy scheme (CLM-ml v0), they accounted for the effects of vegetation canopy on surface processes. They conducted a series of simulations with different land covers (forest and grassland) and different leaf area index or canopy density. They found that coverage with high leaf area index affects surface energy budget, such as solar radiation transfer and insulation, and that it could play important roles in snow and permafrost dynamics such as active layer thickness. I agree that terrestrial ecosystems in northern high latitude is remarkable in terms of climate change, especially permafrost thawing that is thought as one of the tipping elements of the Earth system. Then, developing advanced models simulating boreal ecosystem processes is highly important.

We thank the reviewer for the positive perspective on the general topic of our study. We absolutely share the opinion that it is extremely relevant to study boreal forest and permafrost interactions under amplified climate change. Further, we gratefully acknowledge all critical comments, which help us to improve our manuscript. We have thoroughly gone through all comments and suggestions made by the reviewer. Please note that any changes and additions we propose for the revised manuscript are highlighted in ***bold****.*

Nevertheless, I could not find out what is the original contribution of this study. For example, the model developed in this study seems similar to previous models such as CLM, ORHIDEE, LPJ etc. These previous models have already implemented leaf phenology and dynamic vegetation; at least some versions include permafrost dynamics.

We thank the reviewer for this critical remark on our manuscript and take this as an opportunity to clarify the scientific questions that we aim to answer with the performed modelling exercise. We appreciate your concern that previous models have already implemented leaf phenology or dynamic vegetation and would like to elaborate on this accordingly. The mentioned models such as Orchidee-Can (Chen et al. 2016), Lund-Potsdam-Jena (LPJ DGVM) (Beer et al. 2007), CLM (Levis et al., 2004) or NEST (Zhang et al. 2003) and SiBCliM (Tchebakova et al. 2009) are discussed in the Introduction section on page 2 starting on line 22. Certainly, these models include some sort of dynamic or static vegetation parameterization, leaf phenology and some models also permafrost dynamics. The focus thereof lies on the forest establishment and mortality (Sato et al. 2016), unfrozen vs. frozen ground and fire disturbances (Zhang et al. 2011) or the evolution of the vegetation *carbon density under diverse warming scenarios (Beer et al. 2007). The multilayer canopy module presented here has been developed for a future integration in the CLM scheme, but has not been used in permafrost underlain boreal forests. Further, the presented model is an advancement, as it is specifically developed to study heat transfer processes with both, high-resolution permafrost ground and a high-resolution vegetation canopy. This allows us to quantify the interactions between detailed canopy structures and permafrost. To amplify the importance and uniqueness of our study we propose to add the following section to the introduction (p.2, l. 31):*

"While all of these studies have significantly improved our understanding of essential mechanisms in boreal permafrost ecosystems, it is important to further understand how a forest canopy affects the thermal state and the snow regime of the ground, especially amid ongoing shifts in forest composition (Loranty et al., 2018). The existing model set-ups are often static or not able to capture important processes such as the vertical canopy structure or the leaf physiological properties, which determine the energy transfer between the top of the canopy atmosphere and the ground. These general canopy models focus on reproducing the forest properties, but they have not been evaluated much for permafrost settings and with respect to the impact of forest on permafrost. To our knowledge, so far, none of the existing models is able to capture the important processes of the vertical canopy structure in combination with a physically-based, highly advanced permafrost model. The novel model introduces a robust radiative transfer scheme through the canopy for a detailed analysis of the vegetation's impact on the hydro-thermal regime of the permafrost ground below. This allows us to quantify the surface energy balance dynamics below a complex forest canopy and its direct impact on the hydro-thermal regime of the permafrost ground below."

Further, we have made the conclusions and this study's original contribution clearer by adding the following key points (p.23, l.1):

"This study presents a specific application of a coupled multilayer forest-permafrost model to investigate the energy transfer and surface energy balance in permafrost underlain boreal forest of Eastern Siberia. The comparison of measured and modeled GST at a mixed forest and a grassland site, the comparison of the modeled and measured radiation fluxes at the grassland site, as well as the comparison of modeled and measured radiation fluxes at an external study site, justify the use of the physically-based modeling approach to investigate the thermal regime and surface energy balance in this complex ecosystem. Based on this modeling exercise and field measurements, we investigate the thermal conditions of two landscape entities as they typically occur in the boreal zone. In regard to the forests insulation effect on permafrost and ongoing land cover transition this study delivers important insights into the range of spatial differences and possible temporal changes that can be expected following landscape changes such as deforestation through fires, anthropogenic influences and afforestation in currently unforested grasslands or densification of forested areas. The detailed vegetation model successfully calculates the canopy radiation and water budgets, leaf fluxes, as well as canopy

turbulence and aerodynamic conductance. These canopy fluxes alter the below-canopy surface energy balance, the ground thermal conditions and the snow cover dynamics. We find a strong dampening effect of 19°C on the annual ground surface temperature amplitude of the permafrost.”

Another concern on this study is that the authors used a very limited amount of observations. Especially, they validated the model performance to capture temporal variability only for surface temperature. Because many flux measurement sites are operating and providing a variety of observational data, I highly recommend validating the model by using a larger number of biophysical variables including energy and water fluxes.

We appreciate the suggestion on using a larger number of biophysical variables including energy and water fluxes. In accordance with the comments of reviewer 1, we agree that our study requires a more extensive validation based on surface energy balance measurements. Thus, we extended the model validation to an additional site for which extensive surface energy balance measurements are available in order to demonstrate the capabilities of our model. Not many such flux measurement sites are available in Eastern Siberia, to our knowledge; no such site exists around our study side (Nyurba/Vilnuy area). We suggest using existing and available data from the rather near, well-documented and well-studied research site Spasskaya-Pad at 62°14’N, 129°37’E. We have been provided meteorological and radiation data from beneath and above the larch-dominated forest canopy for 2018 through the Arctic Data Archive system (ADS). This data is used for additional model validation. To justify our model we suggest adding this additional validation site to the appendix of our manuscript.

As described in our answer to reviewer 1 we have set-up and ran a 5-year simulation for this site, using ERA-interim forcing data for the coordinate above and a summer LAI of 3.66 m^2m^{-2} (following the measurement-based LAI in Ohta et al. 2001) and a tree height of 18 m. Since the study site is larch-dominated we have now implemented a simple leaf-off parameterisation which is used here. This results in a winter LAI of 1.66 m^2m^{-2} (again based on Ohta et al. 2001) and a leaf-off period from 10. October - 10. April.

Preliminary analyses of simulation results show a good fit with the modeled surface energy balance. The following preliminary paragraph is added to the Appendix, in a novel section “External validation site "Spasskaya Pad"”: ***“For further validation of the model performance we use existing and available data from the rather near, well-documented and well-studied research site Spasskaya-Pad at 62°14’N, 129°37’E. Through the Arctic Data Archive system (ADS) we have been provided meteorological and radiation data from beneath and above the larch-dominated forest canopy for 2018. Therefore, we have set-up and ran a 5-year simulation for this study site, using ERA-interim forcing data for the coordinate above and a summer LAI of 3.66 m^2m^{-2} (following the measurement-based LAI in Ohta et al. 2001) and a tree height of 18 m. Since the study site is larch-dominated we have now implemented a simple leaf-off parameterisation which is used here. This module allows for a leaf-off period from fall to spring. This results in a winter LAI of 1.66 m^2m^{-2} (again based on Ohta et al. 2001) and a leaf-off period from 10. October - 10. April. Preliminary analyses of simulation results show a good***

fit with the modeled surface energy balance and justify the use of the model in the current version.”

Also, I have a concern about the overly simplified simulation conditions, such as the lack of seasonal change in leaf area index in forest. Though in situ data were not available, at present, we can obtain time-series of leaf area index from satellite remote sensing as a good proxy.

We thank the reviewer for this critical remark concerning the canopy phenology. As discussed in the “Applicability and model limitations” section (p.21, l.14), the development and implementation of a phenology module was considered to be out of scope for this study, mainly because of the little deciduous taxa (only 7%) at the chosen study site. As explained in our response to the previous comment, ***a phenology module allowing for a leaf-off period from fall to spring has now been implemented for the newly included study site at the Spasskaya Pad research station.*** *Here, deciduous larch is dominant and a phenology module is therefore highly important.*

Based on the inadequacy of scientific insights and model simulations, I cannot recommend this manuscript to accept for publication in the present form. The manuscript is too descriptive and needs more model validation with observations. Also, the authors need to devise model simulations to make insightful discussions.

We thank the reviewer for her/his opinion on our submitted manuscript and would like to summarize the substantial changes and adaptations described in detail above and in the responses to Reviewer 1. The main changes we propose to improve our manuscript are:

- Adding a further validation site (Spasskaya Pad) with an extensive record of energy flux measurements which is, to our knowledge, a unique data record for a forested study site in Eastern Siberia. Due to a higher component of deciduous taxa, we have implemented a canopy phenology module to simulate the specific traits of deciduous taxa. With this additional validation site we justify the use of our current model set-up.
- We would also like to point out changes in the introduction and conclusion sections (see above) which now clarify the novelty of our modeling exercise and the importance of the found and described insights in severely understudied high-latitude, permafrost-underlain boreal forest areas.

Minor points
Page 3 Section 2.1: Can you give information on vegetation conditions, such as leaf area index and tree density?

Following our response to reviewer 1, we recognize that the information given on LAI estimation on p.10, l.26 is insufficient, therefore we have modified the paragraph to the following, more detailed description: ***“LAI can be estimated from satellite data, calculated from below-canopy light measurements or by harvesting leaves and relating their mass to the the canopy diameter. Ohta et al. (2001) have described the monitored deciduous-needleleaf forest***

site at Spasskaya Pad research station, which has comparable climate conditions but is larch-dominated. The value of the tree plant area index (PAI), obtained from fish-eye imagery and confirmed by litter fall observations, varied between 3.71 m^2m^{-2} in the foliated season and 1.71 m^2m^{-2} in the leafless season. This value does not include the ground vegetation cover. Further, Chen et al. (2005) compared ground-based LAI measurements to MODIS values at an evergreen-dominated study area (57.3° N, 91.6° E) south-west of the region discussed here, around the city of Krasnoyarsk. The mixed forest consists of spruce, fir, pine and some occasional hardwood species (birch and aspen). They find LAI values between 2 m^2m^{-2} and 7 m^2m^{-2}. To assess the LAI we use data from literature **and the experience from the repeated fieldwork at the described site*****. Following Kobayashi et al. (2010) who conducted an extensive study using satellite data, the average LAI for our forest type is set to 4 m^2m^{-2} and stem area index (SAI) is set to 0.05 m^2m^{-2}, resulting in a plant area index (PAI)of 4.05 m^2m^{-2} and 9 vegetation layers for model simulations."***

To further answer this question, leaf area index has not been measured explicitly, but is described in the study by Kobayashi et al. (2010) and can also be estimated from satellite imagery such as the Copernicus LAI 300m Version 1 product (available through https://land.copernicus.vgt.vito.be/PDF/portal/Application.html#Home). Accordingly, LAI at our study site is between 3 and 4 m^2m^{-2}. Tree density could be estimated from the vegetation survey mentioned on page 5, line 20.

Page 7 Line 3: I am not sure how within-canopy wind profile was parameterized and simulated by the multi-layer canopy model. Can you explain briefly, because this is an important feature of multi-layer canopy models?

This is not discussed in particular here, but described in detail in Bonan et al. 2018. We add this information to our manuscript (p.6, l.21): ***"The within-canopy wind profile is calculated using above- and within-canopy coupling with a roughness sublayer (RSL) parameterization (see Bonan et al. 2018 for further detail)."***

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