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Geoscientific Model Development Discussions
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Interactive comment on "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools" *by* Ignacio Hermoso de Mendoza et al.

Kerkweg

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Received and published: 13 December 2018

Dear authors,

in my role as Executive editor of GMD, I would like to bring to your attention our Editorial version 1.1:

http://www.geosci-model-dev.net/8/3487/2015/gmd-8-3487-2015.html

This highlights some requirements of papers published in GMD, which is also available on the GMD website in the 'Manuscript Types' section:

http://www.geoscientific-model-development.net/submission/manuscript_types.html

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Discussion paper

In particular, please note that for your paper, the following requirements have not been met in the Discussions paper:

- "The main paper must give the model name and version number (or other unique identifier) in the title."
- “If the model development relates to a single model then the model name and the version number must be included in the title of the paper. If the main intention of an article is to make a general (i.e. model independent) statement about the usefulness of a new development, but the usefulness is shown with the help of one specific model, the model name and version number must be stated in the title. The title could have a form such as, “Title outlining amazing generic advance: a case study with Model XXX (version Y)”.”

Therefore please add a reference to CLM 4.5 in the title of your article in your revised submission to GMD. E.g., "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools: a case study with CLM 4.5"

Yours,

Astrid Kerkweg

Interactive comment on Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-233, 2018.

Geosci. Model Dev. Discuss.,
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Geoscientific Model Development Discussions
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Interactive comment on "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools" *by* Ignacio Hermoso de Mendoza et al.

Anonymous Referee #1

Received and published: 8 January 2019

This paper addresses a very interesting topic. The land surface components of Earth System Models usually make two fundamental simplifications in the model used for computing subsurface temperatures: 1) the geothermal heat flow is not taken into account, 2) the models have an insufficient depth extent to compute the effects of typical climatic thermal perturbations in the subsurface, without being affected by the lower thermal boundary condition. The effects, of both simplifying assumptions are addressed in this paper, focusing specifically on permafrost evolution and the storage/release of carbon in vegetation and soil. The subject of the paper is not new, as the authors acknowledge on page 2, but the effects have thus far hardly been quantified. However, the authors have not provided a full description of their permafrost/thermal

Printer-friendly version

Discussion paper

model. Are phase transitions incorporated? Do they couple active layer thickness changes to the hydrology model? What is their definition of permafrost in terms of ice-water content? How are the blanketing and buffering effects of snow on the surface incorporated? Many such descriptions are missing. In addition, the authors assume a constant regolith thickness of a few meters, without porosity-depth changes, and a granitic bedrock to occur worldwide. Also, they assume a spatially constant geothermal heat flow. Both assumptions are very crude approximation of reality, which will severely affect their modelling results. Information on the global variation in subsurface composition and geothermal heat flow is available in literature and databases.

Please find more comments in the supplement

Please also note the supplement to this comment:
https://www.geosci-model-dev-discuss.net/gmd-2018-233/gmd-2018-233-RC1-supplement.pdf

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Interactive comment on Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-233, 2018.

Does the paper address relevant scientific modelling questions within the scope of GMD? Yes

Does the paper present a model, advances in modelling science, or a modelling protocol that is suitable for addressing relevant scientific questions within the scope of EGU? Yes

Does the paper present novel concepts, ideas, tools, or data? Partly

Does the paper represent a sufficiently substantial advance in modelling science? Partly

Are the methods and assumptions valid and clearly outlined? Partly

Are the results sufficient to support the interpretations and conclusions? Partly

Is the description sufficiently complete and precise to allow their reproduction by fellow scientists (traceability of results)? In the case of model description papers, it should in theory be possible for an independent scientist to construct a model that, while not necessarily numerically identical, will produce scientifically equivalent results. Model development papers should be similarly reproducible. For MIP and benchmarking papers, it should be possible for the protocol to be precisely reproduced for an independent model. Descriptions of numerical advances should be precisely reproducible. No

Do the authors give proper credit to related work and clearly indicate their own new/original contribution? Yes

Does the title clearly reflect the contents of the paper? The model name and number should be included in papers that deal with only one model. No, see my suggestion

Does the abstract provide a concise and complete summary? Yes

Is the overall presentation well-structured and clear? Yes

Is the language fluent and precise? Yes

Are mathematical formulae, symbols, abbreviations, and units correctly defined and used? Yes

Should any parts of the paper (text, formulae, figures, tables) be clarified, reduced, combined, or eliminated? Yes

Are the number and quality of references appropriate? Yes

Is the amount and quality of supplementary material appropriate? For model description papers, authors are strongly encouraged to submit supplementary material containing the model code and a user manual. For development, technical, and benchmarking papers, the submission of code to perform calculations described in the text is strongly encouraged. NA general comments:

This paper addresses a very interesting topic. The land surface components of Earth System Models usually make two fundamental simplifications in the model used for computing subsurface temperatures: 1) the geothermal heat flow is not taken into account, 2) the models have an insufficient depth extent to compute the effects of typical climatic thermal perturbations in the subsurface, without being affected by the lower thermal boundary condition. The effects, of both simplifying assumptions are addressed in this paper, focusing specifically on permafrost evolution and the storage/release of carbon in vegetation and soil. The subject of the paper is not new, as the authors acknowledge on page 2, but the effects have thus far hardly been quantified.

However, the authors have not provided a full description of their permafrost/thermal model. Are phase transitions incorporated? Do they couple active layer thickness changes to the hydrology model? What is their definition of permafrost in terms of ice-water content? How are the blanketing and buffering effects of snow on the surface incorporated? Many such descriptions are missing.

In addition, the authors assume a constant regolith thickness of a few meters, without porosity-depth changes, and a granitic bedrock to occur worldwide. Also, they assume a spatially constant geothermal heat flow. Both assumptions are very crude approximation of reality, which will severely affect their modelling results. Information on the global variation in subsurface composition and geothermal heat flow is available in literature and databases. See Kitover et al. (2014, 2015) for inspiration.

I am not familiar with modeling carbon content changes. Thus I have little comments on those sections.

specific comments:

Title: change to a title better reflecting the contents of the manuscript

e.g.: Effects of geothermal heat flow and assumed model thickness on permafrost distribution and carbon pool changes

page 2:

using the word “reflect” for the thermal effect of a too shallow lower boundary condition can only apply to the effects of climate warming. However, models are also used to study implications of climatic cooling (in the past).

l. 22: 20 C/km is a bit low for a general, global geothermal gradient. 30 C/km is more in line with observations

page 4:

l.8: mention that the two parallel planes are the upper and lower surface

l. 16: assuming a constant diffusivity implies that you assume no porosity change with depth (which is unrealistic for the modeled depth interval), and that no phase change occurs (no melting or freezing). Both assumptions are crude simplifications.

page 7:

l. 4: yes, but porosity decreases exponentially with depth. Thus the thermal diffusivity should change with depth, and is not a constant as you assume.

l. 5: this is a crude assumption. Also composition in the upper 41 meters changes with depth, due to porosity change

l. 7: the assumption that all bedrock (below 41 meters) consists of granite is not realistic

l. 13: mention that you later on will modify the model by incorporating a geothermal heat flow at the base of the model

page 9:

l. 2: you should look better. Such database do exist. For inspiration, check the papers by Kitover et al. (2014, 2015).

l. 6: what is the ice/water content for your permafrost definition? Please note that some authors have advocated a thermal definition of permafrost (like your definition of active layer thickness), since some permafrost in fact lacks ice. Also, please not that some permafrost contains more ice than just the normal porosity (i.e. in the forms of cracks and lenses)

page 29:

l. 35: no, permafrost will also melt from below. The phase transition will affect heat balance and thermal properties of the frozen/unfrozen bedrock. But, the ice-content in bedrock pores and fractures will be low.

page 30:

l. 1-2: yes, but increasing the cell size will reduce the resolution of tracing the lower boundary of the permafrost

<u>technical corrections:</u>

page 1:

l.9.: "… under forcings of two…."

l.13.: use "20 mW/m2" instead of "0.02 W/2"

l.14: replace "frontier" by "interface"

page 2:

l. 29: remove one "the" (leading to decay of)

page 3:

l.25: replace " is" by "in"

page 5:

l. 2: Insert "Thus"

page 8:

l. 6 please use 50 m instead of 5000 mm

l. 6 what is the relation between the hydrology model (50 meters) and the thermal model (42.1) meters). How are these linked? In the lines above I get the impression that they are coupled for the upper 3.8 meters. But how about the rest?

page 9:

l. 15: of the top of the permafrost

page 15:

l. 9/10: what do you mean? It should affect the amount of heat being diffused

page 22:

l. 11/12: please explain why his happens

page 29:

l. 13: the virtual aquifer has a thickness of 50 meters, not 5

l. 26: ..as high as 50-80% with respect to…

l. 35: no, permafrost will also melt from below. The phase transition will affect heat balance and thermal properties of the frozen/unfrozen bedrock. But, the ice-content in bedrock pores and fractures will be low.

page 30:

l. 1-2: yes, but increasing the cell size will reduce the resolution of tracing the lower boundary of the permafrost

Geosci. Model Dev. Discuss.,
https://doi.org/10.5194/gmd-2018-233-RC2, 2019

Interactive comment on "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools" *by* Ignacio Hermoso de Mendoza et al.

David Lawrence (Referee)

dlawren@ucar.edu

Received and published: 3 April 2019

This paper evaluates the influence of modeling decisions regarding the depth of the soil. It finds that with shallower soils, the influence of the bottom no heat flux boundary can be detected on century timescales.

The study is pretty straightforward and the conclusions are essentially as expected. There are several other papers that have examined a similar topic (Alexeev et al, 2007, Nicolsky et al, 2007, and Lawrence et al., 2008). From my reading of this paper, in comparison to what I recall about these other papers, I think that there is some new information here, but I would strongly recommend that the authors strive to make it clear how their study is distinct from these previous studies (e.g., global versus site level assessment).

I don't have many technical concerns with the paper. It is fairly straightforward. Run the model at varying soil depths and with and without geothermal heat flux and assess the impact on simulations. The authors covered issues that I would be worried about regarding spinup and computational costs. My main recommendations, in addition to that mentioned above, are:

1. The paper only assesses the impact of extending the depth of ground beyond the default 42m used in CLM4.5. For more context, it would be very useful to also include a simulation with much shallower ground (e.g., 3.5m or so) as is used in most current generation ESMs. My guess, based on the above cited studies, is that the impact of going from 3.5m to 42m is much larger than going from 42m to 342m. That is an important message that needs to be maintained. I wouldn't say that every analysis in the paper needs to be repeated with this shallower version, though for the sake of consistency, it might be worth considering, but for at least the baseline big issues (impact on near-surface permafrost), it should be shown/discussed.

2. There are way too many figures, perhaps even an excess of a factor of 2. Many figures are included that essentially show no change. That doesn't need to be shown in a figure and can easily be characterized in text or a table. The authors should carefully consider each figure and ask whether or not this figure is needed to tell the story. If it isn't required, then remove it, keeping in mind that if the story is that the impact is small (which is part of the story), then that can be stated in words

3. Finally, I think the authors need to carefully consider what their main messages are and, in parallel, put these messages into into context. Currently, they dutifully report about the % change (down to tenths of a percent in many cases) that arises from a deeper column. From my perspective, in the grand scheme of things in Earth System Modeling today, errors of order 1-2% out to 2100 or 2300 are not first order problems.

Uncertainties in climate projections and many other simulated land processes are likely having a much bigger impact on permafrost simulations than the depth of the ground column (once you get beyond a depth of 30m or so). If the authors want to argue otherwise, that's fine, or they can acknowledge that these deep depths may only be relevant on very long timescales or for very specific quantiies. To this end, I would like to see something more in the form of recommendations. An example recommendation could be that if the main interest is in projections of intermediate-depth permafrost thaw, then a deep ground column is required, but if the main interest is in near-surface permafrost, a depth of roughly 50m may be sufficient (and necessary).

Minor points:

1. The reference for CLM4.5 is not Bonan (et al. 2013), it should be Oleson et al. (2013).

2. P.4, line 18: Kirtman et al. is not the correct reference. Kirtman lead the near-term decadal prediction chapter, not the long term projections chapter of AR5.

3. The key reference for the soil biogeochemistry in CLM4.5 is Koven et al. (2013)

4. P.9, line 25: This sentence is not quite correct. Glaciers are represented in CLM4.5 as columns of ice (42m thick, as with the soil). In CESM2, there is the option to run with an ice sheet model beneath CLM, but even in that situation, CLM is still representing the surface mass balance over glaciers and then passing that information to the ice sheet model.

5. One thing that might be worth considering with respect to impact is what the impact might be from having a deep column on the vulnerability of yedoma (not treated in CLM, but with variable soil depths introduced into CLM5, could potentially could be). Yedoma is located deeper in the soil column 5-20m (?) and therefore may be susceptible to the specified soil thickness.

6. Figure 18: You have to study this figure very hard to see the differences. Maybe it

should be removed or difference maps should be shown instead of mean states.

7. P.29, line 12-14. The correct references for variable soil thickness in CLM5 are Brunke et al., 2016 and Swenson and Lawrence (2015)

Nicolsky D. J., V. E. Romanovsky, V. A. Alexeev, D. M. Lawrence, 2007. Improved modeling of permafrost dynamics in a GCM land-surface scheme. Geophys. Res. Lett., 34, L08501, doi.org/10.1029/2007GL029525. Alexeev V. A., D. J. Nicolsky, V. E. Romanovsky, D. M. Lawrence, 2007. An evaluation of deep soil configurations in the CLM3 for improved representation of permafrost, Geophys. Res. Lett., 34, L09502, doi.org/10.1029/2007GL029536. Lawrence, D.M., A.G. Slater, V.E. Romanovsky, and D.J. Nicolsky, 2008. The sensitivity of a model projection of near-surface permafrost degradation to soil column depth and inclusion of soil organic matter. J. Geophys. Res., 113, F02011, doi.org/10.1029/2007JF000883.

Oleson, K.W., D.M. Lawrence, G.B. Bonan, B. Drewniak, M. Huang, C.D. Koven, S. Levis, F. Li, W.J. Riley, Z.M. Subin, S.C. Swenson, P.E. Thornton, A. Bozbiyik, R. Fisher, E. Kluzek, J.-F. Lamarque, P.J. Lawrence, L.R. Leung, W. Lipscomb, S. Muszala, D.M. Ricciuto, W. Sacks, Y. Sun, J. Tang, Z.-L. Yang, 2013. Technical Description of version 4.5 of the Community Land Model (CLM). NCAR Technical Note NCAR/TN-503+STR, doi.org/10.5065/D6RR1W7M.

Koven, C.D., W.J. Riley, Z.M. Subin, J.-Y. Tang, M.S. Torn, W.D. Collins, G.B. Bonan, D.M. Lawrence, and S.C. Swenson, 2013. The effect of vertically-resolved soil biogeochemistry and alternate soil C and N models on C dynamics of CLM4. Biogeosciences, 10, doi.org/10.5194/bg-10-7109-2013.

Swenson, S.C. and D.M. Lawrence, 2015. GRACE-based assessment of interannual variability in groundwater simulated in the Community Land Model. Water Res. Res., 51, 8817-8833, doi.org/10.1002/2015WR017582.

Brunke, M.A., P. Broxton, J. Pelletier, D. Gochis, P. Hazenberg, D.M. Lawrence, L.R.

Leung, G.-Y. Niu, P.A. Troch, and X. Zeng, 2016. Implementing and evaluating variable soil thickness in the Community Land Model, version 4.5 (CLM4.5). J. Climate, 29, doi.org/10.1175/JCLI-D-15-0307.1.

Interactive comment on Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2018-233, 2018.

Interactive comment on “Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools” by Ignacio Hermoso de Mendoza et al.

Authors' response to the Executive editor of GMD

The Executive editor has brought to our attention that the title of the main paper does not fulfill the following requirements for papers published in GMD:

- "The main paper must give the model name and version number (or other unique identifier) in the title."
- “If the model development relates to a single model then the model name and the version number must be included in the title of the paper. If the main intention of an article is to make a general (i.e. model independent) statement about the usefulness of a new development, but the usefulness is shown with the help of one specific model, the model name and version number must be stated in the title. The title could have a form such as, “Title outlining amazing generic advance: a case study with Model XXX (version Y)”.”

Therefore, we will change the title of the paper to include a reference to CLM4.5. We have decided to take the title suggested by the Executive editor: "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools: a case study with CLM 4.5".

Best regards.

Interactive comment on "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools" by Ignacio Hermoso de Mendoza et al.

Authors' response to Anonymous Referee #1

We thank the reviewer for his comments, which show that several points both in the description of the model and in the objectives and limitations of our study needed to be clarified. We have made some corrections and added several paragraphs to address the reviewer's questions. In addition, we have made many editorial corrections throughout the manuscript to improve the readability and flow of the text. We have also changed the Figure 18 (P21) to show the differences to the original model and changed its color code to make it colorblind-friendly. In response to a suggestion made by reviewer 2, we have also moved several figures to supplementary materials. We now provide a response to all the comments and concerns expressed by the reviewer.

1. **However, the authors have not provided a full description of their permafrost/thermal model. Are phase transitions incorporated? Do they couple active layer thickness changes to the hydrology model? What is their definition of permafrost in terms of ice-water content? How are the blanketing and buffering effects of snow on the surface incorporated? Many such descriptions are missing.**

   As requested by the reviewer, we have added qualitative descriptions for the snow model and the hydrology model within the Community Land Model version 4.5 (CLM4.5) in the subsection 3.1 "Original Land Model". The hydrology model parameterizes interception, throughfall, canopy drip, snow accumulation and melt, water transfer between snow layers, infiltration, evaporation, surface runoff, subsurface drainage, redistribution within the soil column, and groundwater discharge and recharge. The vertical movement of water in the soil is determined by hydrological properties of the soil layers, which can be altered by their ice content as increased ice content reduces the effective porosity of the soil. The model also implements an artificial aquifer with a capacity of 5000 mm at the bottom of the soil column, from which discharge is calculated. The parameterization of snow consists of up to 5 layers, whose number and thickness increase with the thickness of the snowpile. Thermal conduction in these layers works like in soil layers, with the thermal properties of ice and water. The model includes fractional snow cover and phase transitions between the ice and water in the soil and snow layers. We have not included the full numerical description of the snow and hydrology models, because they can be found in the technical description paper for CLM4.5. The only explicit numerical description is that for the layer scheme in CLM4.5 and the zero heat flux condition used at the bottom boundary, because these are the only parts of the numerical model that we modify.

   In the subsection 3.4 "Permafrost treatment", we have added the commonly used definition of permafrost as the ground that remains below 0C for two consecutive years. This is a thermal definition of permafrost, i.e. the permafrost is defined only by the temperature of a layer, without regard that the layer actually contains ice. This allows our definition to also apply in bedrock layers, where the numerical model does not include water. Permafrost in the soil, to which we refer in the paper as near-surface permafrost, hinders the infiltration of liquid water from upper layers because the ice fills all pores, reducing the effective porosity of a permafrost layer to zero.

2. **In addition, the authors assume a constant regolith thickness of a few meters, without porosity-depth changes, and a granitic bedrock to occur worldwide. Also, they assume a spatially constant geothermal heat flow. Both assumptions are very crude approximation of reality, which will severely affect their modelling results. Information on the global variation in subsurface composition and geothermal heat flow is available in literature and databases.**

   The assumptions of constant regolith thickness and global granitic bedrock were not made by us, but by the modeling group who developed CLM4.5. We pointed in the paper that the homogeneity of the subsurface and other characteristics of the subsurface model in CLM4.5 are very unrealistic assumptions which affect the thermal state of the subsurface and the hydrology model. However, the goal of this paper is not to make precise predictions with a detailed model of the subsurface including soil composition and thickness, bedrock properties and heat flow variations because the data to build such a model do not exist. Our aim is to investigate and quantify the effects of two unrealistic assumptions made by most land models, i.e. the zero value for the geothermal heat flux and the excessive thinness of the model's subsurface, and to this end we modified CLM4.5. Including fine variations in the composition of the bedrock or thickness of the soil is maybe desirable, but is simply not possible at the spatial resolution of the model because the data are too sparse, and it is outside the scope of this paper.

We agree that using a spatially constant geothermal heat flow is a very crude approximation of reality. However, it allows us to treat the basal heat flow as a parameter which we can increase at regular intervals between 0 (the basal heat flux value used in CLM4.5) and 80 mW/m2, in order to quantify the effect of basal heat flow in CLM4.5 within a range of values of heat flow in stable continents. Likewise, we have systematically changed the thickness of the modeled subsurface in order to demonstrate how the use of a too shallow model affects the energy budget of the subsurface. Maps of geothermal heat flow are available in literature, however these maps are in large part extrapolated from an incomplete data set with many regions void of data, in particular in permafrost regions where these data are most important (Jaupart and Mareschal, 2015). Kitover et al. (2014, 2015) used a map made by Davies and Davies (2010), who extrapolated the data on the basis of crude correlation between geology and heat flux, which leaves a large uncertainty on the mean heat flux for each cell. Wide regions of the globe remain void of measurements of geothermal heat flow, in particular the high-latitude regions.

3. **Please also note the supplement to this comment: https://www.geosci-model-dev-discuss.net/gmd-2018-233/gmd-2018-233-RC1- supplement.pdf**

The supplement to the reviewer's comment states that our description is not sufficiently complete and precise to allow its reproduction. We respectfully disagree. The Community Earth System Model version 1.2 (CESM1.2), which includes the CLM4.5, is released to the public and can be easily found in the website of the University Corporation for Atmospheric Research (UCAR). The paper states explicitly what changes we have made to the numerical model. To reproduce our simulations, one only needs to modify the CLM4.5 codes to program the same changes as ours and run the simulations using the same forcing data. These modifications are described in the paper and the specific code changes are available in the Zenodo repository, as specified in the section "Code availability". The initial state of the model for the simulations is provided in the same Zenodo repository, and we have described the spinup process that it is used to drive the CLM4.5 to this state from arbitrary initial conditions. Finally, the forcing data are publicly available, with references provided in the section "Data availability". Therefore, the paper provides all the information necessary to allow the reproduction of our results.

As stated in the supplement, the title does not include the model name and number. This has already been pointed out in a previous comment, and will be corrected in the final version of the paper. The new name will be "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools: a case study with CLM4.5".

We now address point by point the list of specific comments of the reviewer:

- **Using the word "reflect" for the thermal effect of a too shallow lower boundary condition can only apply to the effects of climate warming. However, models are also used to study implications of climate cooling (in the past).** In the mathematical formulation for the propagation of a surface signal (a wave) into the subsurface, the lower boundary acts by bouncing the signal (with strength damped across the slab of subsurface bounded between the surface and the lower boundary) back to the surface, effectively "reflecting" the signal. This applies to any signal regardless of its sign, therefore we do not understand why would the word "reflect" not be valid for cooling signals, while being appropriate only for warming signals
- **20 C/km is a bit low for a general, global geothermal gradient. 30 C/km is more in line with observations.** We beg to disagree on this point. Mean continental heat flux is 60 mW/m2 and conductivity of bedrock in the model is 3 W/m/K, which gives a geothermal gradient of 20 K/km. Among all the gradients measured in the Canadian Shield, most are between 10 and 15K/km, and none is higher than 15K/km (Jaupart et al., 2015). Similar observations have been reported over all Precambrian and Paleozoic provinces worldwide.
- **Mention that the two parallel planes are the upper and lower surface.** We have made this correction.

- **Assuming a constant diffusivity implies that you assume no porosity change with depth (which is unrealistic for the modeled depth interval), and that no phase change occurs (no melting or freezing). Both assumptions are crude simplifications.** We agree that this is a crude simplification. However, this is a theoretical calculation where we want to show what the difference that a subsurface of 342.1m as opposed to the 42.1m would make in CLM4.5. In CLM4.5, only the upper 3.8m of the subsurface models hydrology and implements some degree of heterogeneity in its thermal or hydraulic properties. In this simplified calculation, we consider it is acceptable to model the upper 3.8 m as having the same homogeneous granitic composition as the subsurface below, as our goal with this rough calculation is to provide justification to the experiments we perform afterwards with several CLM4.5 versions of increased subsurface thickness.
- **Porosity decreases exponentially with depth. Thus the thermal diffusivity should change with depth, and is not a constant as you assume. Composition in the upper 31 meters changes with depth, due to porosity change. The assumption that all bedrock (below 41 m) consists of granite is not realistic.** In the subsection 3.1 "Original Land Model", we limit ourselves to describe the composition, properties and layout of the subsurface scheme in CLM4.5. While we agree that these assumptions in CLM4.5 are very crude approximations of reality, the objective of this paper is not to correct them.
- **Mention that you later on will modify the model by incorporating a geothermal heat flow at the base of the model.** We have added this mention.
- **Such database (of geothermal heat flow) do exist. For inspiration, check the papers by Kitover et al. (2014, 2015).** We are aware of the existence of the heat flow map used in Kitover et al. (2014, 2015). This map was produced by Davies and Davies (2010) and is based on the same heat flow database as that used by Jaupart and Mareschal (2015), using a different methodology and interpolation method. The heat flow measurements, as we stated in the paper, do not cover wide areas of Canada, Siberia, the Middle East, Africa and South America. To create the global map, Davies and Davies (2010) used a correlation between geology and geothermal heat flux to extrapolate in these void areas, which leads to very poor estimates in the areas with no measurements.
- **What is the ice/water content for your permafrost definition? Please note that some authors have advocated a thermal definition of permafrost since some permafrost in fact lacks ice. Also, please note that some permafrost contains more ice than just the normal porosity (i.e. in the forms of cracks and lenses).** We have now added the definition of permafrost in the subsection 3.4 "Permafrost treatment", and defines permafrost as the ground that remains below 0C for two consecutive years, which is indeed a thermal definition of permafrost. In addition to near-surface permafrost (defined for the depth range where the soil extends), we also define intermediate-depth permafrost to cover the portion of the subsurface composed of impermeable bedrock, therefore we believe taht a thermal definition is appropriate. Also, while we are aware that permafrost ice can be contained in interstitial spaces such as cracks and lenses, these are regrettably not defined in the subsurface model for CLM4.5.
- (... the only process taking place in bedrock is thermal diffusion.) **No, permafrost will also melt from below. The phase transition will affect heat balance and thermal properties of the frozen/unfrozen bedrock. But, the ice content in bedrock pores and fractures will be low.** While in reality bedrock holds water, in CLM4.5 (and most land models) bedrock is modeled as not having any water content at all. As such, bedrock layers in CLM4.5 only include thermal diffusion processes, both in and out of the permafrost region. For this reason, we stated that adding more of such bedrock layers to the land model would carry very small computational costs.
- (... if we keep the original scheme where layer thickness increase exponentially, it is possible to increase the thickness of the model to hundreds of meters by adding only a few layers.) **Yes, but increasing the cell size will reduce the resolution of tracing the lower boundary of the permafrost.** We agree, the exponential layer thickness scheme decreases the resolution of the permafrost depth range. This already shows in CLM4.5, as the bottom soil layer has a thickness of 1.5 m, out of a total soil thickness of 3.8 m. However, we think that the exponential scheme used in CLM4.5 is appropriate, because it allows to increase the depth of the model easily. While resolution is important, it is necessary to find a tradeoff between resolution and computational cost, which was the original reason behind the design of the exponential layer thickness by the Community modeling group. This balance between resolution and simplicity can be expressed though the scaling factor for the exponential node depth formula described in Eq. (7), so this parameter could be adjusted to meet a better

compromise between resolution and computational performance. We have added a mention of this concern in the discussion.

In addition to his comments, the reviewer has also made a series of technical corrections for whose we are very grateful. We have corrected the typos and made the text corrections in the reviewer's list. We have addressed the other corrections (with the exception of the two last points, which are repeated in the previous list of specific comments) in the following list:

- **Use "20mW/m2" instead of "0.02W/m2".** As requested, we have changed all the units from Watts to mili-Watts throughout the text.
- **Please use 50 m instead of 5000 mm.** We assume the reviewer means 5 m instead of 50 m. The technical description paper of CLM4.5 used "mm" as the units for water capacity (per unit area), including the explicit use of "5000 mm" as the capacity of this aquifer, which is why we kept these units. As this is not a matter of big importance, we have changed "5000 mm" to "5 m" throughout the paper.
- **What is the relation between the hydrology model (50 m) and the thermal model (42.1 m) How are these linked? In the lines above I get the impression that they are coupled for the upper 3.8 m. But how about the rest?** As we stated in the paper, the aquifer (with a capacity of 5 m, not 50 m) exists as a virtual layer below the soil. It is not coupled for the upper 3.8 m, it is a layer below this depth. To clarify what we call "virtual", we added the explanation in the text: it is a layer that does not interact with the subsurface other that to store water. This is, while it should physically occupy the same space as the bedrock in the subsurface model, it simply takes all the water that percolates from the bottom soil layer without this water affecting the thermal properties of the bedrock or being affected by phase transitions, and then it send the water directly to the river transport model. As we pointed out in the discussion, this model is completely unrealistic, but fortunately ithis has been addressed in the new CLM5.0 version.
- **What do you mean? It should affect the amount of heat being diffused.** By "the magnitude of the heat flux used as bottom boundary condition does not affect heat diffusion" we mean that thermal diffusivity is independent of temperature. Therefore, in a purely conductive regime, the heat equation is linear and the temperature anomaly solution for the propagation of a thermal signal into the subsurface can be superposed to the steady state solution (determined by the non-anomaly initial temperature and the geothermal gradient) This implies that heat diffusion (the transient part of the solution) is not affected by the value of the steady state heat flux. This can be verified in Carslaw and Jaeger (1959) "Conduction of heat in solids".
- (... Increasing the crustal heat flux decreases the initial concentration of soil carbon in some areas while increasing it in others.) **Please explain why this happens.** The local variability of the results across the Northern Hemisphere permafrost region is difficult to interpret with certainty, so we have added an plausible explanation in the discussion, rather than in the results section. The possible explanation is that the increasing the subsurface temperature decreases the period of seasonal freezing for some soil layers, which allows more methane to be produced if there is still a frozen soil layer beneath, which restricts the seepage of water and allowis the active layer to be inundated. However if the entirety of the soil thaws, the water can percolate to the aquifer and less methane is produced. Because the differences in the methane production accumulate over time, this also explains the local differences in the size of the carbon pool. Similarly, the presence of more liquid water allows for a slightly larger vegetation growth while the percolation of water to the aquifer decreases it. The maps for soil carbon, vegetation carbon and methane production match with what we should expect from this explanation: the first situation happens in coldest areas, where the lowermost soil layers remain frozen, and the second situation occurs in the periphery of the permafrost region, where the lowest layer can thaw.
- **The virtual aquifer has a thickness of 50 m, not 5.** As we explained before, this is incorrect. The virtual aquifer has a capacity for 5 m of water.

Jaupart C., Labrosse S., Lucazeau F., Mareschal J.-C. (2015). Temperatures, Heat and Energy in the Mantle of the Earth, in *Treatise on Geophysics, 2nd Edition, vol. 7, The Mantle*, edited by D, Bercovici, 223-270, Elsevier.

Interactive comment on "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools" by Ignacio Hermoso de Mendoza et al.

Authors' response to reviewer #2 (David Lawrence)

We thank the reviewer for his comments, which show that we need to better put the article into context and emphasize its main conclusions. We have made many editorial corrections, including the bibliographic mistakes, and added several paragraphs to address the reviewer's questions.

1. **There are several other papers that have examined a similar topic (Alexeev et al, 2007, Nicolsky et al, 2007, and Lawrence et al., 2008). From my reading of this paper, in comparison to what I recall about these other papers, I think that there is some new information here, but I would strongly recommend that the authors strive to make it clear how their study is distinct from these previous studies (e.g., global versus site level assessment).**

   We have added a paragraph in the introduction, to explain the differences between our study and those mentioned by Dr. Lawrence. To improve the modeling of permafrost, the papers mentioned by Dr. Lawrence pointed out that the subsurface model must be thick enough (at least 30 m) to capture the damping of the annual surface temperature. These papers increased the thickness of the CLM3 from 3.5 m to different depths to capture decadal and centennial variability during the 20th century. Alexeev et al. (2007) used of a slab of variable thickness (30, 100 and 300 m) at the bottom of a several layers representing the soil with high resolution, in order to have sufficient depth to absorb decadal to centennial signals. Nicolsky et al. (2007) did the same by using additional soil layers to increase the thickness of the model to 80 m, which they applied at specific locations with deep permafrost. Lawrence et al. (2008) tried depths up to 125 m by adding extra bedrock layers, and determined how this affected the extent of near-surface permafrost. These studies did not consider crustal heat flux and although they studied the impacts of model depth in near-surface permafrost, they did not analyze the associated effects to the permafrost carbon pool. In our paper, we look into the impacts of the thickness of the subsurface and the crustal heat flux, not only on permafrost but also on the heat content of the subsurface and on the carbon pool, in simulations for the 20th century that we continue until 2300 under two scenarios of anthropogenic emissions.

2. **The paper only assesses the impact of extending the depth of ground beyond the default 42m used in CLM4.5. For more context, it would be very useful to also include a simulation with much shallower ground (e.g., 3.5m or so) as is used in most current generation ESMs. My guess, based on the above cited studies, is that the impact of going from 3.5m to 42m is much larger than going from 42m to 342m. That is an important message that needs to be maintained. I wouldn't say that every analysis in the paper needs to be repeated with this shallower version, though for the sake of consistency, it might be worth considering, but for at least the baseline big issues (impact on near-surface permafrost), it should be shown/discussed.**

   As suggested by Dr. Lawrence, we have included a new simulation with shallow ground (3.8m) by removing the bedrock in the model. We already observed that increasing the thickness of the model provides diminishing returns, therefore, reducing the thickness of the subsurface from 3.5m to 42m has a bigger impact than going from 42m to 342m. The impact of progressively increasing depth depends on the timescale of the simulation, so the increase from 42m to 342m is more significant for a millennial-scale simulation than it is for our centennial-scale simulations. In this new simulation, we observe that decreasing the subsurface thickness from 42m to 3.8m has a much larger effect in the soil carbon pool than from increasing it from 42m to 342m. The loss of soil carbon during the 1901-2300 period is increased by 4.4% in the RCP85 scenario, but more importantly by 35% in the RCP4.5 scenario. The emissions of methane are consistently 1-2% higher for a subsurface of 3.8m than one of 42m, which results in these increased losses of soil carbon. It has already been well established that deepening the bottom boundary below 3.5m improves representation of permafrost significantly, bringing the simulated extent of present permafrost much closer to the observations (Alexeev et al, 2007, Nicolsky et al, 2007, and Lawrence et al., 2008, Koven et al., 2013, Slater & Lawrence, 2013). We have not detected a significant decrease in the areal extent of near-surface permafrost, but decreasing model thickness from 42m to 3.8m affects the thickness and depth of permafrost. We have included this point in the discussion, and we have also emphasized the logical conclusion that can be inferred from the diminishing returns to subsurface thickness and the optimal depths. Increasing subsurface thickness produces modest improvements, but reducing it introduces serious miscalculations to subsurface temperature, permafrost and soil carbon.

3. **There are way too many figures, perhaps even an excess of a factor of 2. Many figures are included that essentially show no change. That doesn't need to be shown in a figure and can easily be characterized in text or a table. The authors should carefully consider each figure and ask whether or not this figure is needed to tell the story. If it isn't required, then remove it, keeping in mind that if the story is that the impact is small (which is part of the story), then that can be stated in words.**

   We agree that the number of figures is too large, and we have reduced it significantly. Following the recommendation of the reviewer, we have removed from the main paper many figures that show very small changes and that can be sufficiently explained in the text or with the support of the tables. These figures have been moved to supplementary materials, which we will submit along with the revised version of the paper. We have moved Figures 9, 10, 11, 12, 14, 15, 17, 23, 24, 28 and 29, cutting the number of figures in the main body of the paper from 29 to 18. We have kept Figure 16 although it shows only a small difference, to have at least one figure showing the evolution of near-surface permafrost, and Figures 19 and 20, because they show the significant differences produced by the crustal heat flux to the evolution of the soil carbon pool. We have also changed Figure 18 significantly, to show the differences to the original model in the same way as Figures 21, 25 and 27 do. We have also eliminated the 2000 CE time frame in Figures 18, 21, 25 and 27, which allows us to enlarge these maps.

4. **Finally, I think the authors need to carefully consider what their main messages are and, in parallel, put these messages into into context. Currently, they dutifully report about the % change (down to tenths of a percent in many cases) that arises from a deeper column. From my perspective, in the grand scheme of things in Earth System Modeling today, errors of order 1-2% out to 2100 or 2300 are not first order problems. Uncertainties in climate projections and many other simulated land processes are likely having a much bigger impact on permafrost simulations than the depth of the ground column (once you get beyond a depth of 30m or so). If the authors want to argue otherwise, that's fine, or they can acknowledge that these deep depths may only be relevant on very long timescales or for very specific quantities. To this end, I would like to see something more in the form of recommendations.**

   We agree that the order of these errors are small compared to other sources of error, and we will not argue otherwise. We however defend that these small errors are very easily avoidable, because the implementation of a crustal heat flux and the extension of subsurface thickness is justified, easy to implement and computationally cheap. We have added a new paragraph at the end of the discussion, where we acknowledge the small scale of the corrected errors, but at the same time arguing our point. We also acknowledge that it is more important to not drop subsurface thickness below 40m than to extend it to 200m, but that the importance of a thick subsurface increases with the time scale of the simulation. We provide a explicit recommendation to have a subsurface thickness of at least 40-50m for a correct reproduction of near-surface permafrost, and increase it to 200 m to avoid errors in the order of 1-4%, even more if we were to include deep carbon deposits in the model.

The reviewer also made several minor points, which we address point by point:

1. **The reference for CLM4.5 is not Bonan (et al. 2013), it should be Oleson et al. (2013).** We have corrected this reference.
2. P**.4, line 18: Kirtman et al. is not the correct reference. Kirtman lead the near-term decadal prediction chapter, not the long term projections chapter of AR5.** We have corrected this reference with Collins et al., 2013 (Climate Change 2013: The physical Science Basis. Long-term Climate Change: Projections, Commitments and irreversibility).
3. **The key reference for the soil biogeochemistry in CLM4.5 is Koven et al. (2013).** We have corrected this reference.
4. **P.9, line 25: This sentence is not quite correct. Glaciers are represented in CLM4.5 as columns of ice (42m thick, as with the soil). In CESM2, there is the option to run with an ice sheet model beneath CLM, but even in that situation, CLM is still representing the surface mass balance over glaciers and then passing that information to the ice**

sheet model. We have corrected this sentence. It now states that CLM4.5 represents the interior of Greenland with the upper 42 m of ice and passes this information to the land-ice model, but it does not represent the soil.

5. **One thing that might be worth considering with respect to impact is what the impact might be from having a deep column on the vulnerability of yedoma (not treated in CLM, but with variable soil depths introduced into CLM5, could potentially be). Yedoma is located deeper in the soil column 5-20m (?) and therefore may be susceptible to the specified soil thickness.** We have added Yedoma and frozen thermokarst deposits as an example of deep carbon deposits in the discussion. These hold an estimated 211 +/- 160 PgC of carbon in depths up to 50 m (Strauss et al., 2013). Our study shows that the thawing of intermediate-depth permafrost is largely overestimated by the 42 m subsurface, therefore an appropriate subsurface thickness of 200m would be necessary if these deep carbon deposits were included in the model.
6. **Figure 18: You have to study this figure very hard to see the differences. Maybe it should be removed or difference maps should be shown instead of mean states.** We have changed this figure to show the active layer thickness of the original CLM4.5 and the differences between the modified versions of the model and the original model. We have also changed the color scale to be colorblind-friendly.
7. **P.29, line 12-14. The correct references for variable soil thickness in CLM5 are Brunke et al., 2016 and Swenson and Lawrence (2015).** We have corrected these references.

Strauss, J., Schirrmeister, L., Grosse, G., Wetterich, S., Ulrich, M., Herzschuh, U., & Hubberten, H. W. (2013). The deep permafrost carbon pool of the Yedoma region in Siberia and Alaska. *Geophysical Research Letters*, *40*(23), 6165-6170.

Koven, C. D., Riley, W. J., & Stern, A. (2013). Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth System Models. *Journal of Climate*, *26*(6), 1877-1900.

Slater, A. G., & Lawrence, D. M. (2013). Diagnosing present and future permafrost from climate models. *Journal of Climate*, *26*(15), 5608-5623.

Author's changes to the manuscript "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools."

Dear Editor,

To address the comments from the referees, we have made numerous corrections to the manuscript. We provide a list of the changes done to the manuscript, following the order of the referees' comments. To facilitate the task of the Topical Editor, we have pointed each modification to its specific location in the marked-up version of the manuscript, that highlights the changes made. In addition, we have corrected typographical mistakes and made many minor corrections throughout the manuscript to improve the readability of the text. Because these corrections are too numerous, we do not include them in a list to avoid making this cover letter tedious, but they can be easily seen throughout the marked-up version of the manuscript that has been produced with latexdiff for LaTeX.

Before discussing the list of specific changes, we would like to bring to the attention of the Editor the most important modifications to the content and the structure of the manuscript:

- In response to the comment of the Executive Editor of GMD, we have changed the title of the manuscript to that he suggested for us: "Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools: a case study with CLM4.5."
- To answer the concern from Reviewer #2 that the manuscript had too many figures, we have moved 11 figures to a supplementary materials file: Figures 9, 10, 11, 12, 14, 15, 17, 23, 24, 28 and 29 from the original manuscript, which have been renamed Figures S1 to S11 in the supplementary materials. Figures 13, 16, 18, 19, 20, 21, 22, 25, 26 and 27 have been relabeled Figures 9 to 18 in the new version of the manuscript.
- As suggested by Reviewer #2, we have added a new simulation (made with a modified version of CLM4.5 that uses a subsurface 3.8 m thick) to those presented in the original manuscript. Consequently, we refer to this simulation and its results in the introduction, results and discussion sections. The results of this simulation have also been added to the Tables 1, 2 and 4, and to the Figures 6, 7, 10, 11, 12, 14, 16, 18, S1, S8 and S10.
- We have split Section 5 "Discussion and Conclusions" into two separate sections: Section 5 "Discussion" and Section 6 "Conclusions".

The Reviewer #1 (anonymous) pointed out in his general comments that several explanations were lacking in the manuscript. He also provided a list of specific comments, which included the points made in his general comments. We made several corrections and additions to the manuscript to address these concerns:

1. Section 2 "Theoretical analysis", P4, lines 24-25. We have clarified that the 2 parallel planes are the surface and the lower boundary.
2. Subsection 3.1 "Original land model", P8, lines 1-2. We have corrected the statement that the thermal properties of the soil are also affected by the soil water content, not only by carbon density.
3. Subsection 3.1 "Original land model", P8, line 2. We have clarified that the bedrock in CLM4.5

does not allow for pores or interstices where water can be held.

4. Subsection 3.1 “Original land model”, P8, lines 9-10. We have added a reminder that we will afterwards modify the model to include geothermal heat flux.
5. Subsection 3.1 “Original land model”, P8, lines 11-22. We have added two new paragraphs with the qualitative descriptions of the snow and hydrology models used in CLM4.5.
6. Subsection 3.4 “Permafrost treatment”, P10, lines 17-19. We have added a paragraph to provide an explicit definition of permafrost.
7. Section 5 “Discussion”, P30, lines 7-13. We have added a paragraph where we defend our reasons to use a uniform heat flux, and we also explain why we did not modify some of the most simplistic assumptions of the model such as global granitic bedrock and constant regolith depth. In this paragraph we also argue that the existing maps of heat flux, bedrock composition and soil thickness are incomplete.
8. Section 5 “Discussion”, P31, lines 21-24. We have added two sentences exposing the concerns of the reviewer of how the exponential layer scheme decreases the resolution of permafrost depth, and our thoughts on the usefulness of the exponential scheme despite these drawbacks.

The Reviewer #1 also provided another list of technical corrections. To address these comments, including the text corrections, we have made the following changes:

1. P1, line 9. In the sentence, “under two future scenarios” has been corrected to “under forcings of two future scenarios”.
2. The units used for heat flux have been changed from W/m^2 to mW/m^2. We have applied this correction throughout the manuscript, as well as all Figures and Tables.
3. P1, line 15. We have replaced “soil-bedrock frontier” by “soil-bedrock interface”. We have also corrected a mistake in the increased temperature: from 0.4 K to 0.04 K.
4. P2, line 34. In “leading to the decay of” we have removed “the”.
5. P4, line 12. We have corrected “the general solution is the time derivative” to “the general solution in the time derivative”.
6. P5, line 13. We have inserted “Thus” at the start of the sentence.
7. P9, line 14. The capacity of the unconfined aquifer in CLM4.5 has been changed from 5000mm to 5m.
8. We have added a clarification of how the aquifer works in the new paragraph describing the hydrological model at the end of the subsection 3.1 “Original land model”, P8, lines 14-17. We have also added a small note to remind this in the subsection 3.2 “Carbon model”, P9, lines 14-15.
9. P10, line 30. In the sentence, “the maximum depth of permafrost” has been corrected to “the maximum depth of the top of the permafrost”.
10. Section 5 “Discussion”, P30, line 34 to P31, line 9. We have added a paragraph where we provide an explanation for the regional variability observed in the results for methane production, soil carbon and vegetation carbon.
11. P28, line 5. In the sentence, we have changed “can be within 50-80% of that of” to “can be as high as 50-80% with respect to”.

The Reviewer #2 (Dr. David Lawrence) made very useful comments showing that our work needed to be differentiated from previous studies, and made several recommendations such as better putting the work into context, reducing the number of figures in the manuscript, and exploring the effects of reducing the subsurface thickness in the model with a new simulation. In response to his comments, we have made the following changes:

1. Section 1 "Introduction", P3, lines 17-24. We have added a few sentences to refer to 3 papers that explored the increase of the subsurface thickness in CLM3, and to explain the innovation in our paper relative to these previous studies.
2. We have included a new simulation with a modified model of subsurface thickness 3.8m. Consequently, we have added the results of this simulation to the figures, tables, and the text in Section 4 "Results". We also added associated mentions to this simulation in the introduction and the description of our changes to the models, and we added a discussion of the new results in Section 5 "Discussion".
3. Section 5 "Discussion", P31, lines 25-35. We have added a new paragraph where we discuss the diminishing returns of increasing the thickness of the subsurface, and how the impact of going from 42m to 3.8m is far more important that going from 42m to 342m. We relate this result with the previous studies with CLM3, where subsurface thickness was increased from 3.5m to more than 30m to improve the simulation of permafrost.
4. We have moved 11 figures from the Section 4 "Results" to a supplementary materials file (Figures 9, 10, 11, 12, 14, 15, 17, 23, 24, 28 and 29 from the original text). The references to these figures throughout the text have been changed to the remaining figures and tables, which are enough to support the exposed results.
5. Figures 18, 21, 25 and 27 (now renumbered to Figures 11, 14, 16 and 18). We have eliminated the second column corresponding to the 2000 CE frame, and we added a new row corresponding to the new modified model with 3.8m subsurface thickness. Because now the figures are taller than they are wide, we have changed the orientation of these figures back to portrait (previously it had been changed to landscape because of these figures were wider than they were tall).
6. Section 5 "Discussion", P32, lines 12-27. We added a paragraph were we acknowledge the small scale of the errors derived from using a subsurface of 42m while we argue for the convenience of increasing the thickness of the model nonetheless. Based on our results, including the large errors observed for a subsurface of 3.8m, we also provide recommendations for the subsurface thickness that LSMs should use, in relation to the time scale of the simulations. These recommendations have also been added to the new Section 6 "Conclusions" in P33, lines 4-8.

The Reviewer #2 also provided a list of minor points, which are very relevant. To address them, we have made the following modifications to the manuscript:

1. We have corrected the reference Oleson et al. (2013), which was mistakenly Bonan et al. (2013) throughout the text (the leading authors Oleson & Lawrence were missing in the author list).
2. Section 2 "Theoretical Analysis" P5, line 9. We have replaced Kirtman et al. (2013), which makes reference to the short-term predictions in IPCC 2013, by the correct reference for long term projections, Collins et al. (2013),

3. Subsection 3.4 "Carbon model", P8, line 25. We have added the reference Koven et al. (2013) for the BioGeoChemical Cycles in Biome-BGC.
4. Subsection 3.4 "Permafrost treatment", P11, lines 8-9. We have corrected the statement where we wrongly said that Greenland is not included in CLM4.5. Now it correctly states that even though CLM4.5 does not represent the soil below the Greenland ice sheet, it represents the upper 42m of the ice sheet.
5. Section 5 "Discussion", P30, lines 18-23. We have included yedoma and frozen thermokarst deposits as an example of deep carbon deposits (up to 50m deep), and discussed the implications that the inclusion of these deposits would have in the land model, on view of our results for intermediate-depth permafrost.
6. Figure 18 in the original manuscript (Figure 11 in the new version) has been changed to show the differences relative to the original CLM4.5 model for the modified versions. We have also changed the color code in this figure to be colorblind-friendly.
7. Section 5 "Discussion", P30, lines 1-6. We have added the references Swenson and Lawrence (2015) and Brunke et al. (2016) for variable soil thickness in CLM5. We have also added the references Pelletier et al. (2016) and Clair et al. (2015) for measurements and global estimations of soil thickness.

We thank again the referees for their comments, which have allowed us to seriously improve our paper. The marked-up version of the manuscript follows,

Ignacio Hermoso de Mendoza

Lower boundary conditions in Land Surface Models. Effects on the permafrost and the carbon pools: a case study with CLM 4.5.

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Abstract.

Earth System Models (ESMs) use bottom boundaries for their land surface model components which are shallower than the depth reached by surface temperature changes in the centennial time scale associated with recent climate change. Shallow bottom boundaries reflect energy to the surface, which along with the lack of geothermal heat flux in current land surface models, alter the surface energy balance and therefore affect some feedback processes between the ground surface and the atmosphere, such as permafrost and soil carbon stability. To evaluate these impacts, we modified the subsurface model in the Community Land Model version 4.5 (CLM4.5) by setting a non-zero crustal heat flux bottom boundary condition and by increasing the depth of the lower boundary ~~by 300 m~~ from 42.1 m to 342.1 m. The modified and original land models were run during the period 1901-2005 under the historical forcing and between 2005-2300 under forcings of two future scenarios of moderate (RCP 4.5) and high (RCP 8.5) emissions. Increasing the thickness of the subsurface by 300 m increases the heat stored in the subsurface by 72 ZJ ($1\ \mathrm{ZJ} = 10^{21}$ J) by year 2300 for the RCP 4.5 scenario and 201 ZJ for the RCP 8.5 scenario (respective increases of 260% and 217% relative to the shallow model), reduces the loss of near-surface permafrost area in the Northern Hemisphere between 1901 and 2300 by 1.6%-1.9%, reduces the loss of intermediate-depth permafrost area (above 42.1 m depth) by a factor of 3-5.5, and reduces the loss of soil carbon by 1.6%-3.6%. Each increase of ~~0.02 W m^{-2}~~ 20 mW m^{-2} of the crustal heat flux increases the temperature at 3.8 m (the soil-bedrock ~~frontier by 0.4 ± 0.01~~ interface) by 0.04 ± 0.01 K, which decreases near-surface permafrost area slightly (0.3-0.8%) ~~, but~~ but produces local differences in initial stable size of the soil carbon pool across the permafrost region, which reduces the loss of soil carbon across the region by as much as 1.1%-5.6% for the two scenarios. We determine the optimal subsurface thickness to be 100 m for a 100 yr simulation and 200 m for a simulation of 400 yr.

1 Introduction

In the current context of anthropogenic climate change, there is a need to forecast future impacts of climate change as reliably as possible. ~~Future climate~~ Climate change projections are based on simulations from ensembles of Earth System Models (ESMs), numerical models of oceans, atmosphere, land, ice, and biosphere subsystems coupled together (Stocker et al., 2013).

Modeling of the land system has mainly focused on the interactions between the land surface and the atmosphere (Pitman, 2003), including biogeochemical cycles taking place in the shallow subsurface or soil, such as carbon dynamics (Ramanathan and Carmichael, 2008), soil moisture (Seneviratne et al., 2010), vegetation cover and land use (Bonan, 2008), and surface processes such as albedo and snow cover (Hansen and Nazarenko, 2004). In these Land Surface Models (LSMs) the bedrock layer present below soil is impermeable, and when explicitly modeled, the only process taking place in bedrock is thermal diffusion.

Thermal diffusion in the subsurface allows the land system to act like a heat reservoir, contributing to the thermal inertia of Earth's climate. However, this contribution is relatively small as the capacity of the oceans to absorb energy is orders of magnitude above that of the continents (Stocker et al., 2013). Estimates of the energy accumulation during the second half of the 20th century in the land system show that the heat stored in continents (9 ± 1 ZJ, where $1\ \mathrm{ZJ} = 10^{21}$ J) is less than the uncertainty on the heat stored in oceans during the same period (240 ± 19 ZJ) (Beltrami et al., 2002; Levitus et al., 2012; Rhein et al., 2013). This ~~justifies~~ allows many ESMs to only consider the land subsurface to the shallow depth ($3 - 4$ m) needed for soil modeling (Schmidt et al., 2014; Wu et al., 2014) and to neglect the bedrock entirely. Still, the thermal regime of the subsurface affects the energy balance at the surface, which in turn influences the surface and soil processes with a feedback on the climate system. Energy variations at the land surface propagate underground, and the use of a too shallow subsurface in land models implies that these signals are reflected towards the surface, altering its energy balance (Smerdon and Stieglitz, 2006; Stevens et al., 2007; Melo-Aguilar et al., 2018; Steinert et al., 2018).

Several works (MacDougall et al., 2008, 2010) have pointed out that, for the long time scales of climate change, the temperature variations at the land surface propagate much deeper than the depths considered in current LSMs, which range between ~ 3.5 m (Schmidt et al., 2014; Wu et al., 2014) and 42 m ~~(Bonan et al., 2013)~~ (Oleson et al., 2013) . Theoretical estimates (MacDougall et al., 2008) of heat stored by the subsurface show a difference of one order of magnitude between models using subsurface thicknesses of 10 m and 600 m. This suggests that the reflected energy in shallow land models affects the surface energy balance in the simulations, and current ESMs should use land models sufficiently deep for the length of the simulations, to avoid bottom boundary effects on the thermal profiles.

Most of the current land models use a zero heat flux as thermal boundary condition at their base, as the geothermal gradient is small (~ 0.02 K/m) and does not affect temperature ~~at much~~ much at shallow depth (Jaupart and Mareschal, 2010). Subsurface models that increase the depth of the bottom boundary to hundreds of meters ~~have to consider~~ must include the geothermal gradient to properly represent the thermal regime of the subsurface. ~~Such a scheme~~ This can be easily ~~implemented by using the Earth's~~ done by using a fixed crustal heat flux as bottom boundary condition of the LSM, as a few models already do (Avis et al., 2011).

Soils in permafrost regions act as a long-term carbon sink that stores an estimated 1100-1500 GtC of organic carbon, twice the carbon content of the pre-industrial atmosphere (MacDougall and Beltrami, 2017; Hugelius et al., 2014). The feedback between climate and permafrost thawing and associated carbon emissions is expected to accelerate global warming (Schuur et al., 2015). Rising temperatures at high latitudes induce the thawing of permafrost, leading to ~~the~~ decay of frozen organic matter and the release of CO_2 and CH_4 into the atmosphere. Because of the potential positive feedback ~~of thawing permafrost~~

on between thawing permafrost and the climate system, ESMs endeavor to make robust assessments of future forecasts of permafrost extent and retreat.

The generation of ESMs used in the fifth phase of the Climate Model Intercomparison Project (CMIP5) show large disagreements in the simulation of present-day permafrost extent. Analyzed across the different used in , the sensitivity The response of permafrost area to global temperature increase the increase of global temperatures shows a wide range $(0.75 - 2.32 \times 10^6\ km^2\ K^{-1})$ of sensitivities across the models, and relative permafrost area losses of different CMIP5's LSMs $(0.75 - 2.32 \times 10^6\ km^2/K)$, which in terms of relative losses of permafrost area range between 6% -29% /K to 29% per K of high-latitude warming (Slater and Lawrence, 2013; Koven et al., 2013b). These differences arise partly from biases in air temperature and snow depth in some models, but mostly from structural weaknesses of the land models that limit their skill to simulate subsurface processes in cold regions (Koven et al., 2013b; Slater and Lawrence, 2013). Most of these land models rely on very shallow (∼3-42 m) subsurface modules (Cuesta-Valero et al., 2016). We expect that, both the thickness of the subsurface and setting a realistic non-zero value of heat flux as bottom boundary condition, will affect the evolution of permafrost in a warming scenario, and therefore the release of permafrost carbon.

It is possible to use analytical methods to estimate the effect that the bottom boundary depth and basal heat flux condition have on the thermal profile of the ground (Stevens et al., 2007). Because of the complexity of the biogeochemical processes in the soil, only numerical simulations can estimate how permafrost dynamics and permafrost carbon content are affected by the changes in the thermal profiles. Previous studies with the Community Land Model version 3 (CLM3) have pointed out that, to obtain a realistic representation of permafrost, the model's soil needs to be deep enough (∼ 30 m) to at least reach the depth needed for the damping of the annual surface temperature signal. Alexeev et al. (2007) used a slab of varying thicknesses (30, 100 and 300 m) at the bottom of a several layers representing the soil at a high resolution, in order to allow sufficient depth to absorb decadal to centennial signals. Nicolsky et al. (2007) used additional soil layers to increase the thickness of the model to 80 m, which they applied at specific locations of deep permafrost. Lawrence et al. (2008) tested soil depths up to 125 m by adding extra bedrock layers, and determined how this affected the extent of near-surface permafrost. However, these studies did not consider the crustal heat flux, and did not study further effects on the carbon pool. In this paper, we study the effect of the increase of the increasing the lower boundary depth and the addition of adding a geothermal heat flux at the base of the Community Land Model version 4.5 (CLM4.5) (Bonan et al., 2013) (Oleson et al., 2013) , which is the deepest (42.1 m) of the current land models LSM used in the CMIP5 (Stocker et al., 2013). We also investigate the effect of these changes on the permafrost and the carbon pools of the Northern Hemisphere. We also reduce the thickness of the subsurface in CLM4.5 to 3.8 m, to study its effects on the soil carbon pool. To explore these effects, we carried out simulations between 1901 CE and 2300 CE, using historical climate reconstruction between 1901 and 2005 (Viovy, 2018) and explored two alternative scenarios of moderate and high radiative forcings between 2006 and 2300 (Thomson et al., 2011; Riahi et al., 2011).

2 Theoretical analysis

The Earth's continental lithosphere (> 100 km) can be considered as a semi-infinite solid for the centennial and millennial time scales considered in the future projection of climate. For a purely-conductive thermal regime of the subsurface, the propagation of a temperature signal at the surface into the ground is governed by the heat diffusion equation in one dimension (Carslaw and Jaeger, 1959):

$$\frac{\partial T}{\partial t} = \kappa \frac{\partial^2 T}{\partial z^2}\,, \tag{1}$$

where κ is thermal diffusivity. The solution of Eq. (1) for a step change T_0 in surface temperature at $t = 0$ yields the temperature anomaly at depth z and at time t:

$$T(z,t) = T_0 \operatorname{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right). \tag{2}$$

The general solution for any surface temperature perturbation $T_0(t)$ starting at $t = 0$ can be obtained as the convolution in time of $T_0(t)$ and the Green function associated to Eq. (1) and the boundary conditions. As the Green function is the solution to a Dirac's delta, it is obtained as the general solution ~~is~~ in the time derivative of the solution to the step function in Eq. (2). Therefore, the general solution is:

$$T(z,t) = \frac{z}{2\sqrt{\pi\kappa}} \int_0^t T_0(\xi)(t-\xi)^{-3/2} \exp\left(-\frac{z^2}{4\kappa(t-\xi)}\right) d\xi\,. \tag{3}$$

Future scenarios (Van Vuuren et al., 2011) predict rising atmospheric temperatures during the present century (Cubasch et al., 2013) with a wide margin of variability and uncertainty. We can represent this future rise in temperatures by a linearly increasing surface temperature $T_0(t) = mt$, with m being the rate of temperature increase. For such surface temperature function, the solution to Eq. (1) is:

$$T(z,t) = mt\left[\left(1+\frac{z^2}{2\kappa t}\right)\operatorname{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right) - \frac{z}{\sqrt{\pi\kappa t}}\exp\left(\frac{-z^2}{4\kappa t}\right)\right]. \tag{4}$$

Numerical models, however, cannot simulate the subsurface as a semi-infinite solid, also known as half space model, but instead limit the subsurface to a given depth, that varies between models. Many land models ~~consider~~ include only the upper $3-4$ m of the subsurface, which ~~is considered~~ they consider as soil, ~~where hydrological processes take place~~to model the most basic hydrological processes such as infiltration and runoff in a first-order approximation. Other models further extend the subsurface to include the bedrock below, the deepest currently being the CLM4.5 with a total depth of 42.1 m. We can simplify these models by considering conduction only and modeling the land subsurface as a solid bounded by two parallel planes (the surface and the lower boundary). Assuming a lower boundary condition of no heat flux (as ~~it is the case in~~ most current models do) and a linearly increasing temperature increasing linearly with time $T_0(t) = mt$ as surface boundary condition, we obtain the following solution to Eq. (1) (Carslaw and Jaeger, 1959):

$$T(z,t) = m\sum_{n=0}^{\infty}(-1)^n \left\{ \left(t + \frac{(2nd+z)^2}{2\kappa}\right) \mathrm{erfc}\left(\frac{2nd+z}{2\sqrt{\kappa t}}\right) - (2nd+z)\left(\frac{t}{\pi\kappa}\right)^2 \exp\left(-\frac{(2nd+z)^2}{4\kappa t}\right) + \right.$$
$$\left. + \left(t + \frac{(2(n+1)d-z)^2}{2\kappa}\right) \mathrm{erfc}\left(\frac{(2(n+1)d-z)}{2\sqrt{\kappa t}}\right) - (2(n+1)d-z)\left(\frac{t}{\pi\kappa}\right)^2 \exp\left(-\frac{(2(n+1)d-z)^2}{4\kappa t}\right) \right\}, \quad (5)$$

where d is the depth of the bottom boundary. Neglecting near-surface processes such as hydrology or snow isolation, the temperature of the subsurface is described by Eq. (5).

Using Eqs. (4) and (5), we can estimate the effect of the thickness of the model. We have calculated the profiles of temperature perturbation for a rate of surface temperature increase of $0.01\ \mathrm{K\ yr^{-1}}$, assuming a thermal diffusivity of $\kappa = 1.5\times10^{-6}\ \mathrm{m^2\ s^{-1}}$ (used for bedrock in the CLM4.5 (Bonan et al., 2013) (Oleson et al., 2013)). This temperature increase is within the range of global temperature projections for the 21st century (Kirtman et al., 2013) (Collins et al., 2013) .

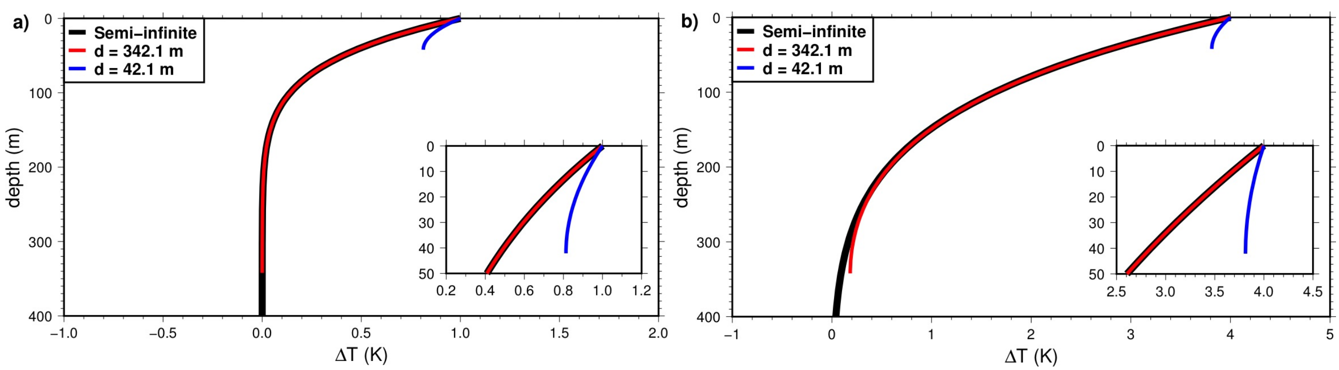

Figure 1. Departure from the initial temperature profile due to constant rate of surface temperature increase of $0.01\ \mathrm{K\ yr^{-1}}$. Analytical solutions for the half space model (black), and for the finite thickness model with bottom boundary at 42.1 m (blue) and at 342.1 m (red). a) Temperature anomaly after 100 yr. b) Temperature anomaly after 400 yr.

We calculated the temperature anomalies for the half space model and the layers of thickness 42.1 m and 342.1 m, after 100 yr and 400 yr. After 100 yr the temperature anomaly for the thinnest (42.1m) model has departed from that of the half space model (Fig. 1a), while the thickest (342.1 m) model cannot be distinguished from the half space solution after 100 yr. After 400 yr the thickest model only has small departure near the base (Fig. 1b). The Thus, the response of a model of finite thickness approaches that of the half space model, as long as the bottom boundary is deep enough for the difference between Eqs. (4) and (5) to be negligible.

The maximum time before the shallow bottom boundary affects the thermal behavior of the model is better appreciated in terms of heat absorption by the subsurface. The heat stored in the subsurface can be calculated from the temperature change in Eq. (5) by assuming a uniform volumetric heat capacity $c = 2\times10^6\ \mathrm{J\ m^{-3}\ K^{-1}}$ (taken from value used for bedrock in the CLM4.5).

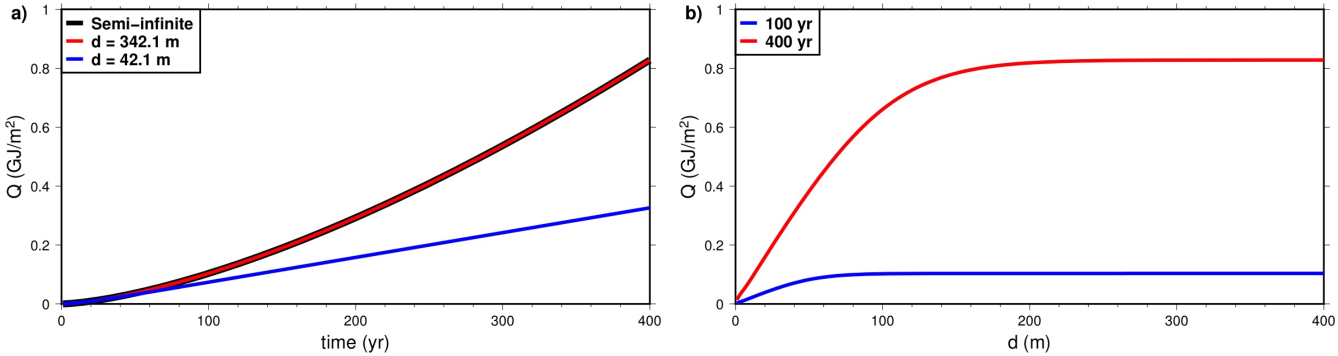

Figure 2. Heat absorbed by the land column per unit of area (Q), following the start of a linear surface temperature increase of 0.01 K yr^{-1}. a): Q as a function of time for the half space model and two models of finite thicknesses 42.1 m and 342.1 m. b): Q as a function of the thickness d of the finite model, at 100 yr and 400 yr.

~~Figure 2a shows that the~~ The heat absorbed per unit of area for the 42.1 m model is slightly smaller than that of the half space model after 100 yr and less than half after 400 yr, while for the 342.1 m model no difference can be observed ~~.~~ (Fig. 2~~b shows how the~~ a). The heat absorbed after 100 yr or 400 yr increases with the thickness of the model, but reaches a plateau where further increase in thickness does not affect heat storage ~~.~~ (Fig. 2b). A bottom boundary depth of 342.1 m is enough for a simulation lasting 400 yr~~, but a~~ . A bottom boundary depth ~~of 42.1 m is not adequate~~ $d = 100$ m is enough for a simulation of 100 yr~~.~~ , as the heat absorbed by the land column does not rise much with further increasing d. A simulation of 400 yr, 4 times longer, needs a bottom boundary depth of $d = 200$ m, only twice as much as 100 yr (Fig. 2b).

The heat equation (1) shows a scaling relationship between ~~bottom boundary depth~~ distance d and time t, $d \propto \sqrt{\kappa t}$. This relation can be used as a first order estimate of the depth where the lower boundary does not affect the thermal profiles for a given duration of the simulation and a value of the thermal diffusivity κ. ~~Fig. 2b shows that a bottom boundary depth $d = 100$ m is enough for a simulation of 100 yr, as the heat absorbed by the land column does not increase much with increasing d. A simulation of 400 yr, 4 times longer, needs a bottom boundary depth of $d = 200$ m, only twice as much.~~

2.1 Geothermal gradient

In the conductive regime described by Eq. (1), the subsurface temperature at a depth z is ~~given as a combination~~ the superposition of the geothermal temperature gradient and the temperature perturbation T_t induced by a time-varying temperature signal at the surface:

$$T(z,t) = T_0 + q_0 \frac{z}{\lambda} + T_t(z,t)\,, \tag{6}$$

where T_0 is the the mean surface temperature, q_0 is the geothermal heat flux~~and~~ , z/λ is the thermal depth and λ is the thermal conductivity of the subsurface.

The propagation into the subsurface of an harmonic temperature signal such as the annual air temperature cycle is characterized by exponential amplitude attenuation $\exp(-\sqrt{\frac{\omega}{2\kappa}}z)$ (Carslaw and Jaeger, 1959), where ω is the frequency of the signal and κ is the thermal diffusivity. At depths of $3-4$ m, the amplitude of the annual signal is several degrees. Given the small values ($\approx 0.02\ \mathrm{K\ m^{-1}}$) of the geothermal temperature gradient in the continents (Jaupart and Mareschal, 2010), the temperature near the surface is dominated by the surface signal T_t. Therefore it may seem reasonable to neglect the geothermal gradient for a thin subsurface layer used in land models (Schmidt et al., 2014; Wu et al., 2014). However, the geothermal temperature gradient can still be influential, even at shallow depths, for temperature-sensitive regimes of subsurface such as permafrost, and it is necessary to determine the lower limit of permafrost. In the case of the CLM4.5 with a subsurface thickness of 42.1 m, the temperature at the bottom of the model is increased by ~~≈ 0.8 K~~ ~ 0.84 K by a geothermal gradient of $0.02\ \mathrm{K\ m^{-1}}$. If we were to further increase the thickness of the subsurface, the temperature at the bottom of the model would ~~increase~~ rise proportionally.

3 Methodology

3.1 Original Land Model

The Community Earth System Model version 1.2 (CESM1.2) is a coupled ESM, consisting of components representing the atmosphere, land, ocean, sea-ice and land-ice. Individual components can be run separately, taking the necessary inputs from prescribed datasets. Because running the coupled model is computationally expensive, we have run only the LSM CLM4.5 ~~(Bonan et al., 2013)~~ (Oleson et al., 2013) , forced with prescribed atmospheric inputs (Viovy (2018); Thomson et al. (2011); Riahi et al. (2011), see section 3.5.2). These inputs are precipitation, solar radiation, wind speed, surface pressure, surface specific humidity, Surface Air Temperature (SAT) and atmospheric concentrations of aerosols and CO_2.

Carbon and nitrogen cycles are included in the CLM4.5 through the BioGeoChemistry (BGC) module, which includes a methane module (Riley et al., 2011). CLM4.5-BGC can be run at several spatial resolutions. We have used the intermediate resolution $1.89°\mathrm{lat} \times 2.5°\mathrm{lon}$ ~~that allows us to compromise between grid fineness and computational requirements~~as the trade-off between resolution and computational efficiency. We used the default timestep of 30 minutes (Kluzek, 2013).

The subsurface is discretized in 15 horizontal layers with exponentially ~~deeper~~ increasing node depths:

$$z_i = f_S \left\{ \exp[0.5(i-0.5)] - 1 \right\}, \tag{7}$$

where $f_S = 0.025$ m is the scaling factor. Layer thickness Δz_i is:

$$\Delta z_i = \begin{cases} 0.5(z_1 + z_2) & i = 1 \\ 0.5(z_{i+1} - z_{i-1}) & i = 2...14 \\ z_{15} - z_{14} & i = 15 \end{cases}. \tag{8}$$

The total thickness of the model is 42.1 m. The upper 10 layers, to a depth of 3.8 m, are soil layers where biogeochemistry and hydraulic processes take place. The lower 5 layers are the bedrock, where the only process is thermal diffusion. The soil in each land column has a vertically-uniform clay/sand/silt composition and a vertically-variable carbon density ~~,~~ which determines its ~~thermal and hydraulic properties~~ hydraulic properties and, along with its time-varying water content, its thermal properties. Bedrock layers, assumed to be made of saturated granite (without pores or interstices that could absorb water), are uniform both ~~horizontal~~ horizontally and vertically. The thermal properties for bedrock in CLM4.5 ~~, assumed to be made of saturated granite,~~ are a thermal conductivity $\lambda = 3\ \mathrm{W\ m^{-1}\ K^{-1}}$ and a volumetric heat capacity $c = 2 \times 10^6\ \mathrm{J\ m^{-3}\ K^{-1}}$, which give a thermal diffusivity $\kappa = \lambda / c = 1.5 \times 10^{-6}\ \mathrm{m^2\ s^{-1}}$ ~~(Clauser and Huenges, 1995))~~(Oleson et al., 2013) .

As the horizontal dimensions of the grid are much larger than the thickness of the subsurface, horizontal heat conduction is considered negligible and thermal diffusion is considered only in the vertical direction as described in Eq. (1). The land subsurface is thermally forced at the surface by its interaction with the atmosphere through latent and sensible heat fluxes, and short and longwave radiation. At the bottom boundary, the model ~~assumes no heat flux~~ uses a zero heat flux condition, which we will modify to experiment with several values of geothermal heat flow.

The hydrology model in CLM4.5 parameterizes interception, throughfall, canopy drip, snow accumulation and melt, water transfer between snow layers, infiltration, evaporation, surface runoff, subsurface drainage, redistribution within the soil column, and groundwater discharge and recharge. The vertical movement of water in the soil is determined by hydrological properties of the soil layers, which can be altered by their ice content as this reduces the effective porosity of the soil. The model also includes an artificial aquifer with a capacity of 5 m below the soil column, from which discharge is calculated. This aquifer is treated as a virtual layer, because it does not interact with the bedrock and it does not simulate any physical process, except for acting as a storage of water percolated from the soil, and draining water to the river transport model.

The parametrization of snow in CLM4.5 follows the approaches of Anderson (1976) , Jordan (1991) and Yongjiu and Qingcun (1997) . The snow consists of up to 5 layers, whose number and thickness increase with the thickness of the snowpile. Thermal conduction in these layers works like in soil layers, with the thermal properties of ice and water. The model includes fractional snow cover following the method of Swenson et al. (2012) , and phase transitions between ice and water in the soil and snow layers.

3.2 Carbon model

The Community Land Model version 4 (CLM4) includes a representation of the carbon and nitrogen cycles (CLM4CN) largely based on the ecosystem process model Biome-BGC (Biome BioGeochemical Cycles) ~~(Running and Hunt, 1993)~~ (Koven et al., 2013a; Runn which is an extension of the previous model Forest-BGC (Running and Gower, 1991). Forest-BGC simulates water, carbon, and nitrogen fluxes in forest ecosystems, which Biome-BGC expanded with more mechanistic descriptions of photosynthesis and by including more vegetation types in its parameterizations. Later versions of Biome-BGC (Thornton et al., 2002) developed the mechanistic calculations of carbon and nitrogen cycles in the soil, control of photosynthesis by nitrogen, differentiation of sunlit/shaded canopies, calculation of fire and harvest, and regrowth dynamics.

In CLM4.5 ~~(Bonan et al., 2013)~~ (Oleson et al., 2013) , we work with the BGC carbon model (Riley et al., 2011). The BGC model expands the Carbon-Nitrogen (CN) model by adding a ~~submodel~~ module of production, oxidation and emission of methane. CLM4.5 also includes updates to photosynthesis, vegetation and hydrology ~~from~~ in CLM4. This improves carbon treatment in CLM4.5-BGC significantly over CLM4CN.

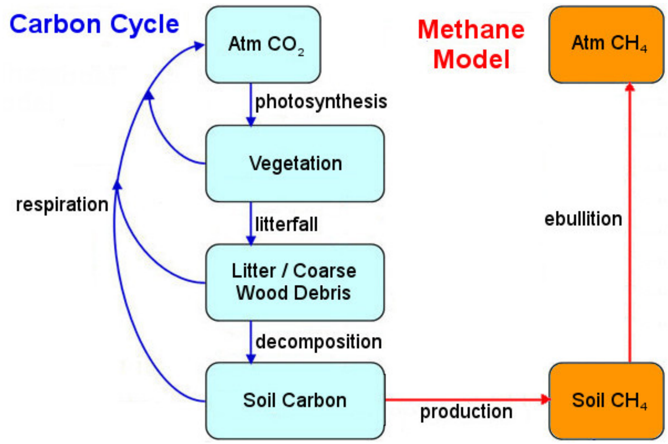

Figure 3. Schema of the carbon flux in CLM4.5-BGC. Figure redrawn from ~~UCAR (2016)~~ Oleson et al. (2013) .

As the ~~schema~~ flow-chart in Fig. 3 shows, there are three main carbon pools in CLM4.5-BGC: the vegetation, the litter (and coarse wood debris), and the soil organic matter (or soil carbon). These pools are subdivided into several sub-pools. The vegetation has distinct pools to account for the different tissues of the plants: leafs, dead/live stems, live/dead coarse roots, fine roots, and ~~storage pools~~a internal storage pool (from where plants can take carbon when they can not photosynthesize). Litter and carbon are each defined in the same 10 ~~vertical~~ horizontal soil layers used for hydrology, and with 3 separate pools each (corresponding to increasingly recalcitrant forms of carbon) arranged as a converging cascade from coarse wood to litter to soil, a structure known as the Century Soil Carbon pool structure ~~(Bonan et al., 2013)~~ (Oleson et al., 2013) .

The methane model (Fig. 3) produces CH_4 in the anaerobic fraction of the soil ~~, which~~ in a land cell (which can be fractionally inundated in CLM4.5), that consists of the entire soil in the inundated portion of ~~a~~ the land cell, and the fraction of soil bellow the water table in the non-inundated portion. The CH_4 ~~stays~~ is produced in the inundated soil where ~~is produced~~ it stays for a short time ~~, until it rises to the atmosphere by ebullition~~until it evaporates into the atmosphere (Wania et al., 2010) . Thus, the production of methane is closely correlated with the hydrology model. In the CLM4.5 hydrology model, the land can store water within the soil (with a thickness of 3.8 m globally, but variable hydrological properties ~~due to its~~ depending on composition) and in an unconfined aquifer with a capacity of ~~5000 mm globally, implemented~~ 5 m globally, treated as a virtual layer (which does not interact with the subsurface other than to store water) beneath the soil. In reality, soil thickness is highly variable worldwide, ~~in some areas~~ reaching depths of hundreds of meters in some areas, while the global mean is estimated ~~at~~ to be $\approx$ 13 m (Shangguan et al., 2017).

3.3 Modifications of the original model

We made two main modifications to the LSM. First, we increased the thickness of the bedrock and the depth of the lower boundary. Second, we assumed uniform and constant heat flux as bottom boundary condition. Increasing the thickness of the LSM is necessary to reduce the effect of the lower boundary on the temperature profile. The non-zero heat flux adds the geothermal gradient to the temperature profiles of the subsurface, which ~~allows~~ is needed to determine the lower limit of permafrost in the land column.

We increased the thickness d of the subsurface by progressively adding new layers of constant thickness at the bottom of the land column, to obtain a set of model versions with increasing values of d. The thickness of the added layers must be small to fine tune the depth of the bottom boundary. However, the size of the set is limited by our computational resources, as we aim to increase the depth of the bottom boundary by several hundred meters. As a compromise, we used 12.5 m as the thickness of these new layers. The ~~lowest~~ value of d in the original model is 42.1 m (no additional layers~~, corresponding to the original model~~) and its highest value is 342.1 m (24 additional layers, with a total thickness of 300 m). In addition, we created a model of reduced thickness $d = 3.8$ m by eliminating all the bedrock layers in CLM4.5. This does not affect hydrology or any process other than thermal diffusion, because the aquifer is a virtual layer and it does not interact with the bedrock layers.

The bottom boundary condition of the LSM is changed to a worldwide uniform value of heat flux. While the continental heat flux is spatially variable, we lack heat flux measurements in wide areas of the world such as South America, Asia and Africa and the Northern Hemisphere permafrost ~~region where heat flux is most important~~regions. We use several values of heat flux ~~0, 0.02, 0.04, 0.06 and 0.08 W m^{-2}~~ 0, 20, 40, 60 and 80 mW m^{-2} to cover the range of heat flow values observed in stable continents (Jaupart and Mareschal, 2010).

3.4 Permafrost treatment

We define a subsurface layer as permafrost if it remains 2 consecutive years below 0 °C. This definition does not account for the water/ice content of a layer, as we also want to define permafrost in the bedrock layers where no water is present. As the ice content in the soil hinders the movement of liquid water within it, permafrost is closely linked with the hydrology model.

Near surface permafrost is commonly defined as the permafrost present within the upper 3 m of the soil (Nicolsky et al., 2007; Koven et al., 2011; Schuur et al., 2015), but this depth can be different for some land models where the soil depth is larger than 3 m (Lawrence and Slater, 2005). As in CLM4.5 the soil layers make the upper 3.8 m of the land column, we define near-surface permafrost as the permafrost present above this depth.

Because natural soils can reach deeper than the 3.8 m used in CLM4.5, we aim at gaining some insight on how bottom heat flux and model thickness affect permafrost deeper than 3.8 m. However, it is outside the scope of this study to ~~implement~~ introduce a realistic soil thickness in CLM4.5. For this reason we will also study the permafrost present between the surface and a depth of 42.1 m, the thickness of the ~~thinnest of our model versions~~CLM4.5 subsurface, which we define as intermediate-depth permafrost.

While near-surface permafrost and intermediate-depth permafrost define permafrost within a depth range, to study the maximum depth of the top of the permafrost we use the concept of Active Layer Thickness (ALT). In environments containing permafrost, the active layer is the upper layer of soil that thaws during summer. The ALT is the maximum depth at which annual temperature variations at the surface are able to thaw the soil, which coincides with the upper limit of permafrost. ALT provides ~~a more complete~~ information on permafrost ~~than the areal extentof soil permafrost~~complementary to its areal extent, as variations in the thermal regime of the subsurface can displace the upper limit of permafrost in the soil and therefore ALT, but be too small to ~~switch the presence of permafrost within~~ completely thaw the permafrost within the soil.

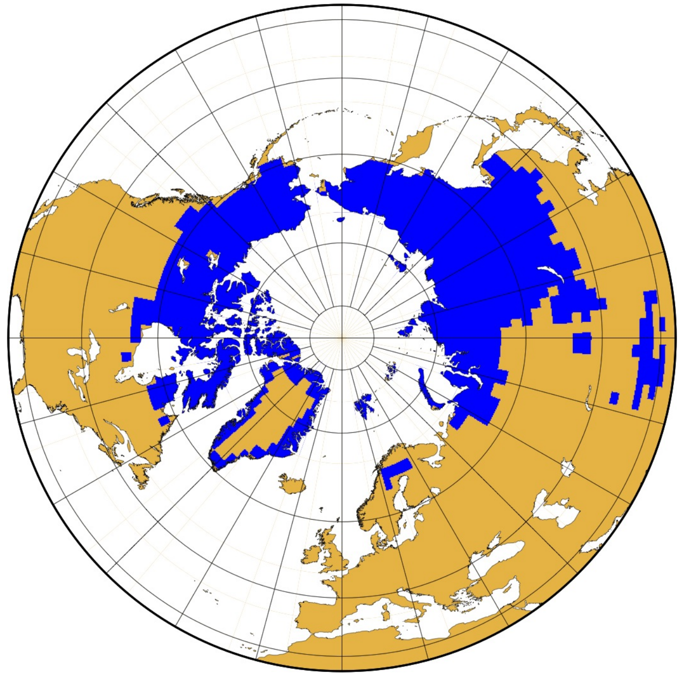

Figure 4. Region of study (blue), which corresponds to the extent of near-surface permafrost in the Northern Hemisphere in the year 1901, for the original CLM4.5 model.

We are interested in how the modifications to the bottom boundary produce changes in the carbon pools of the permafrost region, ~~but~~ and how the areal extent of the permafrost region evolves in time. To avoid ambiguities, we define ~~a constant~~ the region of study ~~,~~ as the region of the Northern Hemisphere where near-surface permafrost is present at the initial time of the simulations ~~(~~in 1901 CE (Fig. 4). This region ~~is shown in Fig. 4, and~~ covers parts of ~~North~~ Northern Canada, Alaska, Siberia, Tibet, Inner Scandinavia, and the coast of Greenland. The interior of Greenland, covered by glaciers, is ~~not included~~ represented in CLM4.5 ~~but it is part of the~~ as a column of ice of thickness 42 m to simulate the surface mass balance of the glacier and pass this information to the land-ice model of CESM1.2, but it does not represent the soil below the glacier.

3.5 Simulations

3.5.1 Initialization of the model

We follow the standard spinup procedure (Kluzek, 2013), where the model is initialized with arbitrary pre-initial conditions (no vegetation and uniform subsurface temperature) and driven by a spinup simulation to a steady state (vegetated world adapted to the atmospheric forcings), which ~~can be~~ are used as initial condition for the simulation. The spinup period required for the initialization of the model depends on the carbon component used by the LSM. In the case of the CLM4.5-BGC, the spinup runs 1000 yr with accelerated decomposition rates (which reduces computational costs and performs consistently well (Thornton and Rosenbloom, 2005)) followed by at least 200 yr with normal decomposition rates. During the spinup phase, we use atmospheric forcings (described in section 3.5.2) that correspond to those of the initial years of the simulation, 1901 to 1910.

Increasing the depth d of the bottom boundary introduces an additional difficulty to the spinup of the model. In the standard spinup procedure, every soil layer is initialized with a temperature of 274 K independent of the grid cell location, then ~~adapts to~~ reaches the steady state determined by the local surface boundary conditions during the spinup. For a subsurface thickness of $d = 42.1$ m, 1200 yr of spinup are enough for the subsurface to adapt to the steady state. However, the time needed for the subsurface to reach the steady state is proportional to d^2, and 1200 yr is insufficient for the thickest subsurface models. Lengthening the spinup time for each model of ~~increasing~~ thickness d would make computational costs prohibitive.

To avoid this problem, we only use the standard spinup procedure for the model with the original bottom boundary depth, $d = 42.1$ m. The initial conditions for the models with $d > 42.1$ m are obtained by ~~extrapolating downwards~~ downward continuing the temperature of the 15th layer with the geothermal gradient ~~of the subsurface~~used as bottom boundary condition ($0\ \mathrm{mW\ m^{-2}}$ for our experiments with modified d). This approach is possible because there are no other variables than temperature in bedrock layers, such as water or carbon content. In addition, as these models ~~depart~~ start from a common initial state, we can determine any difference in the final state ~~of these models as dependent from~~ as due to the parameter d exclusively~~, without the influence of the initial state~~.

~~The models with different basal heat flux F_B at the original bottom boundary depth, are individually initialized with the standard spinup procedure. It is not possible to use a common initial condition for these models, because the thermal steady state is dependent on F_B.~~

3.5.2 Simulation of the 1901-2300 period

Each version of the LSM is run offline between 1901 CE and 2300 CE, taking prescribed atmospheric variables from external sources as input to force the model. These simulations include two phases depending on the input used, (1) between 1901-2005, from reanalysis of historical data, and (2) between 2006-2300, from the IPCC climate projection under two warming scenarios (Thomson et al., 2011; Riahi et al., 2011).

The first phase is a historical 20th century simulation between 1901-2005. The forcing data are taken from the CRUNCEP dataset (Viovy, 2018), combination of the Climate Research Unit Time-Series (CRU-TS) monthly climatology (Harris et al., 2014) and the National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al., 1996) between the years 1901 and 2005.

The second phase continues the first phase between 2006-2300, ~~forcing~~ forces the LSM with the atmospheric output from a simulation for a specific trajectory of greenhouse gas concentration. These trajectories, called Representative Concentration Pathways (RCPs), are based on scenarios of future human emissions and provide a basis to the climate research community for modeling experiments in the long and short terms (Van Vuuren et al., 2011).

We use two scenarios, RCP 4.5 and RCP 8.5, ~~which divide~~ for our simulations after 2005. RCP 4.5 is an mitigation scenario of anthropogenic emissions where radiative forcing reaches $4.5\ \mathrm{W\ m^{-2}}$ in 2100 (Thomson et al., 2011). In comparison, RCP 8.5 is a high emissions scenario of considerable increase of greenhouse gas emissions and concentrations, leading to a radiative forcing of $8.5\ \mathrm{W\ m^{-2}}$ at the end of the 21st century (Riahi et al., 2011).

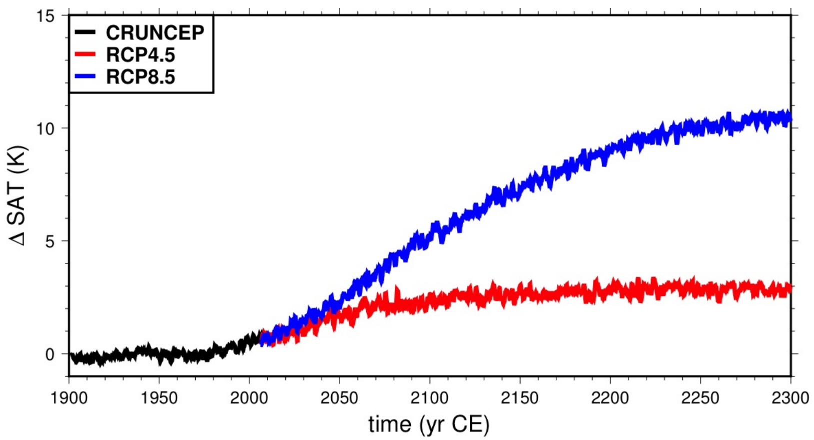

Figure 5. Mean SAT over land relative to the 20th century mean, from the CRUNCEP dataset (black) and the RCP 4.5 (red) and RCP 8.5 (blue) scenarios. Data taken from Viovy (2018); Thomson et al. (2011); Riahi et al. (2011).

Forcing datasets of monthly averages are provided by the Earth System Grid (Stern, 2013) for both scenarios. To produce 6h-resolution datasets suitable for CLM4.5, we calculated the 6h-anomalies to monthly average for temperature and precipitation in the years 1996-2005 of the CRUNCEP dataset, and added this 10 yr series of anomalies to the monthly datasets cyclically, starting in 2006. The 6h-resolution datasets produced this way were then used to force the land system between 2006-2300 for the two scenarios. The mean SAT over the land area for the duration of our simulation time is shown in Fig. 5. The mean SAT ~~at 2300~~ in the last decade 2290-2300 is ≈ 2 K higher than in ~~2005~~ the decade 2000-2010 for the RCP 4.5 scenario, while ~~in~~ for the RCP 8.5 scenario temperature rises ≈ 9.5 K~~for the same period~~.

4 Results

4.1 Heat storage

4.1.1 Effect of the depth of the bottom boundary

~~Given the continuous increase in mean forcing seen in Fig. 5, we can expect the subsurface temperatures to behave as discussed in section 2. If the subsurface is shallow, the bottom boundary of the reflects energy back to the surface instead of propagating it downwards. As explained in section 2, the total energy that is reflected back to the surface increases with time and decreases with the depth d of the bottom boundary. The obtained results are summarized in Table 1.~~

Table 1. Heat stored in the subsurface since 1901 CE at the years 2000, 2100, 2200 and 2300 CE for the RCP 4.5 and RCP 8.5 scenarios.

		RCP 4.5			RCP 8.5		
d (m)	ΔH 1901-2000 (ZJ)	ΔH 1901-2100 (ZJ)	ΔH 1901-2200 (ZJ)	ΔH 1901-2300 (ZJ)	ΔH 1901-2100 (ZJ)	ΔH 1901-2200 (ZJ)	ΔH 1901-2300 (ZJ)
3.8	2.20	4.99	4.86	4.83	6.60	9.66	10.89
42.1	6.03	24.14	26.91	27.74	44.41	78.13	92.64
92.1	7.31	41.12	53.91	57.84	69.90	148.01	191.37
142.1	7.63	45.96	69.59	81.52	75.65	178.98	255.66
192.1	7.66	46.81	75.02	93.67	76.59	187.63	282.66
242.1	7.66	46.94	76.35	98.15	76.73	189.52	291.36
292.1	7.66	46.95	76.67	99.60	76.74	189.89	293.77
342.1	7.66	46.96	76.75	100.00	76.72	189.92	294.31

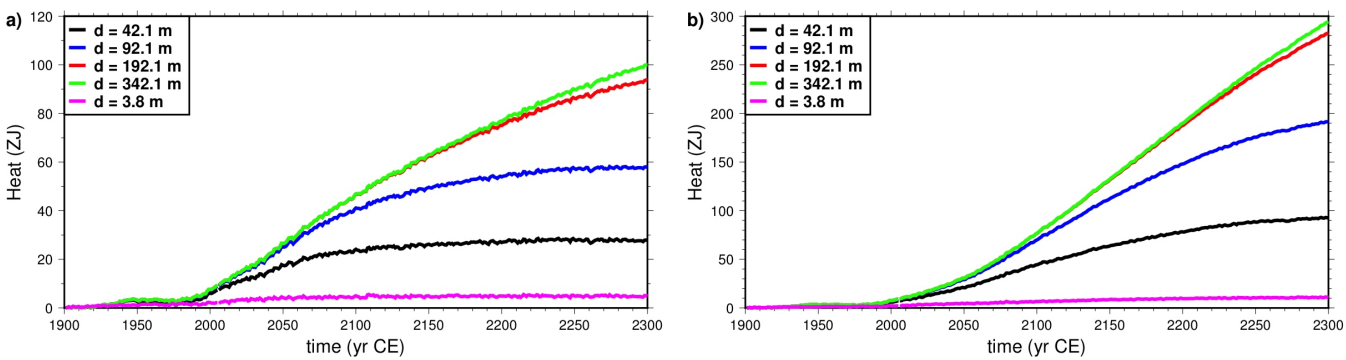

Figure 6. Heat stored in the subsurface as function of time, for models of subsurface thickness d of 42.1 m (black), 92.1 m (blue) 192.1 m (red)~~and~~ , 342.1 m (green) and 3.8 m (magenta). a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data. Note the scale difference between scenarios RCP 4.5 and RCP 8.5.

~~Figure 6 shows how the heat~~ The results summarized in Table 1 confirm the calculations of the absorption of heat by the subsurface discussed in section 2. The heat absorbed by the subsurface varies with time between models of different subsurface thickness d ~~.~~ (Fig. 6). If the bottom boundary is too shallow, the thermal signal from the surface reaches the bottom boundary and further absorption of heat is hindered. For the original depth of the CLM4.5, $d = 42.1$ m, ~~we see that~~ after 100 yr its subsurface absorbs considerably less heat than for the deeper models. As we progressively increase the thickness of the subsurface, this effect is reduced and delayed. By the end of the simulation, the thickest model ($d = 342.1$ m) has absorbed 72 ZJ (72×10^{21} J) in the RCP 4.5 scenario and 201 ZJ in the RCP 8.5 scenario, which are respectively ~~260% and 217% of~~ 3.6 and 3.17 times the heat stored by the ~~thinnest model in these scenarios~~original model. If compared to the thinnest model (3.8 m) instead, the thickest model absorbs 20 and 27 times more heat.

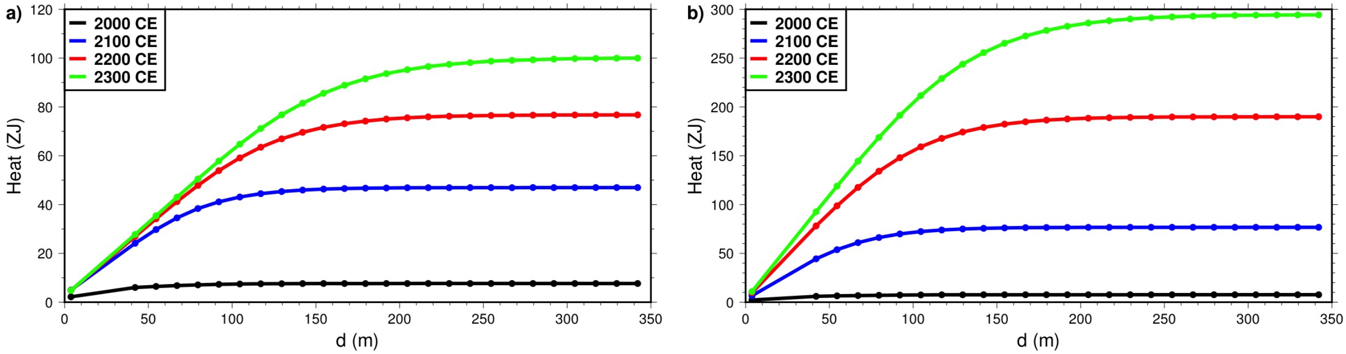

Figure 7. Heat stored in the subsurface as function of subsurface thickness, at the years 2000 (black), 2100 (blue), 2200 (red) and 2300 (green). a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data. Note the vertical scale difference between ~~scenarios 4.5 and 8.5~~the two panels.

~~The influence of d on the subsurface heat storage is clearly displayed in Fig. 7.~~ At a given time, the heat absorbed by the subsurface increases with the depth of the bottom boundary d of the model ~~.~~ (Fig. 7). The amount of heat is not proportional to d and levels off when d increases past ~~some value~~a specific threshold. This value is the thickness required by the model to keep the heat absorbed close to the maximum absorbed by the half space. ~~If we define this threshold as~~ For a threshold of 95%, this depth ~~would be~~ is $\approx$ 90 m if the simulation runs for 100 yr (until 2000 CE). If we look at the heat absorbed after 400 yr, this ~~threshold~~ depth is $\approx$ 200 m in the RCP 4.5 scenario (Fig. 7a), and $\approx$ 180 m in the RCP 8.5 scenario (Fig. 7b), which confirms the theoretical estimates. This difference shows that the SAT forcing, dependent on the scenario, has only a small influence on the threshold. It is ~~mostly~~ determined by the heat conduction time across a layer of thickness d, that is the relationship $d \propto \sqrt{\kappa t}$ deduced from Eq. (5)~~for the perturbation to the thermal profile~~.

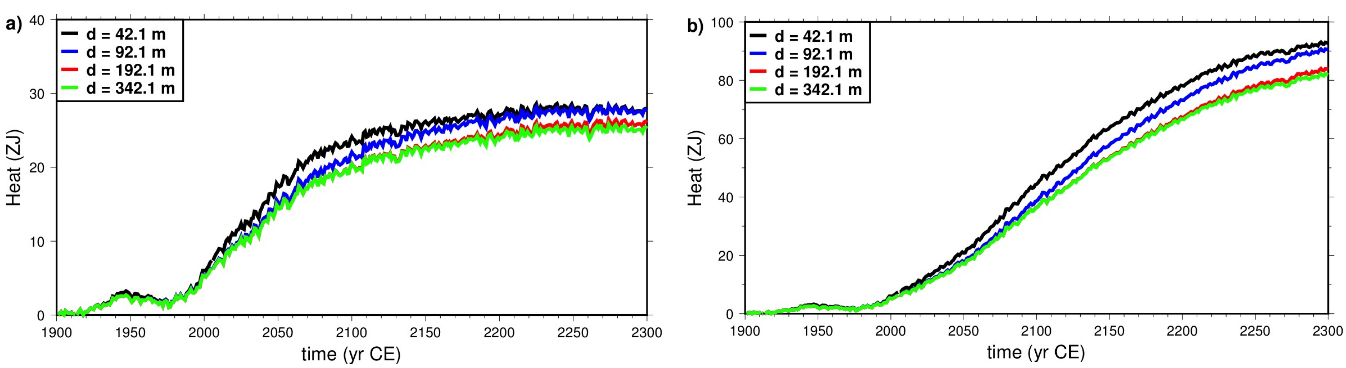

Figure 8. Heat stored in the upper 42.1 m as function of time, for models of subsurface thickness d of 42.1 m (black), 92.1 m (blue) 192.1 m (red) and 342.1 m (green). a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data. Note the vertical scale difference between ~~scenarios 4.5 and 8.5~~the two panels.

Deepening the bottom boundary below 42.1 m also affects the storage of heat within the layers above (Fig. 8). The thermal signal is reflected by the bottom boundary, further heating the region above, but as we increase d, this additional heat decreases. For the thickest model ($d = 342.1$ m), the upper 42.1 m of the subsurface gain 2.5 ZJ less than the thinnest original model in the RCP4.5 scenario (Fig. 8a) and 10.7 ZJ in the RCP8.5 scenario (Fig. 8b), which correspond respectively to a decrease of 9% and of 11.6%.

Table 2. Heat stored in the soil (upper 3.8 m) since 1901 CE at the years 2000 and 2300 CE for the RCP 4.5 and RCP 8.5 scenarios, as function of subsurface thickness d.

			RCP 4.5		RCP 8.5	
d (m)	ΔH 1901-2000 (ZJ)	$\Delta H(d)/\Delta H(42.1)$ 1901-2000	ΔH 1901-2300 (ZJ)	$\Delta H(d)/\Delta H(42.1)$ 1901-2300	ΔH 1901-2300 (ZJ)	$\Delta H(d)/\Delta H(42.1)$ 1901-2300
3.8	2.201	1.2021	4.833	1.0805	10.889	1.0339
42.1	1.831	1	4.473	1	10.532	1
92.1	1.816	0.9917	4.465	0.9984	10.471	0.9942
142.1	1.813	0.9904	4.441	0.9930	10.392	0.9867
192.1	1.817	0.9926	4.427	0.9898	10.348	0.9826
242.1	1.813	0.9904	4.419	0.9879	10.330	0.9809
292.1	1.810	0.9885	4.412	0.9864	10.332	0.9810
342.1	1.814	0.9908	4.411	0.9863	10.321	0.9800

Most of the subsurface is considered as bedrock, where the only heat transport process is thermal diffusion. The region of most interest is the soil, (upper 3.8m) where biogeochemical processes, sensitive to temperature, take place. The heat absorbed by the soil has been summarized in Table 2. Figure S1 shows that the The heat absorbed by the soil is overestimated for the shallow bottom boundary variants of the model in the same manner as heat it was for the upper 42.1 m, however but this effect is much smaller.

The quantitative differences in Fig. S1 Table 2 are small and better analyzed as the heat gained by the soil in each model as relative to the heat gained by the thinnest in the original model (42.1 m thick)(Fig. S2). . Compared to the thinnest original model, the heat stored in the deepest models is $\approx 1\%$ less after 100 years of simulation, and $\approx 1.33\%$ $\approx 1.3\%$ at the end of the RCP 4.5 scenario (Fig. S2a) and $\approx 1.92\%$ and $\approx 2\%$ at the end of the RCP 8.5 scenario(Fig. S2b) . It can be noted that the relative decrease of heat gained by the soil in the deepest models is larger at 2100 CE than at either 2000 CE or 2300 CE. This, as well as for the differences between Figs. S2a and S2b, is . The thinnest model (3.8 m) stores 20% more heat than the original model after 100 yr, a relative difference that is reduced to 8% (RCP 4.5) and 3.4% (RCP 8.5) by the end of the simulations, which shows that decreasing the thickness of the subsurface produces a larger effect on heat storage than increasing it. The differences between scenarios RCP 4.5 and RCP 8.5 are caused by the yearly changes of SAT forcing (Fig. 5), which increases at the fastest rate during the 21st century in both RCP RCP scenarios.

4.1.2 Effect of the bottom heat flux

In a purely conductive thermal regime of the subsurface, the ~~magnitude~~ value of the heat flux used as bottom boundary condition does not affect heat diffusion. This is not the case for the soil, because in CLM4.5 the thermal properties of the soil depend on temperature through the water/ice content. However, because of the shallowness of the soil, the geothermal gradient does not raise soil temperature sufficiently to affect heat propagation. Therefore, while the ~~bottom heat flux increases the heat~~ heat content of the subsurface ~~, it should~~ increases with the lower boundary heat flux, it does not affect its time evolution.

~~The heat content within the subsurface as function of the~~ For the 42.1 m of the subsurface, the bottom heat flux ~~F_B is shown in Fig. S3. The bottom heat flux~~ increases the heat content ~~, adding~~ by 2.058 ± 0.006 ZJ for each ~~$0.02\ \mathrm{W\,m^{-2}}$~~ $20\ \mathrm{mW\,m^{-2}}$. This offset is independent of the forcing scenario and constant in time.

~~If we look at the heat content within~~ The soil (upper 3.8 m) ~~we see~~ exhibits the same behavior as for the upper 42.1 m but with smaller amplitude, ~~as shown in Fig. S4. Heat~~ where heat content is offset by 0.043 ± 0.004 ZJ for every ~~$0.02\ \mathrm{W\,m^{-2}}$~~ $20\ \mathrm{mW\,m^{-2}}$ increase, regardless of the scenario.

This increase of soil heat content due to the bottom heat flux does not translate into a uniform increase of soil temperature across individual cells, because soil composition and thermal properties vary. Each ~~$0.02\ \mathrm{W\,m^{-2}}$~~ $20\ \mathrm{mW\,m^{-2}}$ increase of bottom heat flux increases the temperature of the deepest soil layer (node at depth 2.86 m) by 0.04 ± 0.01 K. Using the mean continental heat flux ~~$0.06\ \mathrm{W\,m^{-2}}$~~ value of $60\ \mathrm{mW\,m^{-2}}$ as bottom boundary condition increases the temperature of the bottom soil layer by 0.12 ± 0.03 K and that of the bottom bedrock layer (node depth at 35.1 m) by 0.8 ± 0.04 K.

4.2 Permafrost

4.2.1 Intermediate-depth Permafrost

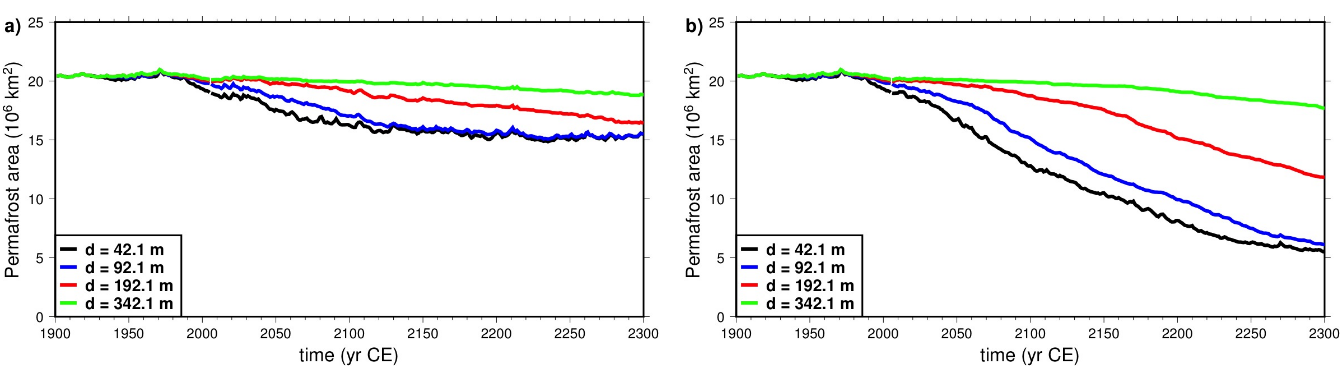

Figure 9. Northern Hemisphere intermediate-depth (0-42.1 m) permafrost area as function of time. Model versions with bottom boundary depth d at 42.1 m (black), 92.1 m (blue) 192.1 m (red) and 342.1 m (green). a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data.

Given the increasing SAT anomalies used to force the model (Fig. 5), we expect to observe a continuous decrease in the area extent of permafrost during the simulation period. The SAT warming signal is expected to propagate ~~into the subsurface~~ downward and, for ~~an excessively~~ a shallow bottom boundary, to be reflected back to the surface, thus overheating the subsurface. ~~Increasing the depth of the~~ A deeper bottom boundary attenuates this effect and therefore decreases the rate of permafrost thawing. Because a shallow ~~bottom~~ lower boundary heats the subsurface from the bottom, this overheating is ~~higher at the bottom of the subsurface~~highest at depth, and the effect on the soil is less noticeable.

In our ~~experiments~~simulations, the area with intermediate-depth permafrost in the Northern Hemisphere (Fig. 9) has an initial areal extent of 20.4×10^6 km^2 in 1901. At the end of the RCP 4.5 scenario, this area has been reduced by 4.94×10^6 km^2 (24.1% of the initial area) for the ~~thinnest~~ original model and by 1.59×10^6 km^2 (7.8%) for the thickest model. For the RCP 8.5 scenario, the area losses of intermediate-depth permafrost are 14.85×10^6 km^2 (72.7%) for the ~~thinnest~~ original model and 2.74×10^6 km^2 (13.4%) for the thickest model.

For both scenarios, the decrease of intermediate-depth permafrost area becomes smaller as we increase the depth of the bottom boundary (Fig. ~~S5~~9). Each increase of the thickness of the subsurface produces diminishing returns, reaching a plateau where the permafrost area is not affected by a further increase of the bottom boundary depth. The depth at which this plateau is reached increases with the length of the simulation, and by the end of the simulations at 2300, it exceeds the largest bottom boundary depth (342.1 m) used in our versions of the model. Table 3 summarizes the evolution of intermediate-depth permafrost for the original CLM4.5 and the modified versions of $d = 342.1$ m and $F_B = 80$ mW m^{-2}.

Table 3. Areal extent of intermediate-depth permafrost at 1901 CE, 2000 CE and 2300 CE for the RCP 4.5 and RCP 8.5 scenarios.

Subsurface parameters		CRU-NCEP		RCP 4.5		RCP 8.5	
d (m)	F_B (~~W m^{-2}~~mW m^{-2})	PF area 1901 ($\times 10^6$ km^2)	PF area 2000 ($\times 10^6$ km^2)	PF area 2300 ($\times 10^6$ km^2)	Fraction PF lost 1901-2300 (%)	PF area 2300 ($\times 10^6$ km^2)	Fraction PF lost 1901-2300 (%)
42.1	0	20.43	19.33	15.49	24.18	5.58	72.68
42.1	~~0.08~~ 80	19.85	18.65	14.72	25.84	5.11	74.25
342.1	0	20.43	20.21	18.84	7.78	17.69	13.41

The addition of a non-zero heat flux boundary condition at the LSM's bottom boundary has a small effect on intermediate-depth permafrost area (~~Fig. S6~~Table 3). The initial extent of intermediate-depth permafrost ~~at 1901 appears~~ is reduced by $0.15 \pm 0.07 \times 10^6$ km^2 (0.7%) for every increase of ~~0.02 W m^{-2}~~ 20 mW m^{-2} in F_B. This difference does not remain constant during the simulation, each increase ~~0.02 W m^{-2}~~ 20 mW m^{-2} of F_B ~~decreases~~ reduces the intermediate-depth permafrost area at the end of the simulation by $0.19 \pm 0.14 \times 10^6$ km^2 in the RCP 4.5 scenario ~~(Fig. S6a)~~ and by $0.12 \pm 0.05 \times 10^6$ km^2 in the RCP 8.5 scenario, a ~~relative decrease of 1.2% and 2.1% respectively(Fig. S6b).~~ decrease relative to the initial permafrost extent of 2.1% and 1.2% respectively.

4.2.2 Near-surface permafrost

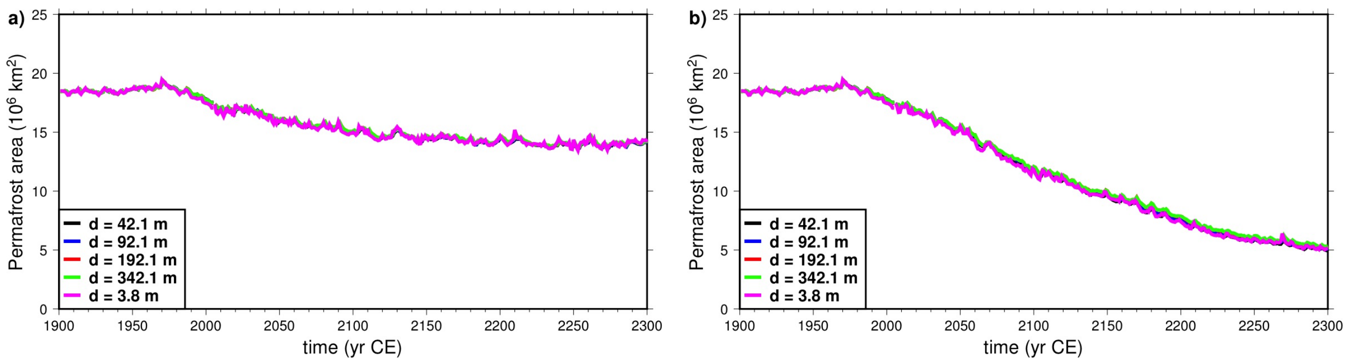

Figure 10. Northern Hemisphere near-surface permafrost area as function of time. Model versions with bottom boundary depth at 42.1 m (black), 92.1 m (blue) 192.1 m (red)~~and~~ , 342.1 m (green) and 3.8 m (magenta). a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data.

The near-surface permafrost (within the upper 3.8 m) area in the Northern Hemisphere is much less affected by the thickness of the model than the intermediate-depth permafrost (Fig. 10). The initial extent of near-surface permafrost is 18.45×10^6 km^2, and by 2300 under the RCP 4.5, this area has been reduced by 4.27×10^6 km^2 (23.1%) for the ~~thinnest~~ original model and 4.20×10^6 km^2 (22.7%) for the thickest model, a relative difference of ~~1.6~~1.8%. In the RCP 8.5 case, the permafrost area is reduced by 13.37×10^6 km^2 (72.5%) for the ~~thinnest~~ original model and 13.11×10^6 km^2 (71.1%) for the thickest model, an area decrease 1.9% smaller. Reducing the thickness of the model to 3.8 m only produces differences in the order of 0.5-1.1% for the areal extent of near-surface permafrost.

Table 4. Areal extent of near-surface permafrost at 1901 CE, 2000 CE and 2300 CE for the RCP 4.5 and RCP 8.5 scenarios.

Subsurface parameters		CRU-NCEP		RCP 4.5		RCP 8.5	
d (m)	F_B (~~W m^{-2}~~mW m^{-2})	PF area 1901 ($\times 10^6$ km^2)	PF area 2000 ($\times 10^6$ km^2)	PF area 2300 ($\times 10^6$ km^2)	Fraction PF lost 1901-2300 (%)	PF area 2300 ($\times 10^6$ km^2)	Fraction PF lost 1901-2300 (%)
3.8	0	18.45	17.40	14.13	23.41	5.12	72.25
42.1	0	18.45	~~17.8~~ 17.80	14.17	23.17	5.07	72.49
42.1	~~0.08~~ 80	18.25	17.09	13.80	24.40	4.90	73.15
342.1	0	18.45	~~17.5~~ 17.76	14.25	22.75	5.34	71.07

The effect of the bottom heat flux F_B on near-surface permafrost area is similar to that on intermediate-depth permafrost, but quantitatively smaller (~~Fig. S7~~Table 4). Each ~~0.02 W m^{-2}~~ 20 mW m^{-2} increase reduces the initial near-surface permafrost extent by $0.05 \pm 0.04 \times 10^6$ km^2 (0.3%). At 2300, this ~~difference is $0.09 \pm 0.8 \times 10^6$ km^2~~ increase in bottom heat flux reduces the final permafrost extent by $0.09 \pm 0.08 \times 10^6$ km^2 (0.6%) for the RCP 4.5 scenario and by $0.04 \pm 0.01 \times 10^6$ km^2 (0.8%) for the RCP 8.5 scenario~~(Fig. S7b)~~. The results for the original CLM4.5 and the modified versions of $d = 3.8$ m, $d = 342.1$ m and $F_B = 80$ mW m^{-2} are summarized in Table 4.

The initial state of the subsurface in 1901 is identical for model versions with different subsurface thickness, provided they use the same bottom heat flux. The temperature of the upper subsurface increases at a slower rate for a deeper bottom boundary, thus the ALT increases at a slower rate for model versions ~~of~~ with deeper subsurface. At the end of the simulations in 2300, the ALT is ~~visibly~~ in some areas larger for the original model (42.1 m) than for the model ~~of subsurface~~ with thickness increased to 342.1 m and smaller than for the model with thickness of 3.8 m, for both scenarios (Fig. 11).

The bottom heat flux increases temperature ~~proportional~~ proportionally to the flux and the depth. Therefore, bottom heat flux does not alter ALT if permafrost is shallow. Where ALT is large, the ~~increase in~~ higher temperature due to the bottom heat flux is enough to induce thawing and lower the upper limit of permafrost (Fig. 11).

4.3 Carbon

4.3.1 Soil Carbon

The size of the soil carbon pool increases during the first ≈ 150 yr of simulation and thereafter begins decreasing, losing during the period 1901-2300 a total of 5.6 PgC in the RCP 4.5 scenario and 41.2 PgC in the RCP 8.5 scenario, for the original model. Increasing the depth of the bottom boundary reduces the loss of soil carbon, as expected because it slows the rate of permafrost thawing. The loss of soil carbon for the thickest subsurface (342.1 m) is 0.15 PgC (3.6%) less than for the ~~thinnest~~ original subsurface model (42.1 m) in the RCP 4.5 scenario, and 0.56 PgC (1.3%) less in the RCP 8.5 scenario (Fig. 12). Decreasing the subsurface thickness to 3.8 m produces a much larger effect, with soil carbon decreasing by 7.66 PgC (RCP 4.5) and 43.02 PgC (RCP 8.5) during the simulation, which amounts to an increase of the soil carbon lost in the period 1901-2300 of 35% (RCP 4.5) and 4.4% (RCP 8.5), relative to the original model.

Increasing the bottom heat flux F_B slows down the rate at which soil carbon in the permafrost region decreases during the simulation. An increase of ~~0.02 W m^{-2} decreases~~ 20 mW m^{-2} reduces the loss of soil carbon between 1901 and 2300 ~~and~~ by 0.3 ± 0.1 PgC (5.6% of the decrease of soil carbon in this period for the original CLM4.5) in the RCP 4.5 scenario and 0.45 ± 0.2 PgC (1.1%) in the RCP 8.5 scenario (Fig. 13).

~~The regional distribution of soil carbon can be found in Fig. 14. For the original model, the biggest concentrations of soil carbon are located in the permafrost regions of the northern hemisphere, mainly in Alaska and Eastern Siberia.~~ Because the changes in soil carbon due to the modification of model thickness ~~of~~ and bottom heat flux are very small relative to the size of the pool, we have ~~represented~~ calculated the difference in soil carbon ~~to~~ between the original model ~~for~~ and the modified models ~~of~~ with increased thickness $d = 342.1$ m and with bottom heat flux ~~$F_B = 0.08$ W m^{-2}.~~ 80 mW m^{-2}. For the original model, the biggest concentrations of soil carbon are located in the permafrost regions of the northern hemisphere, mainly in Alaska and Eastern Siberia (Fig. 14). While model versions of different thickness share a common initial state, ~~over time~~

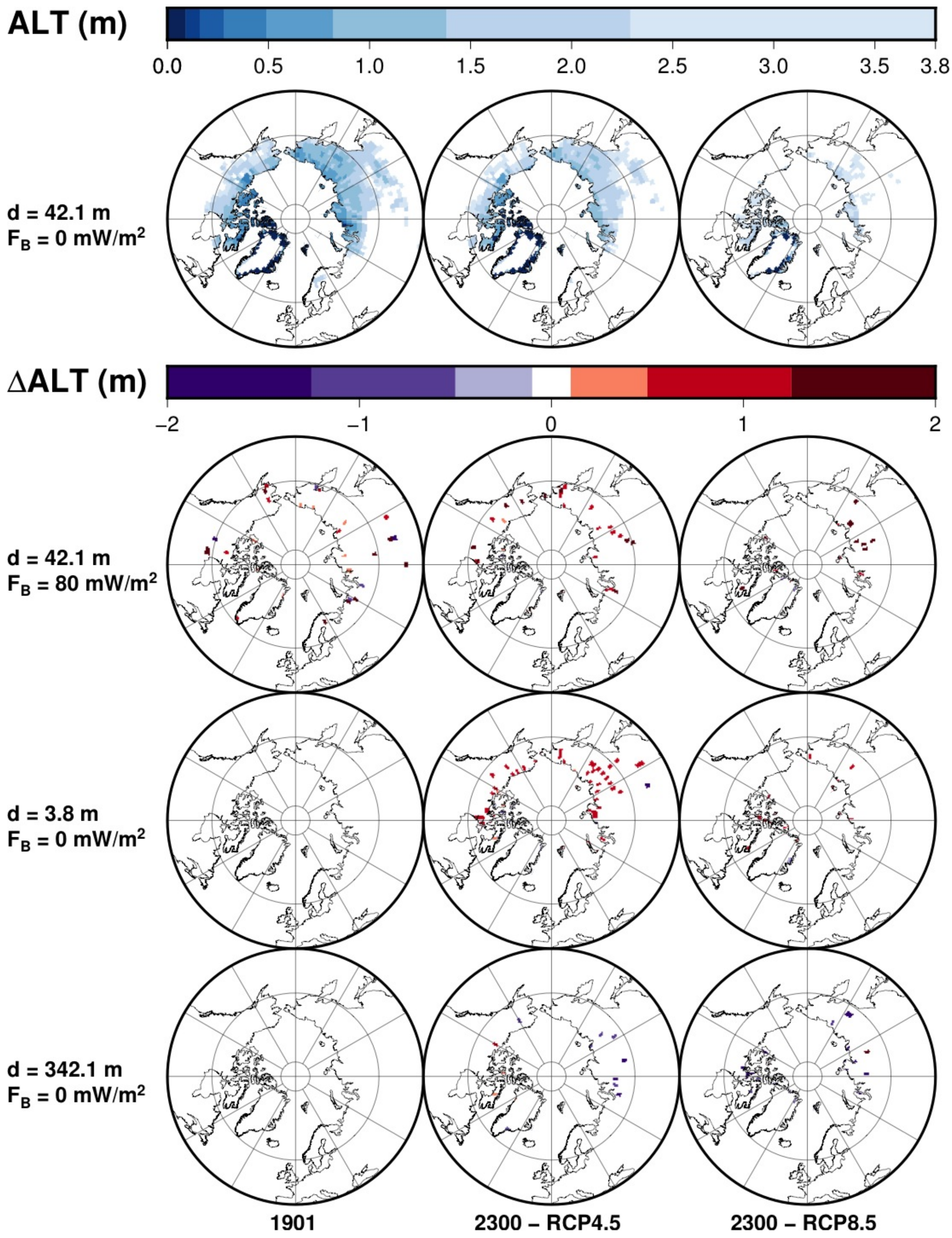

Figure 11. Active Layer Thickness for the unmodified model (top row), and differences to the original model at each time frame for the modified model with ~~bottom heat flux 0.08 W m^{-2}~~ 80 mW m^{-2} (~~middle~~second row), the modified model with $d = 3.8$ m (third row) and the modified model with ~~bottom boundary depth~~ $d = 342.1$ m (bottom row). Time frames at 1901 CE ~~, 2000 CE,~~ and 2300 CE for the scenarios RCP 4.5 and RCP 8.5.

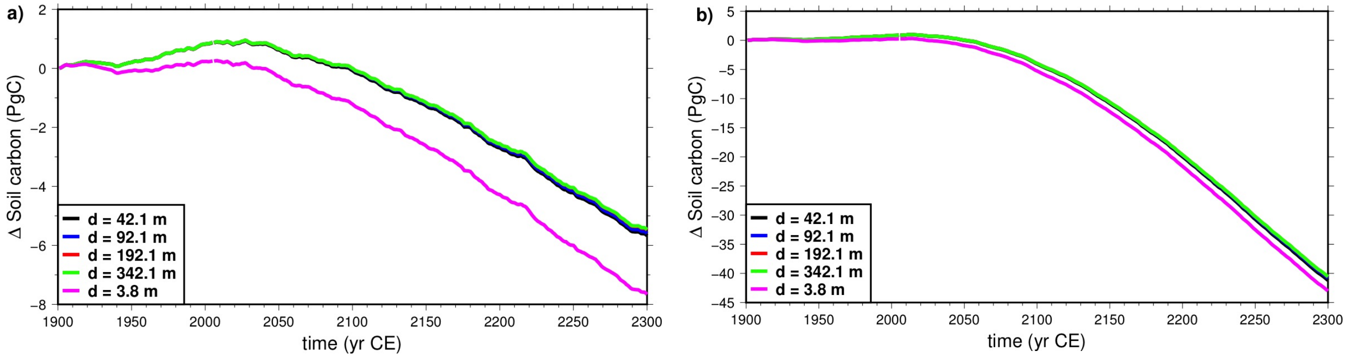

Figure 12. Evolution of soil carbon pool in the Northern Hemisphere permafrost region, compared to the size for the original model at 1901 CE. Models with varying bottom boundary depth. a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data. Note ~~different~~ the vertical scale ~~in panel a and b~~difference between the two panels.

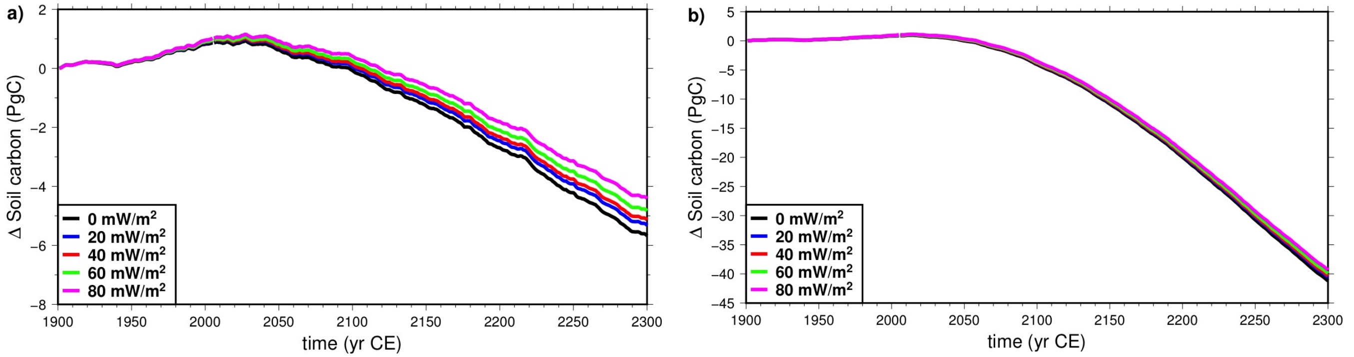

Figure 13. Evolution of soil carbon pool in the Northern Hemisphere permafrost region, compared to the size for the original model at 1901 CE. Models with varying basal heat flux. a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data. Note ~~different~~ the vertical scale ~~in panel a and b~~difference between the two panels.

~~increasing the thickness of the model has the effect of increasing~~ a thicker model increases soil carbon concentration across the region.

Models with different bottom heat flux F_B depart from different initial conditions (since the bottom heat flux determines the thermal steady state of the subsurface). ~~We can see that increasing~~ A higher F_B decreases the initial concentration of soil carbon in some areas ~~while increasing~~ but increases it in others. These differences can be of the same order of magnitude as the carbon concentration in the original model in token gridcells. Some cells have quantities of soil carbon in the ~~$F_B = 0.08$ W m^{-2}~~ 80 mW m^{-2} model half of that of the original model, while other have 10 times as much ~~. As these differences have different sign, the effect on the whole region is proportionally much smaller~~ (Fig. 14).

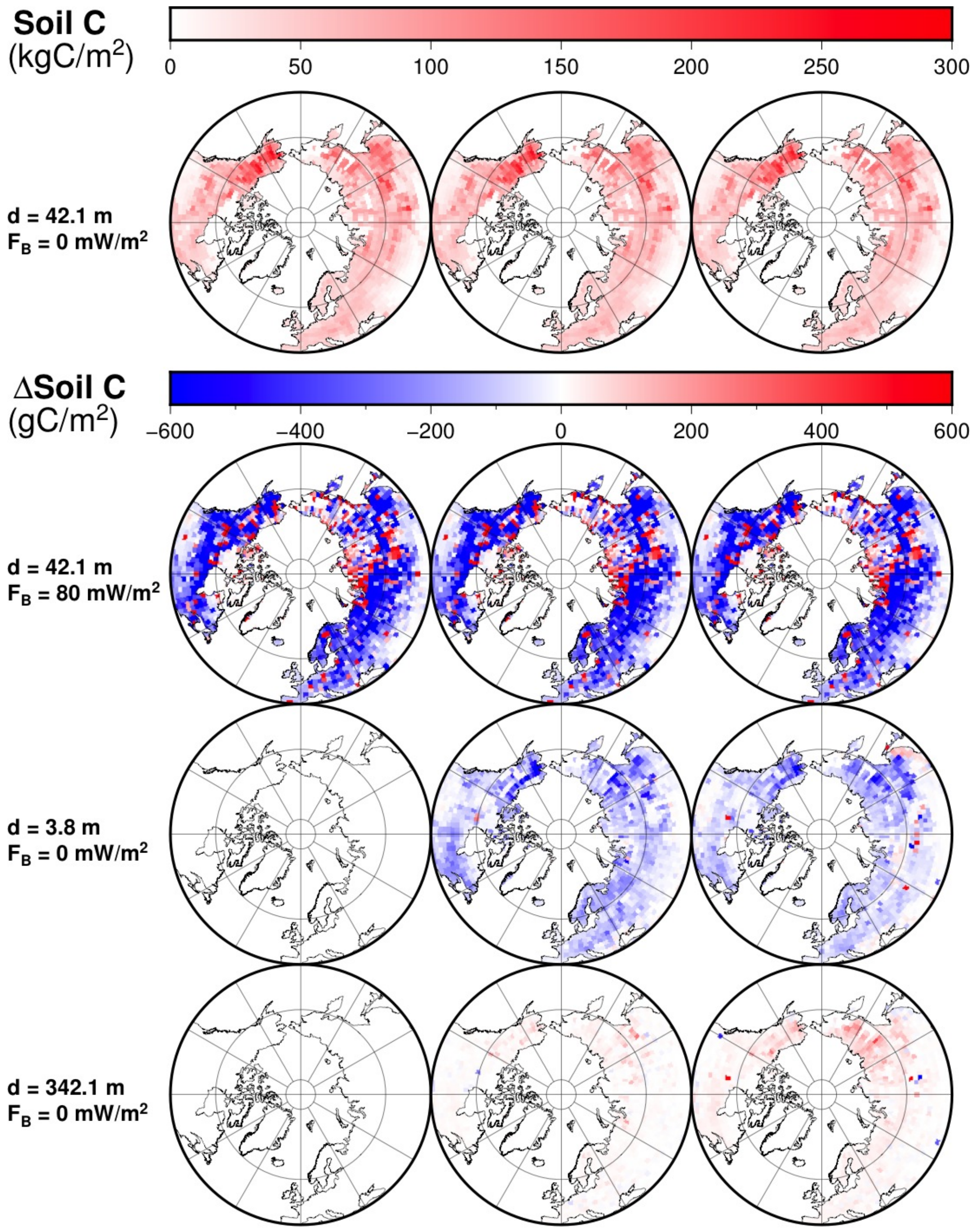

Figure 14. Distribution of soil carbon for the original model (top row), and differences to the original model at each time frame for the modified model with ~~$F_B = 0.08$ W m^{-2}~~ 80 mW m^{-2} (~~middle~~second row), the modified model with $d = 3.8$ m (third row) and the modified model with $d = 342.1$ m (bottom row). Time frames at 1901 CE ~~, 2000 CE,~~ and 2300 CE for the scenarios RCP 4.5 and RCP 8.5.

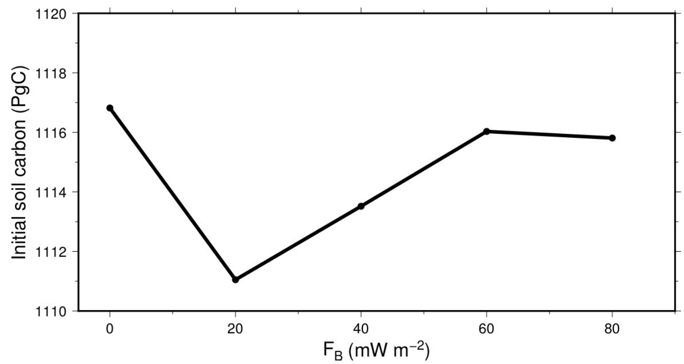

Figure 15. Mean initial size (1901-1910) of the soil carbon pool in the Northern Hemisphere permafrost regionbetween 1901-1910, as in function of basal bottom heat flux.

Figure 15 shows the initial size of Because the local differences on the soil carbon pool in the Northern Hemisphere permafrost region for models with different due to the bottom heat flux . The have different signs, the effect on the whole region is proportionally much smaller, and also produces the absence of a consistent trend in the initial size of the soil carbon pool as we increase the bottom heat flux is due to the regional variability seen in Fig. 14, since the soil carbon in each gridcell can either increase or decrease due to the basal heat flux(Fig. 15).

4.3.2 Vegetation Carbon

The vegetation carbon in the Northern hemisphere is also affected by the depth of the bottom boundary. Because rising temperatures allow plants to colonize higher latitudes, the vegetation increases for both RCP scenarios, reaching a stable level during the last two centuries between 2100-2300. Increasing d and F_B results in more vegetation carbon in some areas and less in others (Fig. S8). 16). For both RCP scenarios, the effect is a net decrease of vegetation carbon in the Northern Hemisphere at the end of the simulations both for greater thickness and for higher bottom heat flux.

While the models with different depth of the bottom boundary d depart start from the same initial state at 1901, increasing the thickness of the a thicker model leads to slightly smaller masses of vegetation carbon. For the thickest model (342.1 m), the pool of vegetation carbon is 0.17 ± 0.01 PgC smaller during the last two centuries of simulation than it is for the thinnest original model (42.1 m) for in the RCP 4.5 scenario, and 0.11 ± 0.08 PgC smaller in the RCP 8.5 scenario. Decreasing the thickness of the model from 42.1 m to 3.8 m produces an effect of comparable magnitude, increasing vegetation carbon by 0.04 ± 0.01 PgC for the RCP 4.5 scenario and by 0.08 ± 0.01 PgC for the RCP 8.5 scenario during the last two centuries of simulation.

The bottom heat flux also has a small effect in the evolution of vegetation carbon in the Northern Hemisphere (Fig. S9) for both RCP scenarios. The average vegetation carbon between 2100-2300 for the model with $F_B = 0.08$ W m^{-2} 80 mW m^{-2} is 0.35 ± 0.03 PgC less for the RCP 4.5 scenario and 0.54 ± 0.05 PgC less for the RCP 8.5 scenario than for the model with zero basal heat flux, a relative decrease of 0.8 ± 0.08% and $1.2 \pm 1$$1.2 \pm 0.1$% respectively.

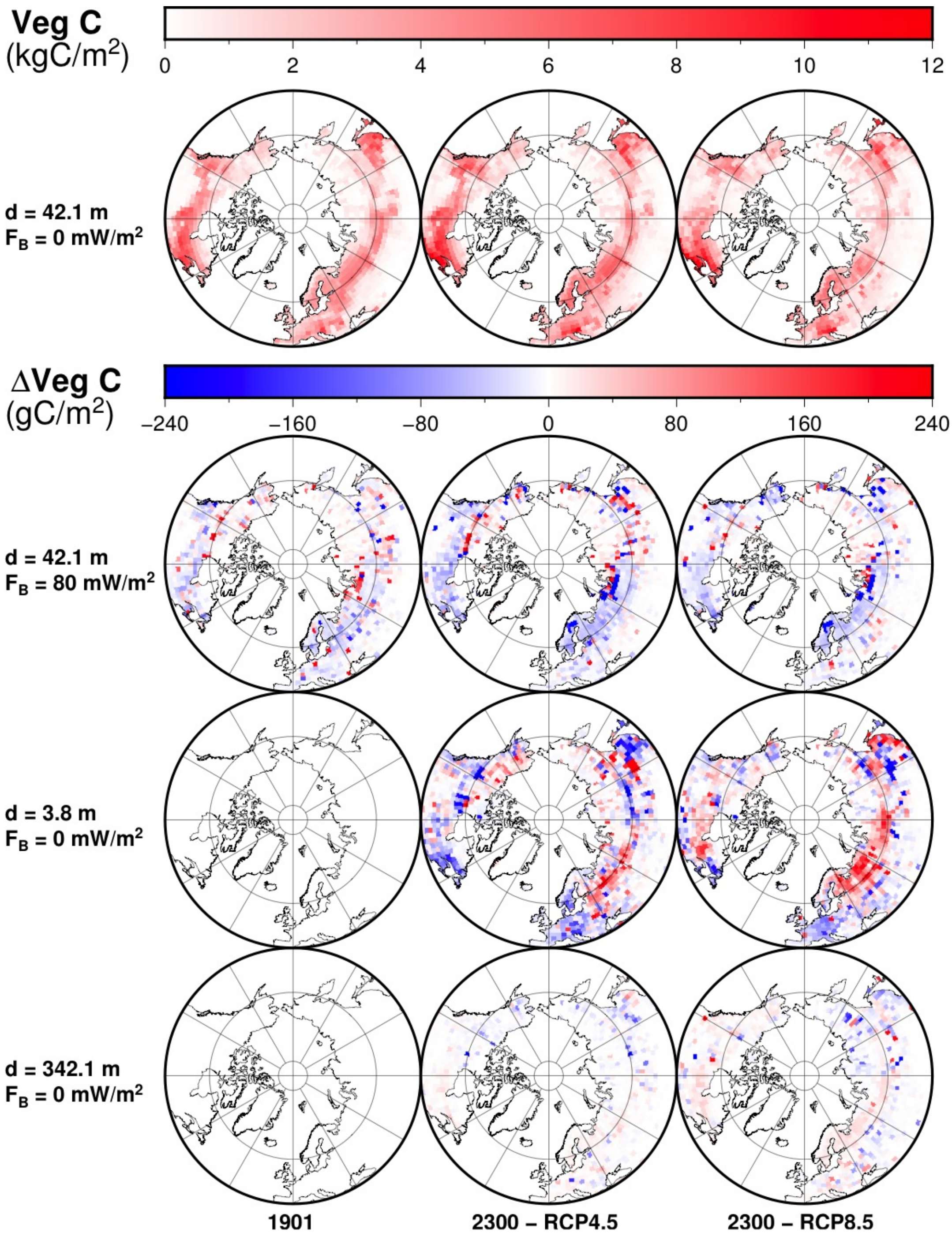

Figure 16. Distribution of vegetation carbon for the original model (top row), and differences to the original model at each time frame for the modified model with ~~$F_B = 0.08$ W m^{-2}~~ 80 mW m^{-2} (~~middle~~second row), the modified model with $d = 3.8$ m (third row) and the modified model with $d = 342.1$ m (bottom row). Time frames at 1901 CE ~~, 2000 CE,~~ and 2300 CE for the scenarios RCP 4.5 and RCP 8.5.

Figure 16 shows the regional distribution of vegetation carbon for the original model, and the difference between the original model and the modified versions of increased thickness $d = 342.1$ m and bottom heat flux $F_B = 0.08$ W m^{-2}. Increasing d and F_B results in a larger amount of vegetation carbon in some areas and a smaller quantity in others. At the end of the simulation, the effect is a net decrease of vegetation in the Northern Hemisphere for both scenarios. There are differences in vegetation carbon at the start of the simulation in 1901 CE, where the increase in vegetation carbon with F_B is dominant.

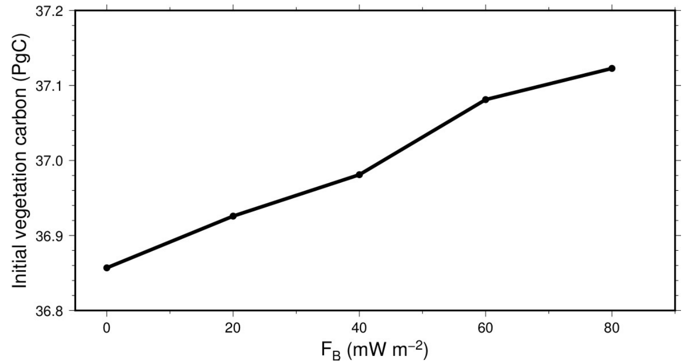

Figure 17. Mean initial size between (1901-1910) of the vegetation carbon pool in the Northern Hemisphere permafrost region, for models in function of different bottom heat flux.

The initial size of the vegetation carbon pool depends on the bottom heat flux . Fig. 17 shows how the bottom heat flux affects the mean changes the initial stable size of the vegetation carbon in the Northern pool in individual cells, that results in a positive change over the North Hemisphere permafrost region during the years 1901-1910 (used for the spinup period(Fig. 17). There is a consistent linear increase of 0.066 ± 0.02 PgC of the initial vegetation for each 0.02 W m^{-2} 20 mW m^{-2} increase of the bottom heat flux.

4.3.3 Methane

Methane is produced by methanogenic microbes in the anaerobic fraction of soil. Therefore, it concentrates in areas where the water table rises high enough to reach the carbon-rich soil near the surface, or in inundated areas. The production of methane in natural wetlands is mainly located in the tropical areas, responsible for 64%-88% of the global wetland production (O'Connor et al., 2010).

In our CLM4.5-BGC simulations, most of the methane production is concentrated in the high-latitude wetlands Northern Hemisphere cold regions, including not only the permafrost region but the areas of seasonal soil freezing as well (Fig. 18). In contrast, the tropical wetlands areas produce almost no methane. The reason is that the tropical areas do not get inundated and the water table remains low, never reaching the higher soil layerswhere most lies in the unconfined aquifer present below the soil in the hydrological model of the CLM4.5, which allows the subsurface to absorb water before the water table rises to the upper soil layers, where most of the soil carbon is concentrated, even . In the simulations, the water table rarely rises above a depth of 3.8 m during the monsoon season. The water table remains low due to flaws in the hydrology model of , which we

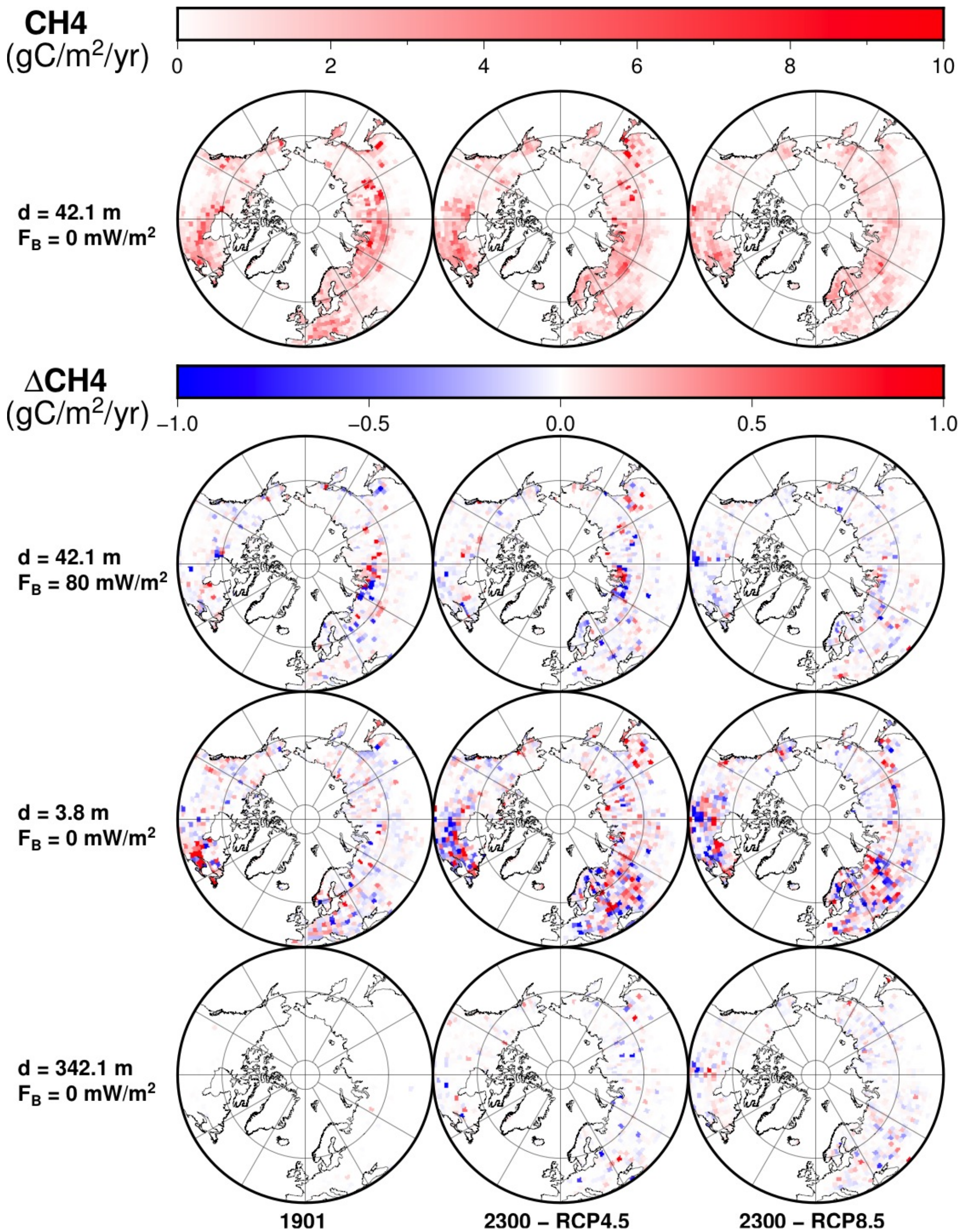

Figure 18. Distribution of methane yearly production for the original model (top row), and differences to the original model at each time frame for the modified model with ~~$F_B = 0.08$ W m^{-2}~~ 80 mW m^{-2} (~~middle~~second row), the modified model with $d = 3.8$ m (third row) and the modified model with $d = 342.1$ m (bottom row). Time frames at 1901 CE ~~, 2000 CE,~~ and 2300 CE for the scenarios RCP 4.5 and RCP 8.5.

discuss later. High-latitude areas have low water tables as well, but they get partially inundated during the year because the soil is frozen (impeding the filtration percolation of water), and can produce methane.

In the Northern Hemisphere there are significant differences in the production of methane due to the bottom heat flux and the depth of the bottom boundary. These differences occur in In a few areaswhere , the difference in methane production can be within as high as 50-80% of that of with respect to the original model. However, as the sign of these differences can be either positive or negative, the net effect over methane production is less pronouncedsmall.

As shown in Figs. S10 and S11, the The net effect of the subsurface thickness and the bottom heat flux on the global methane production is much smaller than for the localized areas displayed in Fig. 18. Increasing the thickness of the model from 42.1 m to 342.1 m can result in increases and decreases of global methane production during the simulation between 0.1 to 0.2 $\mathrm{TgC\,yr^{-1}}$ (1 $\mathrm{TgC} = 10^{12}$ g of C), only 0.3-0.5% , of the methane production at 2300 for the scenarios RCP 4.5 and RCP 8.5, respectively. Decreasing subsurface thickness from 42.1 m to 3.8 m results in methane emissions rising by 1.11 ± 0.35 $\mathrm{TgC\,yr^{-1}}$ in the RCP 4.5 scenario and by 0.83 ± 0.34 $\mathrm{TgC\,yr^{-1}}$ in the RCP 8.5 scenario, a relative increase of 1.5-2% that leads to a larger depletion of the soil carbon pool in the long term. The bottom heat flux has a slightly larger effect, as a bottom heat flux of $F_B = 0.08$ $\mathrm{W\,m^{-2}}$ 80 $\mathrm{mW\,m^{-2}}$ decreases methane production by 0.6 to 1.0 $\mathrm{TgC\,yr^{-1}}$, a relative decrease reduction of 1-1.6% of the total production at 2300 for the scenarios RCP 4.5 and RCP 8.5, respectively.

5 Discussionand conclusions

In this paper we have examined the effects of two simplifications made by most ESMs: not taking the geothermal gradient into account, and using an excessively thin subsurface. This paper follows previous estimations (MacDougall et al., 2008, 2010) and quantifies the effects of these simplifications, through the use of numerical simulations with two sets of modified versions of CLM4.5, one where we increase the thickness of the subsurface, and another where we impose a uniform heat flux at the bottom of the land model.

Our results show that deepening the bottom boundary by 300 m increases the heat stored in the subsurface by 72 ZJ and 201 ZJ at the end of the simulations at 2300 CEfor the two scenarios, which correspond respectively to 260% and 217% of the heat stored by the original shallow model model for scenarios RCP 4.5 and RCP 8.5 respectively. Heat absorption within the soil (upper 3.8 m) is reduced by 1-3% depending on the scenario and the length of the simulation. On the other hand, moving the bottom boundary from 42.1 m to 3.8 m increases the heat absorbed by the soil between 1901 and 2000 by 20%, while the heat absorbed by 2300 only increases by 8% (RCP 4.5) and 3.4% (RCP 8.5), because the heat reflected at the bottom boundary has had time to return to the surface and affect soil temperature. Increasing the bottom heat flux by 0.02 $\mathrm{W\,m^{-2}}$ 20 $\mathrm{mW\,m^{-2}}$ raises the temperature at the bottom of the soil (3.8 m deep) by 0.04 ± 0.01 K, with some differences between cells due to the variable thermal properties of soil. Using For the mean continental heat flux 0.06 $\mathrm{W\,m^{-2}}$ (Jaupart and Mareschal, 2010) increases value of 60 $\mathrm{mW\,m^{-2}}$ (Jaupart and Mareschal, 2010) the bottom soil temperature is raised by 0.12 ± 0.03 K, and the temperature at the base of the model (42.1 m deep) by 0.8 ± 0.04 K.

Permafrost is affected by the depth of the bottom boundary, in a degree that depends on the depth to which we consider permafrost, in the same manner as the heat absorption by the subsurface. Permafrost near the surface is only slightly affected, but ~~as we increase the depth to which we consider permafrost , the differences made by the~~ for intermediate depth permafrost the thickness of the model ~~became more and more significant . As Fig. 9 shows, the~~ has a more significant effect. Increasing the thickness of the subsurface from 42.1 m to 342.1 m reduces the area loss of intermediate-depth permafrost ~~is reduced~~ by a factor of 3 in the RCP 4.5 scenario and by a factor of 5.5 in the RCP 8.5 scenario ~~.~~ (Fig. 9). The effect of the crustal heat flux ~~in permafrost grows linearly with the magnitude~~ on permafrost is proportional to the value of the heat flux and the depth of the permafrost, but even a bottom heat flux of ~~$F_B = 0.08$ W m^{-2} only~~ 80 mW m^{-2} reduces intermediate-depth permafrost extent by only 1-2%.

Increasing the depth of the bottom boundary leads to less vegetation and more soil carbon in the Northern Hemisphere permafrost region at the end of the simulations, compared to the thinner models. This is to be expected, as the increasing the depth of the subsurface leads to reduced permafrost loss, which opens less area to vegetation and exposes less soil carbon to microbial activity. These effects are small, as the stable vegetation level reached between 2100-2300 in the thickest model is only reduced by 0.8-1.2% compared to the ~~thinnest~~ original model, while soil carbon is reduced by 1.3-3.6%. On the other hand, a subsurface of 3.8 m overestimates the soil carbon lost by 2300 considerably, by as much as 35% in the RCP 4.5 scenario, although this is reduced to 4.4% in the RCP 8.5 scenario, where the loss of soil carbon is greater.

A higher basal heat flux has a regionally variable effect across the Northern Hemisphere, increasing soil carbon and vegetation where near-surface permafrost is present, but decreasing both outside of the permafrost region. The loss of soil carbon in the permafrost region is 4-22% smaller with ~~$F_B = 0.08$ W m^{-2}~~ 80 mW m^{-2} than with zero basal heat flux, while the initial quantities of carbon ~~can range from half to~~ in individual gridcells vary between half and 10 times as much ~~in individual gridcells. This~~ as for no heat flux. The heat flux also reduces by 0.8-1.2% the stable vegetation level in this region during the last two centuries of the simulation. On the other hand, the bottom heat flux reduces methane production within areas where permafrost is present but increases it where soil only freezes seasonally.

In CLM4.5 subsurface biogeochemistry only takes place within the soil, the upper 3.8 m. For this reason, the small effect of the bottom boundary depth on near-surface permafrost translates into a small effect on the soil carbon and vegetation pools and the methane production. While the same could be expected from the basal heat flux, it has a ~~varied~~ variable effect across the Northern Hemisphere, specially in the areas where seasonal freezing of the soil occurs, but no soil permafrost is present.

While CLM4.5 uses as uniform soil thickness value of 3.8 m, natural soil thickness varies ~~significantly~~notably, with an estimated global mean of ≈ 13 m and reaching depths of several hundred meters ~~in~~ i some areas (Shangguan et al., 2017). Soil affected by permafrost is therefore much deeper than in CLM4.5, and future models should use realistic ~~maps~~ values of soil thickness~~, which makes the~~. The results obtained for intermediate-depth permafrost ~~relevant~~are therefore useful to understand the effects that the thickness of the subsurface and the bottom heat flux would have in a soil of realistic depth. The uniform soil thickness also affects the hydrology model in CLM4.5 ~~, which~~which, in addition to the use of a virtual aquifer with a capacity of 5 m, makes the hydrology model unrealistic. The ~~new version 5.0 of CLM includes~~ excessive capacity of this aquifer results in the water table rarely rising above 3.8 m depth, much lower than the natural levels of the water table, specially for the tropical wetlands (Fan et al., 2013) . The newer version Community Land Model version 5.0 (CLM5) attempts to address the main issues of the hydrology model in CLM4.5 by eliminating the aquifer and including a spatially variable soil thickness within a range of 0.4 m to 8.5 m~~and eliminates the virtual aquifer, which address the issues of~~ , which is still below the global average (Swenson and Lawrence, 2015; Brunke et al., 2016) . The soil thickness is derived from survey data where typical values of soil thickness are between 7 m and 10 m (Pelletier et al., 2016) , although the growing consensus is that regolith thickness varies between 10-40 m (Clair et al., 2015) .

Even though in nature the bottom heat flux is not uniform, the ~~hydrology model~~ use of uniform values allows us to establish a quantitative relationship between the value of the bottom heat flow and the effects it has on permafrost and biogeochemistry. We also keep other simplifications made in CLM4.5~~(Lawrence et al., 2018) .~~ , such as a global granitic bedrock and a constant regolith thickness of a few meters. Quantifying the effect of these simplifications would require important code modifications and more simulations, thus more time and computational resources. Also, while there are some maps of regolith thickness, bedrock composition, as well as crustal heat flow (Jaupart and Mareschal, 2015) , these maps are incomplete with many regions void of data.

~~The increased depth of~~ A thicker soil in some areas ~~imply~~ implies that the effect of the basal heat flux and the bottom boundary depth ~~would be~~ are bigger than our estimations, made for a soil depth of 3.8 m. While soil carbon pools in the permafrost region concentrate within the upper 3 m, additional reserves exist below 3 m which contain $\sim 60\%$ as much carbon as the upper 3 m (Hugelius et al., 2014). If ~~considered~~ included in the model, these reserves would be more severely affected by the depth of the bottom boundary and the bottom heat flux than the shallow carbon deposits are. An example of this would be the yedoma and frozen thermokarst deposits, which hold an estimated 211 ± 160 PgC of carbon in depths up to 50 m in some areas of Siberia and Alaska (Strauss et al., 2013) . Our study showed that the thawing of intermediate-depth permafrost (below 42.1 m) is largely overestimated (3-6 times larger) for a subsurface of 42.1 m than a subsurface of 342.1 m. Therefore, the inclusion of deep carbon deposits in LSMs will require the use of an appropriate subsurface thickness ($\sim$ 200 m for a 400 yr simulation).

The methane production in CLM4.5-BGC is dependent on the hydrology model used in CLM4.5, which keeps the water table too low in the tropical regions of the Earth where most (64%-88%) wetland methane is produced (O'Connor et al., 2010). The consequence is that no methane is produced in these regions, and all methane is produced in the Northern Hemisphere where frozen soil can be inundated. Compared to the original model, a bottom heat flux of ~~$F_B = 0.08$ W m^{-2} produces~~ 80 mW m^{-2} causes a reduction of 1-1.6% across the whole permafrost region~~, while deepening~~ . Deepening the bottom boundary to 342.1 m only ~~produces~~ induces variations smaller than 0.5%, while moving the bottom boundary from 42.1 m to 3.8 m consistently increases methane emissions by 1.5-2%. However, there can be differences as high as 50-80% with respect to the original model, located in individual cells near the permafrost frontier. The lack of methane production in tropical regions associated to the hydrology should ~~not be expected to~~ no longer occur in CLM5.0, which ~~addresses the lack of realism of the hydrology model in .~~ uses a more realistic hydrology model than CLM4.5.

The local variability of the results across the Northern Hemisphere permafrost region is difficult to interpret. Increasing the thickness of the subsurface or the crustal heat flux reduces the size of the carbon pools and the production of methane in some areas, but it increases it in others. There is a possible explanation for the local differences in the production of methane: the increase in ALT allows more methane to be produced if there is still a frozen soil layer beneath, because it restricts the seepage of water and allows the active layer to be inundated, however if the entire soil thaws, the water can percolate to the aquifer and less methane is produced. This might also explain the local differences in the size of the carbon pool, as the differences in the production of methane accumulate over time. The local differences in vegetation carbon are more difficult to interpret, but the dominant trend is that warmer soil (because of a larger crustal heat flux or a thinner subsurface) results in more vegetation carbon in the coldest areas of the permafrost region, and less vegetation carbon in the periphery. A tentative explanation is that, while a warmer soil favors the colonization of plants, it may result in less available water in areas where additional heat thaws the soil completely and allows water to percolate to the aquifer and slightly reduce the growth of the vegetation.

The depth of the bottom boundary has a considerable effect on the heat absorbed by the subsurface. We have shown that, in a simulation spanning 400 years, the LSM requires a thickness of at least 200 m to correctly estimate the temperature profile. The thickness d needed increases with the length t of the simulation, but this is not prohibitive for simulations running on much longer timescales, because the depth of the bottom boundary follows a square-root relation $d \propto \sqrt{\kappa t}$. This result matches the estimation obtained from the theoretical analysis, which indicates that we can rely on theoretical estimates of the optimal depth (Stevens et al., 2007) , despite the differences between the theoretical approximation and the numerical model, i.e. the thermal properties of the upper 3.8 m and the thermal signal from the surface. Longer simulations such as the 1000 yr long simulations of the last millennium ensemble (Stocker et al., 2013), require subsurface thicknesses of $\sim 300-350$ m. The computational costs associated to each additional layer are almost negligible when compared to the whole LSM, because the only process taking place in bedrock is thermal diffusion. We also used a fixed thickness for the additional layers, but if we keep the original scheme where layer thickness increase exponentially, it is possible to increase the thickness of the model to hundreds of meters by adding only a few layers. A downside to this exponential scheme is the loss of resolution to determine the depth range of permafrost, however we consider that the exponential scheme is still a good compromise between the resolution of the subsurface model and its computational cost. If a need to increase the resolution of the layer scheme appears, changing the scaling factor f_S in Eq. (7) is a better solution than abandoning the exponential layer thickness scheme currently used.

We have determined that each successive increase of ground thickness provides diminishing returns for subsurface heat storage and permafrost and soil carbon stability. Therefore, it is to be expected that the improvement from increasing the thickness of the model from 42.1 m to 342.1 m is much smaller than that from increasing it from 3.8 m to 42.1 m. This was already investigated by several studies with the CLM3, where the thickness of the subsurface was increased from 3.5 m to more than 30 m, which improved the estimates of the permafrost significantly during the 20th century (Alexeev et al., 2007 ; Nicolsky et al., 2007 ; Lawrence et al., 2008). A depth of 3.8 m is not enough to damp the annual signal of SAT, and the temperature in a layer of this thickness closely follows the SAT. In future scenarios of global warming such as RCP 4.5 and RCP 8.5, where SAT rises by 2 K and 9.5 K respectively between 2000-2300, this largely overestimates the temperature of the subsurface for the model relative to the real world. In the Northern Hemisphere permafrost region, while we do not detect an effect on the total area extent of near-surface permafrost, the thickness and depth of this permafrost are significantly affected.

This results in consistently higher emissions of methane, which lead to considerable overestimates of the losses of soil carbon (up to 35% in the RCP 4.5 scenario).

Any LSM, before a simulation starts, must be initialized with appropriate initial conditions, i.e. an initial state of the model that ~~resembles the reality~~ is close to the real profile at the time. An appropriate initial condition for the temperature of the subsurface is the steady state determined by the surface temperatures at the start of the simulation. This state can be reached during the length of the spinup from arbitrary initial temperatures, if the depth of the bottom boundary is much shallower than the depth determined by the relation $d \propto \sqrt{\kappa t}$, being t the length of the spinup. However, if we increase d enough to prevent the bottom boundary from affecting the thermal diffusion during the length of the simulation, we may also prevent those arbitrary initial temperatures reaching a steady state during the length of the spinup. This problem can be avoided if the spinup does not ~~depart from~~ start with arbitrary initial subsurface temperatures, but instead from a temperature profile as close as possible to the steady state ~~. As the steady state is determined by~~ determined by the surface temperature and linear temperature gradient in Eq. (6)~~, it is possible to obtain an appropriate initial temperature profile by ignoring the time-varying perturbation T_t in this equation~~.

The ~~thermal anomalies associated with~~ temperature differences due to insufficient depth of the bottom boundary and lack of basal heat flux are considerable throughout the subsurface. However, ~~this effect is~~ they are of little importance ~~within~~ for the global heat budget~~model~~, as the heat absorbed by the continents is less than even the uncertainty ~~of heat absorption~~ on the heat absorbed by the oceans (Rhein et al., 2013). The most important consequences are those on the carbon pools and fluxes in the North Hemisphere. These effects are ~~not distributed homogeneously across the region, but located in small areas across the region. These areas are those where permafrost is~~ quantitatively small, and a 1-4% error in the ~~most affected by~~ soil carbon pool by 2300 is hardly a first order problem for CLM4.5, compared to the errors introduced by other land systems such as the hydrology model, or the uncertainties on climate projections themselves. However, adding a crustal heat flux and increasing the thickness of the model are computationally cheap and easy to implement. and they will be necessary to avoid higher errors in the stability of reserves of deep carbon if they are included in the model. In addition to the small errors caused by assuming too shallow lower boundary, we observe large differences when decreasing subsurface thickness to 3.8 m. These results confirm that LSMs should never use subsurface thickness inferior to 30-40 m, as previously concluded by several studies (Alexeev et al., 2007; Nicolsky et al., 2007; Lawrence et al., 2008) . Thus, we suggest the use of crustal heat flux and a subsurface thickness enough to avoid these errors, 200 m for a 400 yr simulation, in centennial simulations of LSMs that include deep carbon deposits. For the correct determination of near-surface permafrost in LSMs, the minimum required subsurface thickness is 40-50 m, but it can be increased to 200 m to avoid errors on the order of 1-4%.

6 Conclusions

The area loss of intermediate-depth permafrost (below 42.1 m) in the 1901-2300 period is largely overestimated (3-6 times larger, for the scenarios RCP 4.5 and RCP 8.5 respectively) for a subsurface of 42.1 m than a subsurface of 342.1 m. Therefore, the inclusion of deep carbon deposits in LSMs will require the use of an appropriate subsurface thickness ($\sim$ 200 m for a 400 yr simulation). The thickness d needed increases with the length t of the simulation following the square-root relation $d \propto \sqrt{\kappa t}$ that was obtained from the theoretical analysis (Stevens et al., 2007) , therefore we can rely on theoretical estimates of the bottom boundary depth and the basal heat flux , or that are located just outside the limit of the region where soil permafrost exists, which suggests that seasonal soil freezing also affects the carbon pools significantly. Methane production can variate within one order of magnitude due to the changes to model thickness and basal heat flux. optimal depth.

To correctly determine near-surface permafrost in LSMs, the subsurface requires a minimum thickness of 40 m. We suggest the use of a subsurface thickness of 200 m in 400 yr simulations (100 m for 100 yr) and the use of the crustal heat flux, to avoid errors on the order of 1-4%. These changes will be most relevant in centennial simulations of LSMs that include deep carbon deposits.

Code availability

The modified CLM4.5 software, as well as the instructions for its use in a functional CLM4.5 installation, are available in the Zenodo repository (https://zenodo.org/record/1420497) under the doi 10.5281/zenodo.1420497 (Hermoso de Mendoza, 2018).

Data availability

The dataset used to produce the initial conditions used in the simulations can be found in the Zenodo repository (https://zenodo.org/record/1420497) under the doi 10.5281/zenodo.1420497 (Hermoso de Mendoza, 2018). Implementation of these initial conditions requires modifications to the software, which can be found in the same package.

Three datasets are used as boundary conditions for the simulations (i.e. the atmospheric datasets used to force the land model). The CRUNCEP dataset used to force the model between 1901-2005 is available in the NCAR-UCAR Research Data Archive (Viovy, 2018). The two datasets used to force the model between 2006-2300, RCP 4.5 and RCP 8.5, are available in the Earth System Grid repository (Stern, 2013).

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Acronyms

ALT Active Layer Thickness. 10, 11, 20, 31

BGC BioGeoChemistry. 7–9, 12, 26, 30

CESM1.2 Community Earth System Model version 1.2. 7, 11

CLM3 Community Land Model version 3. 3, 31

CLM4 Community Land Model version 4. 8

CLM4.5 Community Land Model version 4.5. 3–5, 7–14, 17, 18, 20, 26, 28–30, 32

CLM5 Community Land Model version 5.0. 30

CMIP5 fifth phase of the Climate Model Intercomparison Project. 3

CN Carbon-Nitrogen. 8

CRU-TS Climate Research Unit Time-Series. 12

ESM Earth System Model. 1–3, 7, 28

LSM Land Surface Model. 2, 3, 7, 9, 10, 12, 18, 30–33

NCEP National Centers for Environmental Prediction. 12

RCP Representative Concentration Pathway. 12–16, 18–20, 24, 28, 29, 31, 32

SAT Surface Air Temperature. 7, 13, 15, 16, 18, 31

References

Alexeev, V., Nicolsky, D., Romanovsky, V., and Lawrence, D.: An evaluation of deep soil configurations in the CLM3 for improved representation of permafrost, Geophysical Research Letters, 34, doi:10.1029/2007GL029536, 2007.

Anderson, E. A.: A point energy and mass balance model of a snow cover, NOAA Technical Report NWS, 19, 1976.

Avis, C. A., Weaver, A. J., and Meissner, K. J.: Reduction in areal extent of high-latitude wetlands in response to permafrost thaw, Nature Geoscience, 4, 444, doi:10.1038/NGEO1160, 2011.

Beltrami, H., Smerdon, J., Pollack, H. N., and Huang, S.: Continental heat gain in the global climate system, Geophysical Research Letters, 29, 1–3, doi:10.1029/2001GL014310, 2002.

Bonan, G., Drewniak, B., Huang, M., et al.: Technical Description of Version 4.5 of the Community Land Model (CLM), Tech. rep., NCAR Technical Note NCAR/TN-503+ STR, Boulder, Colorado, doi:10.5065/D6RR1W7M, 2013.

Bonan, G. B.: Forests and climate change: forcings, feedbacks, and the climate benefits of forests, Science, doi:10.1126/science.1155121, 2008.

Brunke, M., Broxton, P., Pelletier, J., Gochis, D., Hazenberg, P., Lawrence, D., Leung, L., Niu, G.-Y., Troch, P., and Zeng, X.: Implementing and Evaluating Variable Soil Thickness in the Community Land Model, Version 4.5 (CLM4.5), Journal of Climate, 29, 3441–3461, doi:10.1175/JCLI-D-15-0307.1, 2016.

Carslaw, H. S. and Jaeger, J. C.: Conduction of heat in solids, Oxford: Clarendon Press, 1959, 2nd ed., 1959.

Clair, J. S., Moon, S., Holbrook, W., Perron, J., Riebe, C., Martel, S., Carr, B., Harman, C., Singha, K., et al.: Geophysical imaging reveals topographic stress control of bedrock weathering, Science, 350, 534–538, doi:10.1126/science.aab2210, 2015.

Clauser, C. and Huenges, E.: Thermal conductivity of rocks and minerals, in: Rock physics & phase relations: AGU handbook of physical constants, edited by Ahrens, T. J., pp. 105–126, doi:10.1029/RF003, 1995.

Collins, M., Knutti, R., Arblaster, J., Dufresne, J. L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W. J., Johns, T., Krinner, G., Shogwe, M., Tebaldi, C., Weaver, A. J., and Wehner, M.: Long-term Climate Change: Projections, Commitments and Irreversibility, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T., chap. 12, Cambridge University Press, 2013.

Cubasch, U., Wuebbles, D., Chen, D., Facchini, M., Frame, D., Mahowald, N., and Winther, J.-G.: Introduction, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T., chap. 1, Cambridge University Press, 2013.

Cuesta-Valero, F. J., García-García, A., Beltrami, H., and Smerdon, J. E.: First assessment of continental energy storage in CMIP5 simulations, Geophysical Research Letters, 43, 5326–5335, doi:10.1002/2016GL068496, 2016.

Fan, Y., Li, H., and Miguez-Macho, G.: Global patterns of groundwater table depth, Science, 339, 940–943, doi:10.1126/science.1229881, 2013.

Hansen, J. and Nazarenko, L.: Soot climate forcing via snow and ice albedos, Proceedings of the National Academy of Sciences, 101, 423–428, doi:10.1073/pnas.2237157100, 2004.

Harris, I., Jones, P., Osborn, T., and Lister, D.: Updated high-resolution grids of monthly climatic observations–the CRU TS3. 10 Dataset, International Journal of Climatology, 34, 623–642, doi:10.1002/joc.3711, 2014.

Hermoso de Mendoza, I.: Lower boundary conditions improvement in CLM4.5, doi:10.5281/zenodo.1420497, https://zenodo.org/record/1420497, 2018.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., et al.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps, Biogeosciences, 11, 6573–6593, doi:10.5194/bg-11-6573-2014, 2014.

Jaupart, C. and Mareschal, J.-C.: Heat generation and transport in the Earth, Cambridge university press, 2010.

Jaupart, C. and Mareschal, J.-C.: Heat flow and thermal structure of the lithosphere, in: Treatise on Geophysics, edited by Watts, A., vol. 6, pp. 217–253, Elsevier BV, 2 edn., doi:10.1016/B978-0-444-53802-4.00114-7, 2015.

Jordan, R.: A one-dimensional temperature model for a snow cover: Technical documentation for SNTHERM. 89., Tech. rep., Cold Regions Research and Engineering Lab Hanover NH, http://acwc.sdp.sirsi.net/client/en_US/search/asset/1011960;jsessionid=0DD89186E5D788FB1D334F4331245C4D.enterprise-15000, 1991.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., et al.: The NCEP/NCAR 40-year reanalysis project, Bulletin of the American meteorological Society, 77, 437–471, doi:10.1175/1520-0477(1996)077<0437:TNYRP>2.0.CO;2, 1996.

Kirtman, B., Power, S., Adedoyin, A., Boer, G., Bojariu, R., Camilloni, I., Doblas-Reyes, F., Fiore, A., Kimoto, M., Meehl, G., et al.: Near-term climate change: projections and predictability, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T., chap. 11, Cambridge University Press, 2013.

Kluzek, E.: CESM Research Tools: CLM4.5 in CESM1.2.0 User's Guide Documentation, http://www.cesm.ucar.edu/models/cesm1.2/clm/models/lnd/clm/doc/UsersGuide/x12544.html, 2013.

Koven, C., Riley, W., Subin, Z., Tang, J., Torn, M., Collins, W., Bonan, G., Lawrence, D., and Swenson, S.: The effect of vertically resolved soil biogeochemistry and alternate soil C and N models on C dynamics of CLM4, Biogeosciences, 10, 7109, doi:10.5194/bg-10-7109-2013, 2013a.

Koven, C. D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G., and Tarnocai, C.: Permafrost carbon-climate feedbacks accelerate global warming, Proceedings of the National Academy of Sciences, 108, 14 769–14 774, doi:10.1073/pnas.1103910108, 2011.

Koven, C. D., Riley, W. J., and Stern, A.: Analysis of permafrost thermal dynamics and response to climate change in the CMIP5 Earth System Models, Journal of Climate, 26, 1877–1900, doi:10.1175/JCLI-D-12-00228.1, 2013b.

Lawrence, D., Fisher, R., Koven, C., Oleson, K., Swenson, S., Vertenstein, M., et al.: Technical Description of version 5.0 of the Community Land Model (CLM), Tech. rep., NCAR Technical Note NCAR/TN-503+ STR, Boulder, Colorado, http://www.cesm.ucar.edu/models/cesm2/land/CLM50_Tech_Note.pdf, 2018.

Lawrence, D. M. and Slater, A. G.: A projection of severe near-surface permafrost degradation during the 21st century, Geophysical Research Letters, 32, doi:10.1029/2005GL025080, 2005.

Lawrence, D. M., Slater, A. G., Romanovsky, V. E., and Nicolsky, D. J.: Sensitivity of a model projection of near-surface permafrost degradation to soil column depth and representation of soil organic matter, Journal of Geophysical Research: Earth Surface, 113, doi:10.1029/2007JF000883, 2008.

Levitus, S., Antonov, J. I., Boyer, T. P., Baranova, O. K., Garcia, H. E., Locarnini, R. A., Mishonov, A. V., Reagan, J., Seidov, D., Yarosh, E. S., et al.: World ocean heat content and thermosteric sea level change (0–2000 m), 1955–2010, Geophysical Research Letters, 39, doi:10.1029/2012GL051106, 2012.

MacDougall, A. H. and Beltrami, H.: Impact of deforestation on subsurface temperature profiles: implications for the borehole paleoclimate record, Environmental Research Letters, 12, 074 014, doi:10.1088/1748-9326/aa7394, 2017.

MacDougall, A. H., González-Rouco, J. F., Stevens, M. B., and Beltrami, H.: Quantification of subsurface heat storage in a GCM simulation, Geophysical Research Letters, 35, doi:10.1029/2008GL034639, 2008.

MacDougall, A. H., Beltrami, H., González-Rouco, J. F., Stevens, M. B., and Bourlon, E.: Comparison of observed and general circulation model derived continental subsurface heat flux in the Northern Hemisphere, Journal of Geophysical Research: Atmospheres, 115, doi:10.1029/2009JD013170, 2010.

Melo-Aguilar, C., González-Rouco, J. F., García-Bustamante, E., Navarro-Montesinos, J., and Steinert, N.: Influence of radiative forcing factors on ground–air temperature coupling during the last millennium: implications for borehole climatology, Climate of the Past, 14, 1583–1606, doi:10.5194/cp-14-1583-2018, 2018.

Nicolsky, D., Romanovsky, V., Alexeev, V., and Lawrence, D.: Improved modeling of permafrost dynamics in a GCM land-surface scheme, Geophysical research letters, 34, doi:10.1029/2007GL029525, 2007.

O'Connor, F. M., Boucher, O., Gedney, N., Jones, C., Folberth, G., Coppell, R., Friedlingstein, P., Collins, W., Chappellaz, J., Ridley, J., et al.: Possible role of wetlands, permafrost, and methane hydrates in the methane cycle under future climate change: A review, Reviews of Geophysics, 48, 2010.

Oleson, K., Lawrence, D., Bonan, G., Drewniak, B., Huang, M., et al.: Technical Description of Version 4.5 of the Community Land Model (CLM), Tech. rep., NCAR Technical Note NCAR/TN-503+ STR, Boulder, Colorado, doi:10.5065/D6RR1W7M, 2013.

Pelletier, J. D., Broxton, P. D., Hazenberg, P., Zeng, X., Troch, P. A., Niu, G.-Y., Williams, Z., Brunke, M. A., and Gochis, D.: A gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses for regional and global land surface modeling, Journal of Advances in Modeling Earth Systems, 8, 41–65, doi:10.1002/2015MS000526, 2016.

Pitman, A.: The evolution of, and revolution in, land surface schemes designed for climate models, International Journal of Climatology, 23, 479–510, doi:10.1002/joc.893, 2003.

Ramanathan, V. and Carmichael, G.: Global and regional climate changes due to black carbon, Nature geoscience, 1, 221–227, doi:10.1038/ngeo156, 2008.

Rhein, M., Rintoul, S., Aoki, S., Campos, E., Chambers, D., Feely, R. A., Gulev, S., Josey, G. C. J. S. A., Kostianoy, A., Mauritzen, C., Roemmich, D., Talley, L. D., and Wang, F.: Observations: Ocean, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by Stocker, T., chap. 3, pp. 264–265, Cambridge University Press, 2013.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., and Rafaj, P.: RCP 8.5—A scenario of comparatively high greenhouse gas emissions, Climatic Change, 109, 33, doi:10.1007/s10584-011-0149-y, 2011.

Riley, W., Subin, Z., Lawrence, D., Swenson, S., Torn, M., Meng, L., Mahowald, N., and Hess, P.: Barriers to predicting changes in global terrestrial methane fluxes: analyses using CLM4Me, a methane biogeochemistry model integrated in CESM, Biogeosciences, 8, 1925–1953, doi:10.5194/bg-8-1925-2011, 2011.

Running, S. W. and Gower, S. T.: FOREST-BGC, a general model of forest ecosystem processes for regional applications. II. Dynamic carbon allocation and nitrogen budgets, Tree physiology, 9, 147–160, doi:10.1093/treephys/9.1-2.147, 1991.

Running, S. W. and Hunt, E. R.: Generalization of a forest ecosystem process model for other biomes, BIOME-BCG, and an application for global-scale models, in: Scaling Physiological Processes: Leaf to Globe, chap. 8, pp. 141–158, Elsevier, doi:10.1016/B978-0-12-233440-5.50014-2, 1993.

Schmidt, G. A., Kelley, M., Nazarenko, L., Ruedy, R., Russell, G. L., Aleinov, I., Bauer, M., Bauer, S. E., Bhat, M. K., Bleck, R., et al.: Configuration and assessment of the GISS ModelE2 contributions to the CMIP5 archive, Journal of Advances in Modeling Earth Systems, 6, 141–184, doi:10.1002/2013MS000265, 2014.

Schuur, E., McGuire, A., Schädel, C., Grosse, G., Harden, J., Hayes, D., Hugelius, G., Koven, C., Kuhry, P., Lawrence, D., et al.: Climate change and the permafrost carbon feedback, Nature, 520, 171–179, doi:10.1038/nature14338, 2015.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating soil moisture–climate interactions in a changing climate: A review, Earth-Science Reviews, 99, 125–161, doi:10.1016/j.earscirev.2010.02.004, 2010.

Shangguan, W., Hengl, T., de Jesus, J. M., Yuan, H., and Dai, Y.: Mapping the global depth to bedrock for land surface modeling, Journal of Advances in Modeling Earth Systems, doi:10.1002/2016MS000686, 2017.

Slater, A. G. and Lawrence, D. M.: Diagnosing present and future permafrost from climate models, Journal of Climate, 26, 5608–5623, doi:10.1175/JCLI-D-12-00341.1, 2013.

Smerdon, J. E. and Stieglitz, M.: Simulating heat transport of harmonic temperature signals in the Earth's shallow subsurface: Lower-boundary sensitivities, Geophysical research letters, 33, doi:10.1029/2006GL026816, 2006.

Steinert, N., Fidel González-Rouco, J., Hagemann, S., De-Vrese, P., García-Bustamante, E., Jungclaus, J., Lorenz, S., and Melo-Aguilar, C.: Increasing the depth of a Land Surface Model: implications for the subsurface thermal and hydrological regimes., in: EGU General Assembly Conference Abstracts, vol. 20, p. 17035, 2018.

Stern, I.: Permafrost Carbon RCN forcing data, http://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.permafrostRCN_protocol2_forcing.html, 2013.

Stevens, M. B., Smerdon, J. E., González-Rouco, J. F., Stieglitz, M., and Beltrami, H.: Effects of bottom boundary placement on subsurface heat storage: Implications for climate model simulations, Geophysical research letters, 34, doi:10.1029/2006GL028546, 2007.

Stocker, T., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M.: Climate Change 2013: The Physical Science Basis, 2013.

Strauss, J., Schirrmeister, L., Grosse, G., Wetterich, S., Ulrich, M., Herzschuh, U., and Hubberten, H.-W.: The deep permafrost carbon pool of the Yedoma region in Siberia and Alaska, Geophysical Research Letters, 40, 6165–6170, doi:10.1002/2013GL058088, 2013.

Swenson, S. and Lawrence, D.: GRACE-based assessment of interannual groundwater dynamics in the Community Land Model, Water Resources Research, 51, 8817–8833, doi:10.1002/2015WR017582, 2015.

Swenson, S., Lawrence, D., and Lee, H.: Improved simulation of the terrestrial hydrological cycle in permafrost regions by the Community Land Model, Journal of Advances in Modeling Earth Systems, 4, doi:10.1029/2012MS000165, 2012.

Thomson, A. M., Calvin, K. V., Smith, S. J., Kyle, G. P., Volke, A., Patel, P., Delgado-Arias, S., Bond-Lamberty, B., Wise, M. A., Clarke, L. E., et al.: RCP4. 5: a pathway for stabilization of radiative forcing by 2100, Climatic change, 109, 77, doi:10.1007/s10584-011-0151-4, 2011.

Thornton, P. E. and Rosenbloom, N. A.: Ecosystem model spin-up: Estimating steady state conditions in a coupled terrestrial carbon and nitrogen cycle model, Ecological Modelling, 189, 25–48, doi:10.1016/j.ecolmodel.2005.04.008, 2005.

Thornton, P. E., Law, B. E., Gholz, H. L., Clark, K. L., Falge, E., Ellsworth, D. S., Goldstein, A., Monson, R. K., Hollinger, D., Falk, M., et al.: Modeling and measuring the effects of disturbance history and climate on carbon and water budgets in evergreen needleleaf forests, Agricultural and forest meteorology, 113, 185–222, doi:10.1016/S0168-1923(02)00108-9, 2002.

UCAR: Community Land Model, http://www.cesm.ucar.edu/models/clm/, 2016.

Van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., et al.: The representative concentration pathways: an overview, Climatic change, 109, 5, doi:10.1007/s10584-011-0148-z, 2011.

Viovy, N.: CRUNCEP Version 7 - Atmospheric Forcing Data for the Community Land Model, http://rda.ucar.edu/datasets/ds314.3/, 2018.

Wania, R., Ross, I., and Prentice, I.: Implementation and evaluation of a new methane model within a dynamic global vegetation model: LPJ-WHyMe v1. 3.1, Geoscientific Model Development, 3, 565–584, doi:10.5194/gmd-3-565-2010, 2010.

Wu, T., Song, L., Li, W., Wang, Z., Zhang, H., Xin, X., Zhang, Y., Zhang, L., Li, J., Wu, F., et al.: An overview of BCC climate system model development and application for climate change studies, Journal of Meteorological Research, 28, 34–56, doi:10.1007/s13351-014-3041-7, 2014.

Yongjiu, D. and Qingcun, Z.: A land surface model (IAP94) for climate studies part I: Formulation and validation in off-line experiments, Advances in Atmospheric Sciences, 14, 433–460, doi:10.1007/s00376-997-0063-4, 1997.

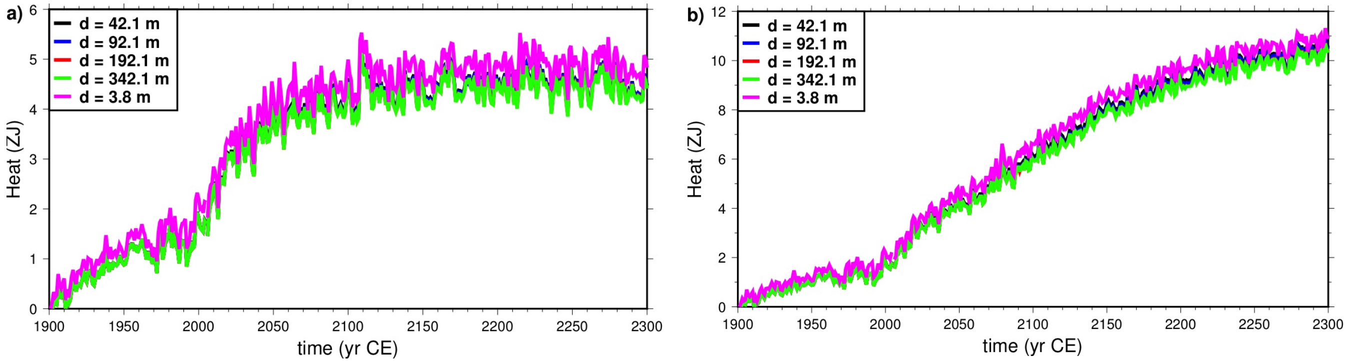

Figure S1. Heat stored in the soil (upper 3.8 m), for models of subsurface thickness d of 42.1 m (black), 92.1 m (blue) 192.1 m (red)~~and~~ , 342.1 m (green), and 3.8 m (magenta). a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data. Note the vertical scale difference between ~~scenarios 4.5 and 8.5~~the two panels.

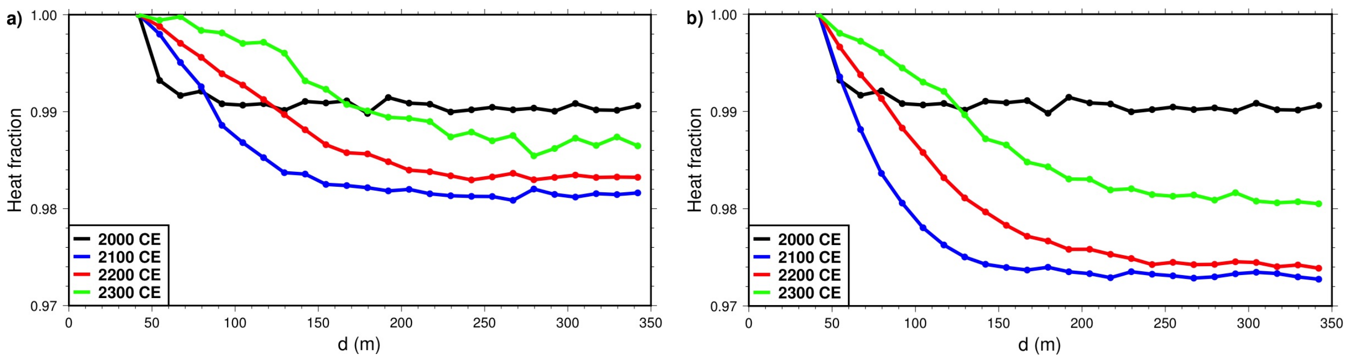

Figure S2. Heat stored in the soil as function of subsurface thickness, as fraction of that the ~~thinnest~~ original model (~~d=42.1~~ $d = 42.1$ m). Years 2000 (black), 2100 (blue), 2200 (red) and 2300 (green). a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data. Note the vertical scale difference between ~~scenarios 4.5 and 8.5~~the two panels.

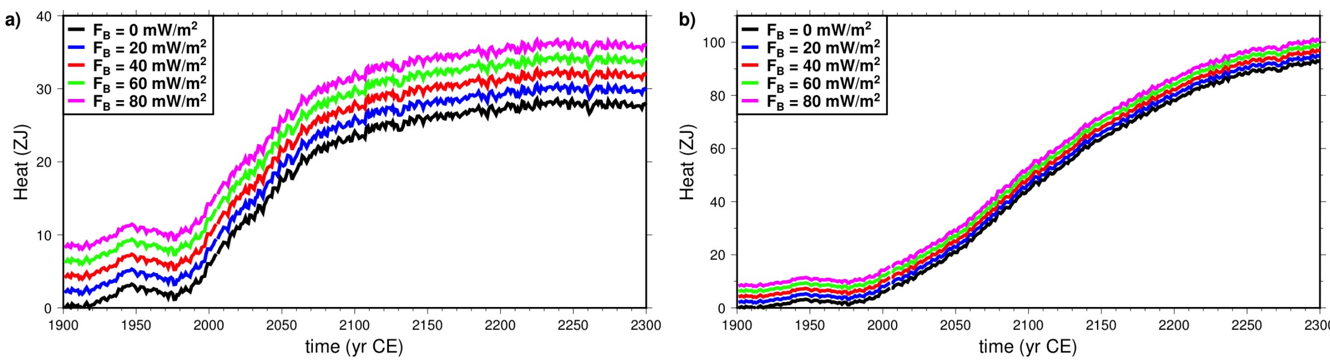

Figure S3. Heat stored in the upper 42.1 m (the thickness of all models is 42.1 m) as function of crustal heat flux, ~~referenced~~ relative to the initial heat content of the original model (~~$F_B = 0\ \mathrm{W\ m^{-2}}$~~$F_B = 0\ \mathrm{mW\ m^{-2}}$). The heat content in each model is a static shift from that of the original model. a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data. Note the vertical scale difference between ~~scenarios 4.5 and 8.5~~the two panels.

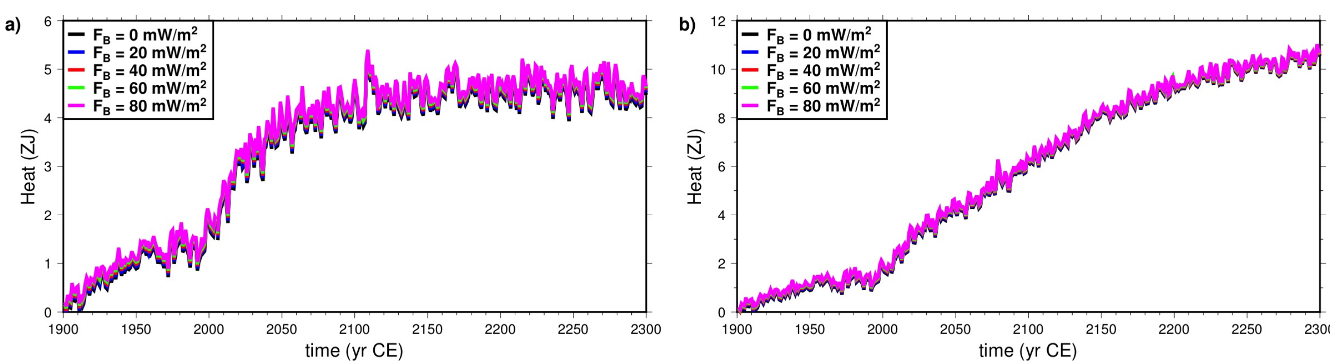

Figure S4. Heat stored in the soil (upper 3.8 m) as function of crustal heat flux, ~~referenced~~ relative to the initial heat content of the original model (~~$F_B = 0\ \mathrm{W\ m^{-2}}$~~$F_B = 0\ \mathrm{mW\ m^{-2}}$). a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data. Note the vertical scale difference between ~~scenarios 4.5 and 8.5~~the two panels.

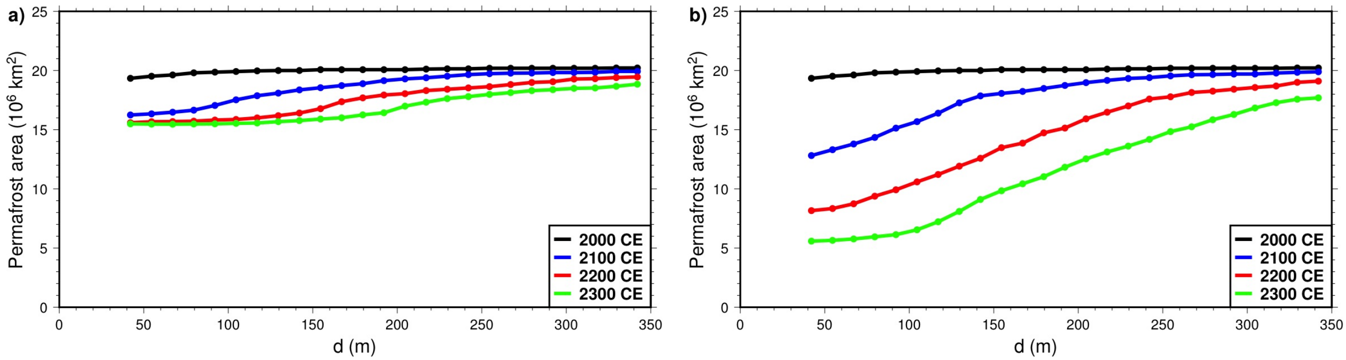

Figure S5. Northern Hemisphere intermediate-depth permafrost area as function of subsurface thickness d, at the years 2000 (black), 2100 (blue), 2200 (red) and 2300 (green). a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data.

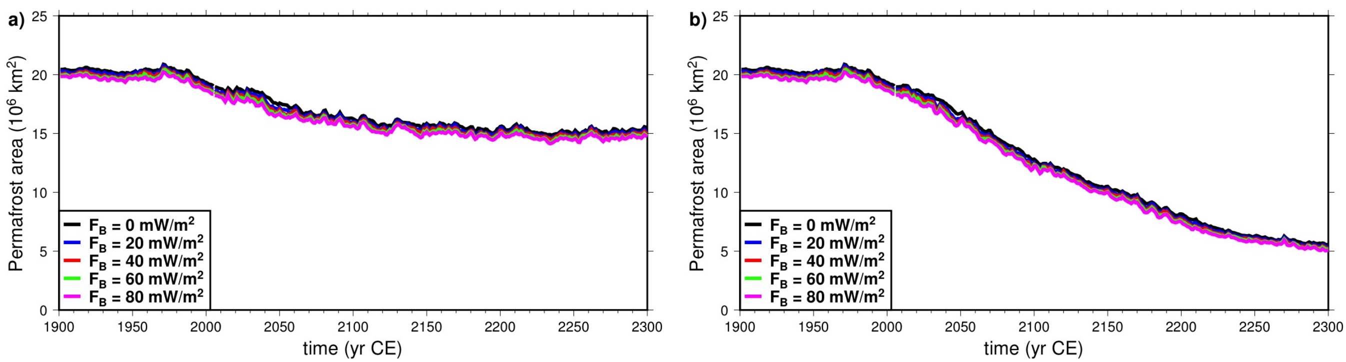

Figure S6. Northern Hemisphere intermediate-depth permafrost area as function of time. Model versions using different heat flux as bottom boundary. a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data.

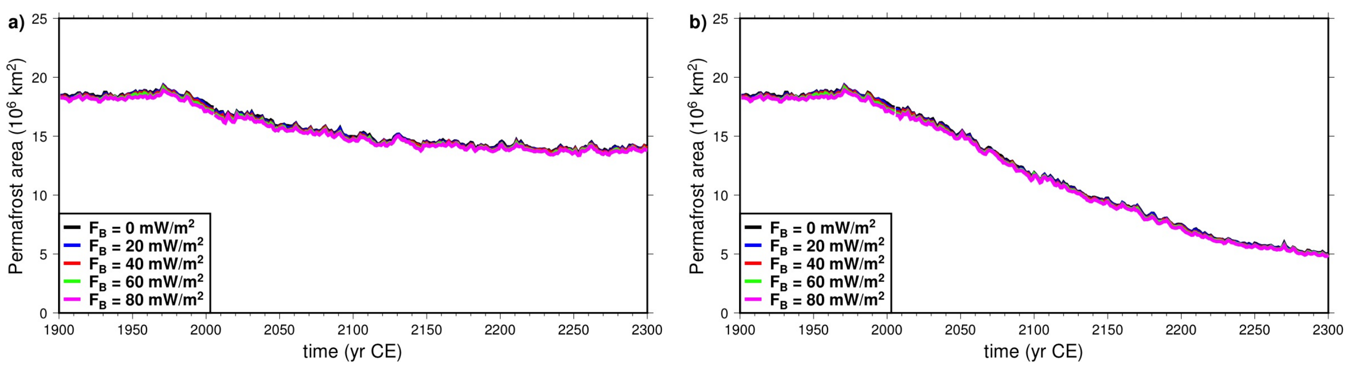

Figure S7. Northern Hemisphere near-surface permafrost area as function of time. Models using different heat flux as bottom boundary. a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data.

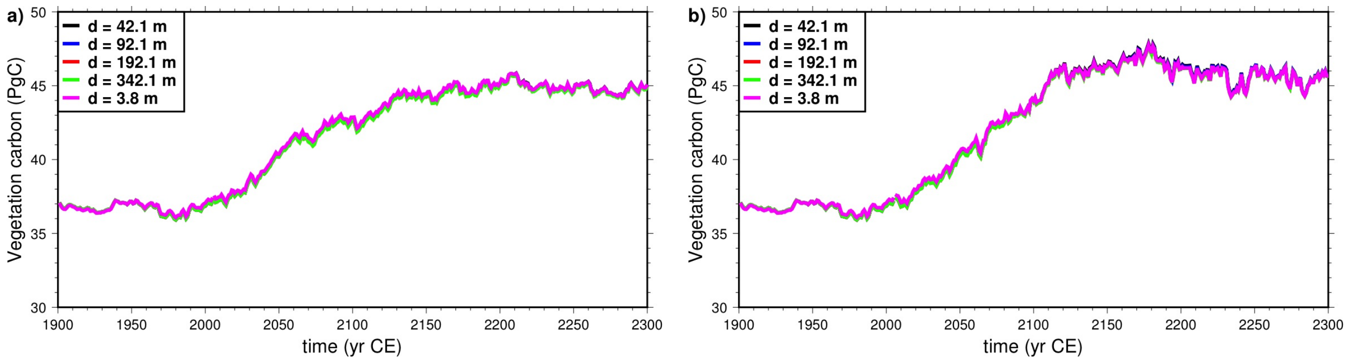

Figure S8. Vegetation carbon pool in the Northern Hemisphere permafrost region. Models with varying bottom boundary depth. a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data.

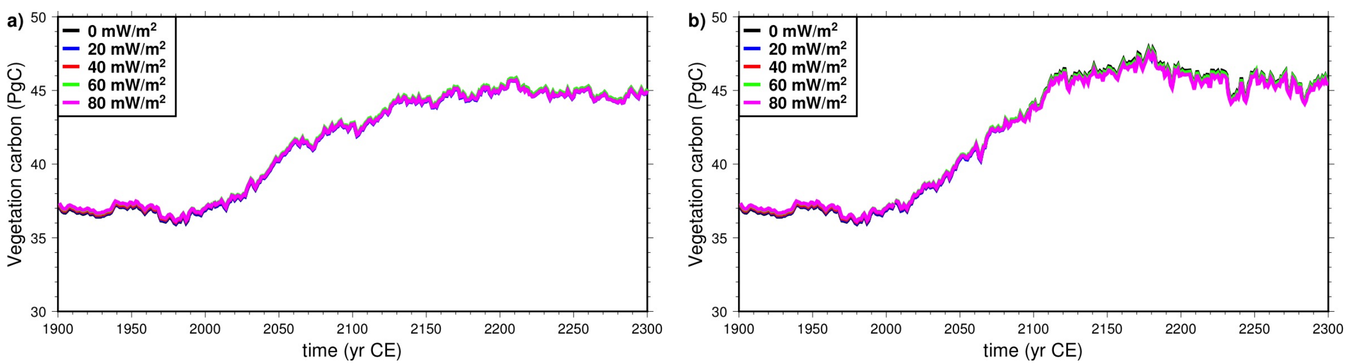

Figure S9. Vegetation carbon pool in the Northern Hemisphere permafrost region. Models with varying basal heat flux. a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data.

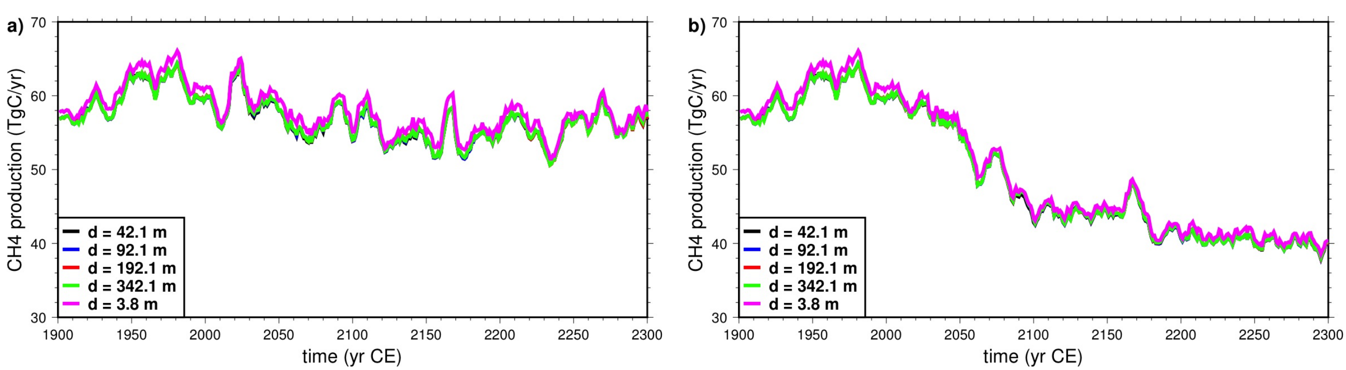

Figure S10. Global yearly methane production as function of time, moving average of 10 years. Models with varying bottom boundary depth. a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data.

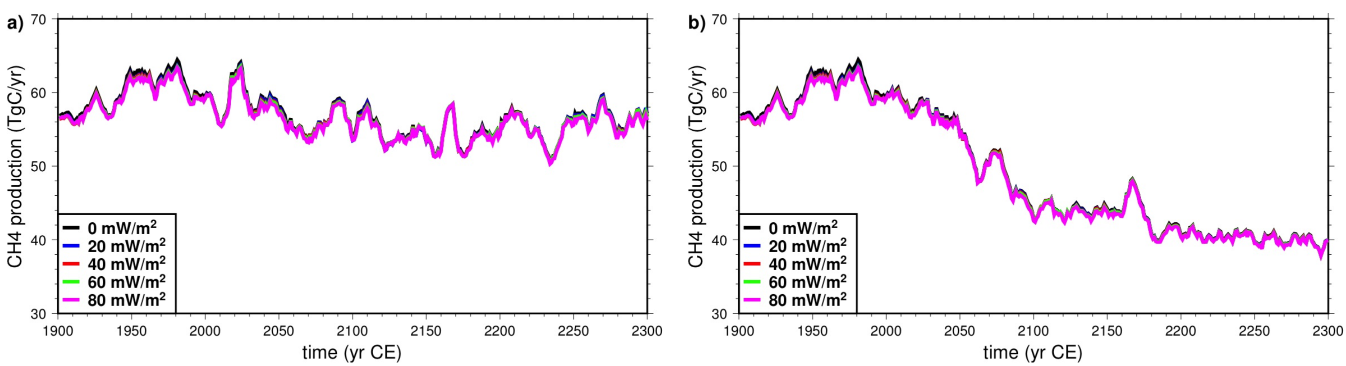

Figure S11. Global yearly methane production as function of time, moving average of 10 years. Models with varying basal heat flux. a) Simulations forced with CRUNCEP + RCP 4.5 data. b) Simulations forced with CRUNCEP + RCP 8.5 data.