Geosci. Model Dev. Discuss.,
https://doi.org/10.5194/gmd-2018-233-AC2, 2019

Geoscientific Model Development Discussions

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.

Ignacio Hermoso de Mendoza et al.

ihmn.zgz@gmail.com

Received and published: 6 May 2019

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.geoscimodel-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:

1. **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

2. **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.

3. **Mention that the two parallel planes are the upper and lower surface.** We have made this correction.

4. **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.

5. **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.

6. **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.

7. **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 that 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.

8. *(... 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.

9. *(... 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:

1. **Use “20mW/m2” instead of “0.02W/m2”.** As requested, we have changed all the units from Watts to mili-Watts throughout the text.

2. **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.

3. **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.

4. **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”.

5. *(... 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.

6. **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.

Also note that, as part of the changes demanded by reviewer 2, we have moved 11 figures (9, 10, 11, 12, 14, 15, 17, 23, 24, 28 and 29) to supplementary materials, cutting the number of figures in the main body of the paper from 29 to 18. We have also included a new simulation where we reduce the thickness of the subsurface to 3.8 m.

References:

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.

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

Davies, J. H., Davies, D. R. (2010). Earth's surface heat flux.Âă*Solid Earth,Âă1*(1), 5-24.

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