Response to Interactive Comment by A. Atchley

The authors thank the referee for providing a thorough review of the manuscript. His ideas and corrections will surely improve the clarity and message of the work.

General Comments

1. *"While the authors provide a good background of VAMPER and iLOVECLIM development, specifics of* ***how these improvements compare to the state of other large-scale Earth system models is missing*** *(at least in the introduction), and therefore the contribution of this new capability is somewhat lost to the reader.* ***Specifically how this model is well suited to capture the transient nature of permafrost compared to what is already available from other Earth system models****?"*

   Response: We agree that a review of the current state of Earth system models with respect to permafrost modeling would bring additional relevance to the work.

   Change: We propose to add a section in the Introduction reviewing other model capabilities in capturing permafrost.

2. *"The manuscript would also benefit with a more detail description in section 2.2.2 of how VAMPER(s) is coupled to ECBilt, that moves beyond figure 3 to provide specific equations and mechanics of the coupling process. Is this an implicit or explicit coupling scheme? Specifically, equations showing how air surface temperature is incorporated in VAMPER(s) and how the ground heat flux is used in ECBilt would be beneficial to readers interested in coupling processes across the land atmosphere boundary."*

   Response: This work is focused on the VAMPER side (i.e. semi-coupling) of the coupling where the air temperature from ECBilt is taken by VAMPER. This is fairly simple and the authors believe is described sufficiently. The associated equations and how this is solved within VAMPER is described in Kitover et al., 2013. The ground heat flux on the ECBilt side will be described in the future when the full coupling experiments are published. It is not relevant for this work beyond the conceptual idea, as illustrated in Figure 3.

   Change: We propose to give a reference to the reader in section 2.2.2, which allows them to look at all the equations and how they are solved within the VAMPER model.

3. *By carefully reading the paper it is apparent that the VAMPER(s) surface temperature is simply the air temperature, and while that may be adequate for the scale of the model,* ***it is then not clear how heat flux or for that matter latent and sensible fluxes are (mentioned page 8000 paragraph 5) calculated.***

Response: We agree with the referee that this is not a clear description of how the full coupling works, particularly with no equations. At this time, we choose to give a conceptual description of the full coupling without the equations since they are not actually applied in this work.

Change: We propose to additionally mention that that this description (page 8000, lines 5 – 9) is for a full coupling, which is to be described in detail with associated equations in the future work of a fully coupled ECBilt-VAMPER iLOVECLIM experiments. We have also provided more clarity on the heat fluxes at the ground surface: "The air surface temperature is calculated within ECBilt as a function of the heat balance equation where the major heat fluxes across the air/surface interface are incorporated: sensible heat flux, latent heat flux, shortwave radiation, and longwave radiation."

Specific Comments

1. *Page 7993, L15-20: It is not clear that the subdaily time step is forced by diurnal air temperature because it is later stated (Page 7994 L9-13) that the temperature forcing is a sine function for the annual temperature with no subdaily (night versus day) signal.*

   Response: Authors agree that these are conflicting statements. The larger timesteps of previous research of course neglects diurnal effects. But it is also the case that our model, although using a 4-hr timestep, cannot capture these either.

   Change: We propose to remove "in turn ignoring diurnal air temperature behavior".

2. *Page 7994, L9-13: Why not use a daily timestep instead of a subdaily timestep of 4hrs? How is the sine forcing function able to capture diurnal effects? Is the 4-hour timestep only due to model convergence issues?*

   Response: As assumed by the referee, a subdaily timestep is used for convergence issues within VAMPER. The approximation error is reduced by using a smaller timestep. Since the suggestion of diurnal effects was removed (see specific comment 1 above), we do not claim to capture diurnal effects.

   Change: no change needed

3. *Page 7994, L25-28 & 7995, L1-5: The process behind the thermal offset is not well described here. I assume it is due to differences in ice, water, and air thermal conductivities and that during the summer when positive thermal propagation is occurring the active layer is more insulative thus reducing permafrost warming. Conversely during the winter when the active layer is frozen, it is more thermally conductive and permafrost is cooled. This processes is not well described here and therefore the results by themselves seem counter intuitive.*

Response: Since we have a simple model (absent of vegetation, organics, an unsaturated subsurface, or variable water content) we can easily attribute the thermal offset to seasonal differences in thermal conductivity, whereas the thermal conductivity of ice is four times that of unfrozen water and therefore the freezing front is propagated more effectively than the warming front. This difference causes a shift in the average depth-temperature profile (Fig. 1a)

Change: Additional clarity is provided in this section with the above explanation.

4. *Page 7996, L25: equation 3: Is there a reference for this equation?*

   Response: reference available

   Change: reference of Lynch-Stieglitz (1994) provided

5. *Page 7998, L10-15: Here, the snowpack is discretized into three layers, but it is not clear has to how each layer evolves due to snow age and snow deformation. Why not just a one layer snow model? Perhaps it would be beneficial to describe the differences of each layers deformation process.*

   Response: VAMPER is a finite difference model and integrates the snowpack using three overlying snow nodes (layers). As with standard finite difference models, it typically results in a better (reduced error) approximation when multiple nodes are used. There is no unique deformation process to each layer. It simply depends on the timing and degree of the freezing/warming into the snow layers. They undergo the same deformation/melting/freezing rules. The model redistributes the snow layer thicknesses and associated density with each time step.

   Change: We propose to add a simple explanation stating that there is no difference in deformation between the layers: "All three snow layer are subject to the same processes and simply depend on temperature, time, and thickness for their respective deformation and/or melting."

6. *Page 7999, L22-23: It is not clear what is meant by, "In this case, the air surface temperature from ECBilt is assumed to be above the snow." Does this mean that the snow surface temperature is the air temperature? If so, that should probably be explicitly stated as there are other ways to assign snow surface temperature.*

   Response: We agree that this is a bit ambiguous. As the referee assumes, this indeed means the snow surface temperature is the air temperature.

   Change: We propose to rewrite as suggested: "In this case, the snow surface temperature is taken to be the air surface temperature."

7. *Page 7999: Given that VAMPER(s) is a 1-D model, there is no lateral heat conduction or water flow, and while this is not uncommon at this scale, it is worth mentioning, so that the reader is aware of this simplification.*

   Response: We agree that it would provide added awareness of the VAMPER simplification and limitations.

   Change: We propose to add sentence: "As VAMPER is a 1-D model, there is no lateral energy (heat/water) transfer between adjacent grid cells in the subsurface."

8. *Page 8000, L7-8: Here a heat balance equation is mentioned for use in VAMPER(s), but this equation is not presented in this manuscript. In order for the reader to understand exactly how VAMPER(s) is coupled to ECBilt it is necessary to present this equation in order to show which terms are provided from and to ECBilt. This will also help, the reader understand how exactly sensible and latent heat fluxes are calculated, which is an important bit of information. On that note, it is worth presenting any equations on the ECBilt side to show how the coupling of subsurface and atmospheric models function*.

   Response: As responded to in the General Comments 2 and 3, the semi-coupling does not use any equations but rather just a passing of the air temperature variable from ECBilt to VAMPER. To find the set of equations used by VAMPER, the reader is referred to an earlier paper (Kitover et al., 2013) which presents the equations, including the standard heat diffusivity equation.

   Change: As also explained in the General Comments 2 and 3, we propose that some additional clarification is provided in this section. The equation which describes the full coupling is not yet necessary for a semi-coupled model. The equations for the individual models, VAMPER and ECBilt, are available in Kitover et al., 2013 and Opsteegh et al., 1998, respectively.

9. *Page 8001, L19: Was the whole model run for just the northern latitudes or whole globe? Please clarify for the reader.*

   Response: Model is run for whole globe.

   Change: We propose as suggested to clarify that this was run for the whole globe

10. *Page 8002, L5-14: While this is somewhat discussed later in the paper, it is also important here to acknowledge that while assuming the permafrost is at equilibrium with the atmosphere is perhaps an acceptable approach to this difficult problem, it is known that permafrost is not currently at equilibrium.*

    Response: We agree that we should make this disclaimer.

Change: We propose to add in the sentence: “Although the model approaches a steady state through the subsurface depth, we acknowledge that in reality, some of the permafrost regions are not at equilibrium since they are responding to recent warming.”

11. *Page 8003, L8-10: “This swing of inaccuracy is the result of attempting to match results for a low resolution grid to spatial overage of much higher resolution.” This is somewhat of a simple answer to a much more complicated problem, which really high-lights the need for to reconcile observational scales and modeling results. However, without specifically testing a model with spatial resolution matching the observations, it is not appropriate to state the miss match is uniquely due to scale issues, though probably part of the problem. Instead it may be more appropriate to ask if this low resolution grid is a valid approach to investigate the utility of simulating a snowpack? Is the snowpack really a model enhancement?*

    Response: We agree that there may be other factors which contribute to the inaccuracy or mismatch that occurs whether the snow model is used or not. However, we still contend that it is better to model the surface offset induced by the snowpack, which is one of the most dominant factors in air-ground coupling (Smith and Riseborough, 1998) rather than ignoring it. The offset map (Figure 8) and comparison to observations (mentioned in the discussion in section 3.2.1) support the VAMPERS results. In addition, because the model works at a coarse spatial scale, we cannot paramterize it to specific observation sites. During the model development, as a single site permafrost model, we were able to match observation values. These figures, one for Alaska and one for Minnesota, are provided in the supplements.

    Change: We propose to add in some discussion at this point regarding, as the reviewer suggests, problems with modeling snow at this resolution. In addition we will mention other factors which cause mismatch in the model results, e.g. air-ground coupling.

12. *Page 8003, L15: I am not convinced that at this resolution, the snowpack model is an ‘enhancement’. It is however an alternative model formulation that could be used to test some idea’s, though I would argue that a more spatially resolved model would be more helpful in this case.*

    Response: We understand the reviewer’s point that the snow model does not enhance (as to improve) the results. However, improving the number of options in the VAMPER model so that there is a more realistic representation does itself “enhance” or improve the model. Because of this distinction, we have rephrased, when appropriate, description of the snow component as an additional option rather then it as enhancing the results.

    Change: We propose to describe, throughout the paper when appropriate, the snow component as an option rather than as an enhancement.

13. Page 8007, L4-6: Could the fact that the simulated colder subsurface temperature is due to the lack of calculating a surface energy balance to assign a surface temperature? Doing so would account for incoming radiation fluxes, which can warm the surface relative to the air temperature.

    Response: The ECBilt land surface temperature which forces the VAMPER model is already a function of a prior computed surface energy balance. The interactions at the surface include standard energy fluxes: longwave and shortwave radiation, and latent and sensible heat fluxes. This is described in Goosse et al., 2010. Therefore, it is more likely that the colder than expected subsurface temperatures are a function of either the air-ground coupling which may overlook effects from vegetation and organic layers or the porosity (water content) parameter. This was already mentioned and discussed as possibilities (3.2.1, fourth paragraph, 3.2.2 last paragraph, 3.2.3 last paragraph)

    Change: We propose no change here although due to some other comments the discussion points for this topic have been extended.

Technical Corrections

All technical corrections have been accepted and used to edit the manuscript accordingly.

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Response to Interactive Comment by C. Avis

The authors thank the referee for providing a thorough review of the manuscript. His ideas and corrections will surely improve the clarity and message of the work.

General Comments

1. *One area that I found that the paper was a little lacking was that there was not much comparison or discussion of how the model stacks up against other coupled permafrost models in terms of the level of complexity of the processes represented and how well the model captures the observed distribution of permafrost. The validation comparisons for the coupled model are compatible with how other coupled climate/permafrost models have been evaluated in the literature and so it should be fairly straightforward to compare the results of this model's validation against the work done by other permafrost modeling groups and I think would strengthen the paper.*

   Response: We also agree that the paper would benefit from some comparison with similar studies. Although there are not many, we will discuss comparison with a recent larger project from Koven et al. 2012, which compared Earth System models ability to reconstruct permafrost.

   Change: We propose to compare our results of modeling present permafrost distribution to the work of Koven et al. 2012. This is done at the end of section 3.2.1.

2. *A second area that I found a little lacking was that there is not much description of the hydrology of the model (or lack thereof). From a read through of the paper, it seems that the model is solely tracking heat flow through the subsurface layers and no fluxes of water are explicitly described in the subsurface layers. The authors suggest that they account for some of the influence of water and ice in the ground (e.g. p. 7989, L19 "deep 1-D heat conduction model with phase change capability",) but a little more detail as to how this is handled is appreciated. I.e. is it assumed that the ground layers are saturated at all times with moisture in order to perform these calculations? If hydrology is not explicitly handled in the model, the authors might want to comment about how this omission may impact their results.*

   Response: The authors agree that hydrology is an important factor in permafrost modeling and was largely skipped in terms of a discussion piece. The VAMPER model does not explicitly handle any hydrology other than assuming a saturated subsurface. On the other hand ECBilt integrates a simplified surface hydrology and a bucket model but as of now, these elements are not coupled to VAMPER. It is indeed likely that the results are impacted by a lack of coupled hydrology between VAMPER and ECBilt.

   Change: We propose to acknowledge the state of hydrological modeling when appropriate throughout the manuscript, including as the reviewer suggests 1) more detail on the hydrology in the VAMPER model description (section 2.1.1), its presence in ECBilt (section 2.2.2) and, impact of no coupled hydrology between VAMPER and ECBilt on the results (section 3.2.1, 4th paragraph) .

3. *Finally, I think there are a few other climate metrics that could be included in the paper. The authors' inclusion of a reasonably sophisticated snowpack scheme into the VAMPERS model produces fairly substantially different results compared against the model being run without a snow component. Yet, there is no discussion of how well the model represents the timing, extent and thickness of snow*

cover. The authors might consider comparing their model's snow cover output against observation or reanalysis based datasets and discussing how well snow cover is captured, especially if this is indeed a major determinant of permafrost characteristics.

Response: Modeling the snowpack against observations was previously validated while in development. However, these validations required specific site parameterizations when compared with observations. For a global earth system model of coarse resolution, this kind of observation validation is simply not possible. What would be parameterized for a very dense, wet snowpack near Anchorage Alaska would not apply for a dry thin snowpack on the windy plains of Siberia. This applies likewise for the characteristics of the snowpack along with the snowmelt model. Further, it should also be acknowledged that the role of VAMPERS in terms of adding a snowpack was to simply prescribe general snowpack characteristics so that we can simulate the effect of the snowpack offset between the air temperature and ground temperature, essentially adding some layers to the 1-d heat conduction model. The actual snowpack melting, timing, runoff, etc. is performed within ECBilt and description of this model is already published in Goosse et al. (2010) and Opsteegh et al. (1998).

Change: We propose to add as a supplement some figures (shown below as Figures S1 and S2) showing the ability of the parameterized, site-specific version of VAMPERS to reproduce the snowpack as compared to observations. The provided graphs were made for two sites: Crescent Lake, Minnesota and Slate Creek, Alaska. These sites were selected because they had all the available data: daily air temperature, daily soil temperature, and daily snowfall in meters of snow water equivalent.

4. *Similarly, the authors suggest that ECBilt does a good job of simulating surface air temperatures save for a few noted anomalous regions. But a plot using the same polar projection as the others in the paper showing how well annual average (and/or seasonal average) surface air temperatures from the model compare to observations would be quite useful to back up this claim.*

   Response: Thank you for pointing this out but a lot of research, in varying model configurations, has been produced to discuss the results of ECBilt. It would be outside the scope of this work to substantiate and re-analyze how well the air temperatures are produced. It is the goal of this work to highlight VAMPER and how well as a semi-coupled version within iLOVECLIM, the present permafrost state can be reproduced.

   Change: We propose to maintain the current discussion as it is presently written in the manuscript.

Specific Comments

1. *p. 7991, L3: I was initially confused by what was meant by saying VAMPER(S) was "semi-coupled", though the authors clarified this at the start of section 3.1. My suggestion would be to present this information when the term semi-coupled is first used much earlier in the article. Also, in section, 2.2.2, the authors describe a two-way coupling between VAMPER(S) and ECBilt via VAMPER(S) passing GT heat fluxes to ECBilt. I presume that it is meant that the coupled components are capable*

of this two-way interaction, but for the purposes of the validation experiments described in section 3.1, the model is run in a semi-coupled configuration?

Response: Thank you for highlighting an early point confusion. We agree that bringing more clarity between semi-coupled and coupled would do better for the manuscript. Indeed, as the referee concluded, the model is run semi-coupled as intermediary step to fully coupling and for validation of the VAMPERS model to recreate the contemporary extent/thickness of permafrost as function of the *i*LOVECLIM climate. In 2.2.2, pursuant to comments from the other referee, the authors have already provided additionally clarity that the coupled version is for future model experiments.

Change: We propose as the referee suggests to better describe the term "semi-coupled" in the Introduction: "We use the term semi-coupled since not all the model mechanisms are fed back to each other and in this case the effects of permafrost do not impact the climate". We also propose to provide more clarity in section 2.2.2 that the coupled version will be done in future experiments and that the semi-coupled experiments are indeed for validation purposes.

2. *p.7992, L12: The authors mention the inclusion of geothermal heat flux and lithology as new aspects of VAMPER in the coupled version of the model. How significant are the differences in the model results if these modifications are not included? I ask, because both of these are modifications that are not always included in coupled permafrost models and it might be an interesting sensitivity analysis to compare these different configurations. It is mentioned (p. 8000, L. 12) that a sensitivity analysis was conducted for the geothermal heat flux, but the authors do not comment on the results of that analysis*.

   Response: In the (semi) coupled version, we incorporated spatially varying maps which allowed the parameters of porosity and geothermal heat flux to vary in the VAMPERS model, depending on location. This is what we refer to as enhancements. Allowing heat flux and lithology to spatially vary, as opposed to a constant value throughout the globe, did not provide any notable change in the simulated permafrost distribution. This implies that the forcing of air temperature, regardless of the lithology or geothermal heat flux, dominantly determined whether permafrost was present or not. As a result, changing the lithology / geothermal heat flux will not be noticeably different in a map which only illustrates permafrost extent, i.e. whether it exists in the given gridcell or not. On the other hand, however, permafrost thickness is indeed sensitivity to subsurface lithology and geothermal heat flux. It is the sensitivity of permafrost thickness to porosity and the geothermal heat flux, which was demonstrated in the earlier sensitivity study published (Kitover et al., 2013). The authors acknowledge this differentiation between sensitivity to permafrost extent versus permafrost thickness was ambiguous.

   Change: We propose to rewrite the sections on geothermal heat flux and lithology enhancements in order that there is clearer understanding between sensitivity of spatially varying the parameters and sensitivity of permafrost thickness to the parameters.

3. *p. 7994, L16. The authors mention a constant heat flux and porosity setting used in the timestep comparison section. How were these values chosen? I presume they are simply values for a chosen gridcell in the model but is there a particular reason these values were chosen, or were they selected at random? I have the same comment regarding the values used for the parameters in the Stefan equation (Table 1) could the authors provide a source for these values or justification as to why they were selected ?*

   Response: In the timestep comparison section, the heat flux (60 mW/m2) and porosity (0.3) were chosen because 1) they are very commonly occurring values in the subsurface since 60 mW/m2 is around the global average (Davies, 2013) and 0.3 is near the porosity for a sandy mineral material (Magara, 1980) and 2) the values are the same used in the prior sensitivity study from Kitover et al. (2013) and therefore keep in continuity with previous studies regarding VAMPER. For the Stefan equation, the parameter values such as dry density and thermal conductivity are the same values used in a stand-alone version of the VAMPER model, which in turn calculates based on methods such as the geometric mean of the composite of subsurface components (water, ice, and dry soil). The methods behind these calculations can be found in Kitover et al., (2013). The forcing is a reasonable range of cold region temperatures (for example, -6 C is about the average annual ground surface temperature in Barrow, Alaska) given as a reasonable range of seasonal amplitude.

   Change: The authors feel that the parameter used in both the timestep analysis and Stefan analysis are standard commonly occurring values and as such, are self-explanatory. We propose no change is necessary here.

4. *p. 7995, L4. The authors mention that the thermal offset is often expressed in a ratio format, but then don't make use of this information anywhere else in the article. I suggest cutting this sentence as it's redundant.*

   Response: The authors agree that this is an unnecessary statement.

   Change: We propose to remove this sentence as suggested.

5. *p. 7995, L20, L25. I assume that some of these variables (e.g. thermal conductivity of unfrozen soil, dry density of the soil) are identical or closely related to variables used in VAMPER code itself. Is this the case?*

   Response: Thank you for checking on this since making a fair comparison between the Stefan equation results and the VAMPER model results rely on using the same parameter values. Indeed, the values used in the Stefan equation were specifically chosen (for instance soil thermal conductivity) because they are the same ones calculated by the VAMPER model. These calculations are outlined in the Methods section from Kitover et al., 2013.

   Change: We propose no change is necessary here.

6. *p. 8001, L2. Porosity is not synonymous with soil water content unless the soil is at saturation. I think that's the case in the authors' model, but it should be spelled out*

   Response: The authors agree that it was presumptuous to conclude that in any case soil water content is equal to the porosity. As the referee pointed out, we indeed assume the subsurface is saturated. Also note that in the Methods section, which we make reference to of Kitover et al. (2013), it is stated that the subsurface is assumed to be saturated.

   Change: We propose to explicitly state in this section that we assume a saturated subsurface in the VAMPER model..

7. *p.8002, L4 onwards. The authors state on p.8001 that model experiments are run-semi coupled so that the climate is unaffected by changes in permafrost. Then on p.8002, they describe an asynchronous coupling methodology that is run until "approximate equilibrium between ECBilt temperatures and the VAMPER(S) model is reached." I can see this coupling methodology as being necessary in the full coupled model, but is it needed in the semi-coupled configuration? If the climate does not respond to permafrost, why not just couple the VAMPER(S) model to the climate once the climate component is already in equilibrium and then simply run the VAMPER(S) model using the ECBilt air temperature forcing until it's in equilibrium? This discussion adds to the confusion of how the "semi-coupling methodology" is handled in the paper as mentioned earlier.*

   Response: When the semi-coupled experiments begin, the iLOVECLIM model is already at equilibrium. The asynchronous approach is used because it allows a repetitive forcing (100-yr average temperature values) to the VAMPER model since it needs to spin-up or "catch-up" to the already-equilibrated climate. The repetitive forcing is done "off-line" so that iLOVECLIM does not have to run in synch with VAMPER, in turn making the experiment faster. If the asynchronous method is not used, the VAMPER model would take a lot longer to reflect the iLOVECLIM climate, whether or not it responds to the permafrost. The asynchronous approach has nothing to do with the type of coupling. The same asynchronous approach would be used in a fully coupled scheme as well. This transparency, applicable either coupled or semi-coupled, is why we disagree that it adds confusion. In addition, the semi-coupling is now explained twice (due to specific comment no. 1) for clarity, which includes a figure (3).

   Change: We propose no change here.

8. *p. 8003, L5 Re: Figure 7. I would have found the comparison between the Circumpolar PF map and the model data to be a little clearer had the PF map been plotted as a third panel, rather than beneath the permafrost thickness map. Also, it would be good to compare the total areal extent (i.e. total area in square km) of PF vs. the estimates from the Circumpolar map.*

Response: The authors disagree that the PF map should have been a separate panel. In this case, it would have been more difficult to see the overlap where the agreement and disagreement is. However, it is a good suggestion to compare total areal extent calculations and would better quantify the comparison rather than just make it visual.

Change: We propose to include a calculation of total simulated surface area of permafrost, as compared to the list from Koven et al., (2012).

9. *p. 8003, L8". This swing of inaccuracy is the result of simply attempting to match results from a low resolution grid to much higher resolution." I agree that this is certainly part of the reason for the mismatch, but there are other factors that are known to strongly influence the ground thermal regime in permafrost regions which, I believe, are lacking in the model. For example, as far as I can tell, the authors don't account for snow-vegetation-permafrost interactions, nor the presence of organic components of soil whose thermal and hydrological parameters can be quite different from mineral soils. Also, if there's a problem with the snow scheme in the model (difficult to assess without a snow cover validation), this would presumably have a major impact on the PF distribution*

   Response: We agree with the reviewer that this result is only partially due to grid resolution.

   Change: We propose to reword some of the discussion regarding "the swing of inaccuracy", in particular acknowledging that the resolution is only partially the cause. There is added subsequent discussion of some of the missing air-ground coupling components following in this section 3.2.2.

10. *p. 8007, L2. The authors show that the simulated MAGT are generally slightly lower than observations, indicating either a cold bias in the climate model or some issue in the ground-air coupling. In either case, one would conclude from this observation that the model is typically simulating ground temperatures that are a bit too cold. Can the authors reconcile this observation with the earlier statement (p.8003,L8) that ECBilt-VAMPERS underestimates the permafrost extent ? These two observations seem contradictory shouldn't a model that generally underestimates ground temperatures produce a greater distribution of permafrost? Or is the cold bias specifically something that affects higher latitude points and not points along the southern boundary of the discontinuous permafrost zone?*

    Response: It is understandable how this contradiction could be interpreted the way the reviewer describes. However, there are two separate conclusions here. The first is the extent which is underestimated with the snow component included. The second conclusion is that the subsurface temperatures are bit too cold which implies that the areas which do have permafrost are perhaps overestimating the depth.

    Change: We propose no change.

Technical Corrections

All technical corrections have been accepted and used to edit the manuscript accordingly.

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Supplementary Figures

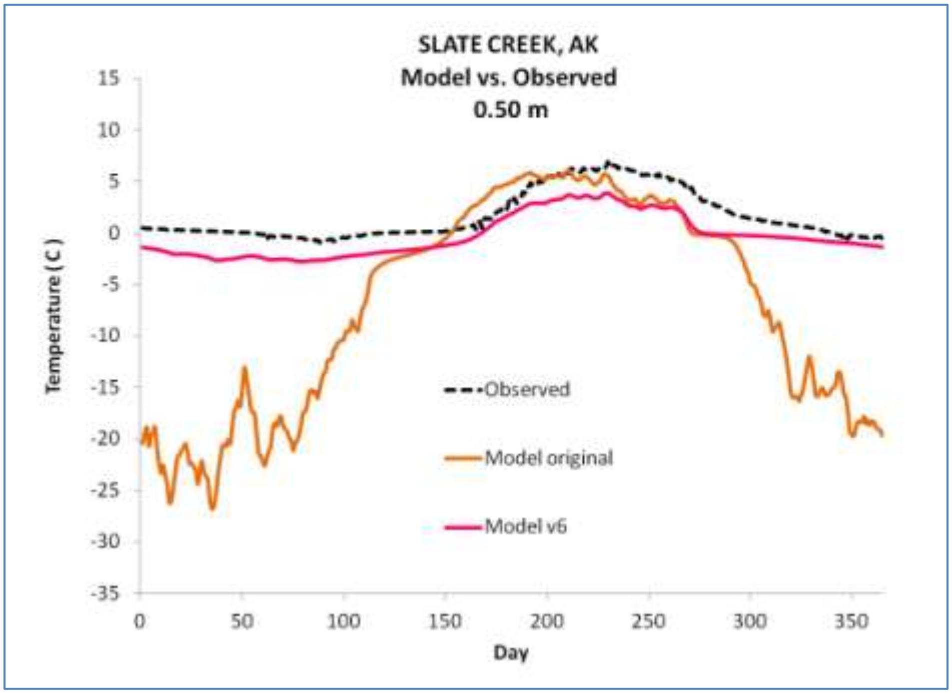

Figure S1. Comparison of observed to modeled soil temperatures (0.5 m deep) with and without using overlying snowpack.

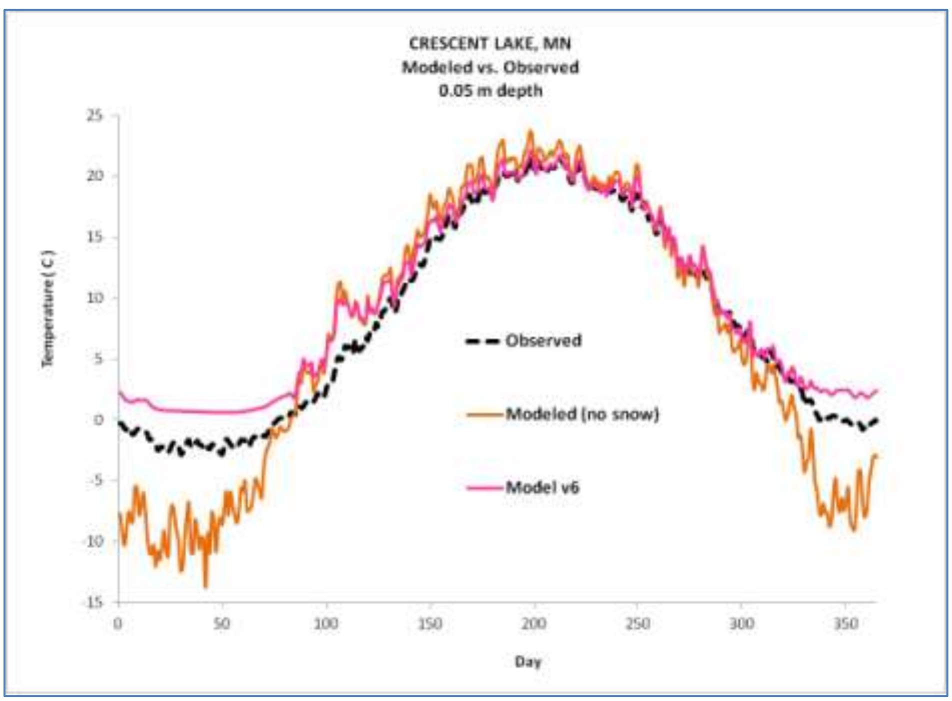

Figure S2. Comparison of observed to modeled soil temperatures (0.05 m deep) with and without using overlying snowpack.

Coupling of the VAMPER permafrost model within the earth system model *i*LOVECLIM (version 1.0): description and validation

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Abstract

The VAMPER permafrost model has been enhanced for coupling within the *i*LOVECLIM earth system model of intermediate complexity by including snow thickness and active layer calculations. In addition, the coupling between *i*LOVECLIM and the VAMPER model includes two spatially variable maps of geothermal heat flux and generalized lithology. A semi-coupled version is validated using the modern day extent of permafrost along with observed permafrost thickness and subsurface temperatures at selected borehole sites. The modeling run not including the effects of snow cover overestimate the present permafrost extent. However, when the snow component is included, the extent is overall reduced too much. It was found that most of the modeled thickness values and subsurface temperatures fall within a reasonable range of the corresponding observed values. Discrepancies are due to lack of captured effects from features such as topography and organic soil layers. In addition, some discrepancy is also due to disequilibrium with the current climate, meaning that some permafrost is a result of colder states and therefore cannot be reproduced accurately with the *i*LOVECLIM preindustrial forcings.

1 Introduction

The **VU Am**sterdam **Per**mafrost (VAMPER) model is a deep 1-d heat conduction model with phase change capability. At a number of arctic/subarctic locations, the model has simulated both equilibrium and transient permafrost depth estimates (Kitover et al., 2012; Kitover et al., 2013). The model was built with the intention to couple it within *i*LOVECLIM, an earth system model of intermediate complexity. Although the VAMPER model simulations have been previously validated and forced using climate model data, a common technique for modeling permafrost, the next step is to build on these developments, providing the ability to investigate the permafrost-climate relationship. Therefore, VAMPER has been enhanced so that it may be more realistically coupled within *i*LOVECLIM. With this coupling, it is the ultimate goal to capture the transient nature of permafrost growth/decay over millennia as a feedback effect during major periods of climate change. However, as a first step, the VAMPER model has been semi-coupled to ECBilt, the atmospheric module that includes the land component within *i*LOVECLIM, to validate the simulation of modern-day permafrost extent and thickness. We use the term semi-coupled since the coupling is only one-directional (from ECBilt to VAMPER). In other words, the effects of (changing) permafrost are not fed back to the climate. The goal of this paper is to describe this coupling and then analyze the validation experiment for modeling present-day permafrost, with detailed explanation of why mismatches occur between simulated and observed data.

The first example of VAMPER as a stand-alone deep permafrost model was for Barrow, Alaska (Kitover et al., 2012) where the experiment simply reproduced the present-day permafrost depth using monthly averaged observation data of ground “surface” (- 1 cm deep) temperatures. In this same study, VAMPER was also validated by comparing results against other developed deep permafrost models (also used for millennial-scale simulations) using similar forcings and parameter settings. In both Kitover et al. (2012) and Kitover et al. (2013), a number of transient simulations at selected locations (e.g. Wyoming, West Siberia, Central Siberia) were performed using the stand-alone version of the VAMPER model, forced by *i*LOVECLIM-generated air surface temperatures over the last 21k years (Roche et al., 2011). In addition, a sensitivity analysis was presented in Kitover et al. (2013), showing the range of simulated permafrost depths under different parameter settings.

Thus far, according to the work summarized above, VAMPER has only been employed as a post-processing , site-specific permafrost model. However, the advantage of the model being simple with limited parameterization requirements, hence resulting in speedy computation times, have not been fully realized since it is not yet coupled within *i*LOVECLIM. As a next step, this paper describes the necessary developments to couple VAMPER with ECBilt, the atmospheric component of *i*LOVECLIM, via the air surface temperature. Specifically, this presented work introduces two enhancements to the VAMPER model : 1) inclusion of ~~a~~ snow as optional layers and 2) change in the timestep. The first in particular is a common issue in modeling permafrost since snow cover is a widely recognized influence on the ground thermal regime (Williams and Smith, 1989) and was not an available option~~built~~ in the previous VAMPER model version. To compensate for this, Kitover et al. (2013) had artificially introduced the effect of snow cover via a surface offset of + 2°C. Not only was this an assumption based on a number of previous reports and observations, but it had to be applied as an annual offset since the time step was one year. This then demonstrates the need for the other enhancement, which is a sub-annual timestep, where the seasonal changes in the ground thermal conditions can be captured, allowing for representation of both the snow cover effect and the active layer. It should be noted that additional coupling mechanisms are possible between *i*LOVECLIM components and VAMPER, which include hydrology and the carbon cycle, but are not yet implemented at this time.

In addition to these VAMPER model enhancements, two global maps were produced (geo-processed from the original maps to fit the horizontal grid of ECBilt) to be used as additional input parameters in the *i*LOVECLIM model: geothermal heat flux and lithology.

Integrating permafrost into earth system models has become of increased interest since research has acknowledged both its sensitivity to climate change along with carbon feedback implications. In fact, Koven et al. (2013) recently reported on the Coupled Model Intercomparison Project phase 5, which specifically looked at how different models represent the subsurface thermal dynamics and how well this class of models simulate permafrost and active layer depth. Despite the fact that this study introduced the variety of how different global coupled models capture permafrost, the overall conclusion was that there is no clear ranking among their reviewed 15+ model configurations. This shows that representing permafrost in earth system models still has some challenges,which Koven et al. (2013) attribute primarily to modeling of both the atmosphere/ground energy exchange and the subsurface thermal regime. Until recently, most simulations of permafrost were calibrated for regional or local study such as Li and Koike (2003) on the Tibetan Plateau, Zhang et al. (2006) in Canada, and Nicolsky et al. (2009) in Alaska. A growing number of studies are now modeling permafrost across a global scale, namely these are from Lawrence and Slater (2005), Schaefer et al.(2011), and Dankers et al. (2011). However, it should be noted that there is a difference between coupled models which actively integrate the role of permafrost (including the thermal and/or carbon feedbacks) and models which simply look at permafrost in a post-processing perspective, meaning they are forced by the predicted temperature changes. It is the full coupling with integrated feedbacks which is of current interest but is still in the early stages since,as just mentioned, there remain challenges to accurately represent permafrost extent and active layer depths. ~~The class of earth system models do not~~ Hence, it is the authors' ultimate goal to fully couple ECBilt and VAMPERS within iLOVECLIM, where the results of the present work serve as an important validation stage.

In the sections following, the two enhancements to the VAMPER model are explained. This includes specific validation of the timestep change by comparing simulated annual active layer depths with empirical-based estimates. The ECBilt-VAMPERS semi-coupling within the *i*LOVECLIM model is then validated using a modern-day map of permafrost extent in the northern hemisphere and observed permafrost thickness and subsurface temperatures values in boreholes.

2 METHODS

2.1 VAMPER model

2.1.1. General Description

VAMPER is a 1-d permafrost model developed to estimate permafrost thickness and was designed for eventual full coupling with *i*LOVECLIM. Because it must fit a relatively coarse earth system model, it is not suitable to undergo cumbersome parameterization schemes. It is meant rather as a generalized model to simulate conceptual permafrost thickness based on the factors which most strongly dictate the subsurface thermal regime. Most notable for our purposes and discussed by Farouki (1981), these factors are mineral composition, water content, and temperature.

Other than what is specified below, construction of the VAMPER model has not changed and the methods as described in Kitover et al., (2013) still apply. In particular, these include assuming only conductive heat transfer in the subsurface, using an apparent heat capacity method for the latent heat component, and employing well-established methods for finding the temperature-dependent thermal properties of heat capacity and thermal conductivity (Farouki, 1981; Zhang et al., 2008). The subsurface is assumed to be saturated (i.e. porosity equals the water content) and there is currently no groundwater flow either horizontally or vertically between the soil layers.

2.1.2 VAMPER Model Enhancements

As compared to most permafrost modeling studies, there are few which have reproduced changes in permafrost thickness over geologic time periods. In these cases, they assume a larger timestep in their numerical simulations (usually one month or one year) (e.g., Osterkamp and Gosink, 1991; Lebret et al., 1994; Lunardini, 1995; Delisle, 1998) since they only need to force the models with the low frequency changes in air temperature or ground temperature that occur over millennia~~, in turn ignoring diurnal air temperature behavior.~~. Since we are also interested in this timescale, we originally employed the same reasoning: relying on large-signal paleoclimatic changes (Kitover et al., 2013). However, in light~~lieu~~ of the coupling mechanism between ECBilt and the VAMPER model, it has become clear that the VAMPER model should run on a 4-hr timestep. Doing this allows the VAMPER model to more closely follow the response timescale of the atmosphere, the subsystem to which the VAMPER model is coupled, while also allowing the numerical solution to converge since the thermal properties are temperature-dependent and hence change on every timestep. Fortunately, being that the VAMPER model is somewhat simplified, and hence flexible, this was done with some modifications to the original version. Although the original makeup of the model was validated, it has since been necessary to perform an additional verification (due to change in the timestep) while also enhancing the model with a snow layer component. *Note that the VAMPER model with the snow enhancement is referred to as the VAMPERS model. When referring to both/either versions, the "VAMPER(S)" term is used.*

Timestep

To illustrate the difference between applying the same annual average temperature forcing but with two different timesteps (4-hr vs. yearly), a sensitivity test was performed (**Fig. 1a**). To generate the sub-daily surface temperature forcing (4 hours), a year-long temperature time-series was calculated using a standard sine function with constant amplitude 20°C and average annual temperature of -6 °C (hereafter referred to as sensitivity run 1 or "sr1"), resulting in an annual range of temperatures between -26 °C and 14°C. Therefore, the case with a yearly timestep, called "sr2", simply used -6 °C as the constant forcing. Besides the change in timestep and corresponding surface temperature forcing, the thermal conductivity and heat capacity values were also allowed~~subject~~ to differ since these variables are temperature-dependent (**Fig. 1b**). However, heat flux and porosity parameter settings were the same in both model runs. Each experiment was run until approximate equilibrium was reached under the same constant (respective) forcing. We consider equilibrium to be when the geothermal heat flux is approximately equal to the ground heat flux (what goes in = what goes out). Comparing the final depth-temperature profiles between sr1 and sr2 shows a shift in the equilibrium depth-temperature profile where using an annual timestep underestimates permafrost thickness by approximately 50 meters (**Fig. 1a**). This difference is attributed to occurrence of the thermal offset within the active layer in sr1 (**Fig. 1b**), whereas sr2 cannot exhibit such seasonal phenomena. Since VAMPER is a simple model (absence of vegetation, organics, an unsaturated subsurface, or temporally varying water content) we can easily attribute the thermal offset to seasonal differences in thermal conductivity, whereas the thermal conductivity of ice is four times that of unfrozen water and therefore the freezing front is propagated more effectively than the warming front. This difference causes the mean annual subsurface temperature within the active layer to be gradually colder with depth. The offset is visible in the mean annual depth-temperature profile within the top meter of Figure 1b. ~~Freezing and thawing within the active layer region causes seasonal variations in thermal conductivity, which is known as the thermal offset (Smith and Riseborough, 2002) and has been well-observed in permafrost environments (Romanovsky and Osterkamp, 1995; Brouchkov et al., 2005). This phenomenon is highly variable and depends on the subsurface material, water content, and climate such as the annual amplitude of the surface temperature forcing (French, 2007). The thermal offset is often expressed in a ratio format, also known as an n-factor, where French (2007) reports that for bedrock this ratio is close to 1, for mineral soils between 0.6 and 0.9, and for organic soils anywhere between 0.3 and 1.~~

Active Layer

Since a sub-daily time step is used, the VAMPER model as expected produces an active layer. Most dynamical permafrost models that simulate near-surface behavior configure the parameter settings to specifically match locally observed data. Common parameterizations include organic and mineral layer thicknesses, which give soil properties such as porosity and bulk density, and unfrozen water content characteristics. Examples of these site-specific studies are numerous (e.g., Romanovsky and Osterkamp, 2000; Buteau et al., 2004, Ling and Zhang, 2004; Zhang et al., 2008; Nicolsky et al., 2009). Since VAMPER is not parameterized to capture site-specific behavior, it is challenging to assess the ability of the model to simulate active layer dynamics. Fortunately, there is a common calculation called the Stefan equation, used originally in engineering applications (Fox et al., 1992), to estimate the thickness of the active layer when the amount of energy input and thermal characteristics are known. From French (2007), the Stefan equation is defined as

$$AL = \sqrt{2\sigma k_{mw}/Q_i} \tag{1}$$

where AL (m) is the thickness of the active layer, σ is the cumulative thawing index (average ground surface temperature (°C) during the thaw season times the duration of thaw season (s)), and k_{mw} is the thermal conductivity of unfrozen soil (W (m K)$^{-1}$). Q_i (J m^{-3}) is defined further as

$$Q_i = L\rho_m(W - W_u) \tag{2}$$

where L is the latent heat of fusion, ρ_m is the dry density of the soil (kg m^{-3}), W is the total moisture content , and W_u is the unfrozen water content . **Table 1** ~~below~~ gives the constant variable values applied in the Stefan Equation, which are the same values used in a comparable run for the VAMPER model~~.~~

Under different forcings as a function of both average annual ground surface temperature and annual amplitude, the VAMPER model's active layer thickness versus results using the Stefan Equation are shown in **Table 2**. It is clear when comparing the empirically-based results with the series of simulations, that the VAMPER model does a suitable job of reproducing annual active layer thickness.

Snowpack parameterization

An additional ~~enhancement~~ option to the VAMPER model is the ability to extend the heat conduction model into the snowpack when present. Prior to this, the surface offset, as illustrated in Smith and Riseborough (2002), could not be applied in the VAMPER model. ~~Goodrich (1982) is a well-known study which recognized the importance of including snow in numerical modeling of subsurface temperatures.~~

The VAMPERS model uses snow water equivalent (*swe*) values (m) with corresponding density to compute snow thickness layers. Snow water equivalent is the depth of water that would result from the complete melting of snow. The precipitation simulated in ECBilt is computed from the precipitable water of the first atmospheric layer (Goosse et al., 2010). When the air temperature is below 0 °C, the precipitation is assumed to be snow. However, this 'snow' is only assumed to be frozen water, meaning it lacks any quantifiable properties besides the actual precipitation amount, and as such is directly considered the *swe* value. As a result, there ~~are~~ is an additional set of necessary functions when coupled with VAMPERS to transfer ECBilt s*we* values into a snowpack thickness (Z) at time *t*:

$$Z^t = \rho_w \, swe^t / \rho_s^t \tag{3}$$

where ρ_w is water density and ρ_s snow density (Lynch-Stieglitz, 1994). The total snow density is determined as a combination of old snow (expressed as swe^{t-1} from the previous timestep) and freshly fallen snow at current timestep (expressed as swe^{fr}) :

$$\rho_s^t = \left(swe^{t-1}\,\rho_s^{t-1} + swe^{fr}\,\rho_{fr}\right) \Big/ swe^t \tag{4}$$

$$swe^t = swe^{t-1} + swe^{fr} \tag{5}$$

where ρ_{fr} is the density of fresh snow (150 kg m^{-3}).

There is snowpack metamorphism that occurs from a number of different processes. Notably, Dingman (2002) distinguishes these as gravitational settling, destructive, constructive, and melt. However, as these different changes occur at highly varying rates and under localized conditions (aspect, slope, vegetation cover), it is nearly impossible to incorporate such processes in an Earth System Model of Intermediate Complexity (~~-~~EMIC) such as *i*LOVECLIM. On the other hand, a snowpack always undergoes densification over time and this effect should somehow be applied to the modeled snowpack. Therefore, we apply to the total snow density an empirical densification function due to mechanical compaction. The maximum allowable density is 500 kg m^{-3}, which ~~is considered a 'ripe' snowpack and~~ typically cannot hold any more liquid water (Dingman, 2002). The compaction equation used (e.g. Pitman et al.,1991; Lynch-Stieglitz, 1994;) is as follows:

$$\rho_s^t = \rho_s^{t-1} + \left(0.5 \times 10^7 \rho_s^{t-1}\, g\, N \exp\left[14.643 - \frac{4000}{\min(T+273.16, 273.16)} - 0.02\rho_s^{t-1}\right]\right) \Delta t \tag{6}$$

where *g* is gravity (9.82 m s^{-2}), *N* (kg) is the mass of half the snowpack, *T* (°C) is the temperature of the snowpack (the average temperature of the snow layer temperatures from the previous timestep), and Δt is the timestep (*s*).

Three snow layers are then discretized from the total snow thickness, depending on whether it is above or below 0.2 m, as outlined in Lynch-Stieglitz (1994). Thermal properties are then calculated for each snow layer based on empirical formulas :

$$K_s = 2.9\,\rho_s{}^2 \qquad \text{(Goodrich, 1982)} \tag{7}$$

$$C_S = 1.9\ \times 10^6 \rho_s/\rho_f \qquad \text{(Verseghy, 1991)} \tag{8}$$

where K_s is the snow thermal conductivity and C_s is the snow heat capacity, and ρ_f is the density of ice (920 kg m^{-3}). All three snow layer are subject to the same processes and simply depend on temperature, time, and thickness for their respective deformation and/or melting.

The following is a stepped description of the snow algorithm for the ECBilt-VAMPERS semi-coupling:

1. Calculate new snow density, Eq. (4) and Eq. (5), using any freshly fallen snow and old snow.
2. Apply compaction function, Eq. (6), to already existing snowpack
3. Calculate total snow thickness using Eq. (3).
4. Discretize the individual layer thicknesses based on total snow thickness.
5. Calculate thermal properties for each layer (Eq. (7) and Eq. (8)).
6. Use snow thicknesses and corresponding thermal properties as additional layers in the VAMPERS model.

2.2 *i*LOVECLIM v 1.0

2.2.1 General Description

*i*LOVECLIM is a “code-fork” of LOVECLIM 1.2 (Goosse et al., 2010), both which belong to a class of climate models called EMICs (Claussen et al., 2002). This type of model, as summarized by Weber (2010), “describes the dynamics of the atmosphere and/or ocean in less detail than conventional General Circulation Models”. This simplification reduces computation time, thus making EMICs suitable for simulations on millennial timescales, incorporating the components with slow feedback effects, such as icesheets, vegetation, and permafrost. Different versions of LOVECLIM have successfully simulated past climates including the LGM (Roche et al., 2007), the Holocene (Renssen et al., 2005, 2009), and the last millennium (Goosse et al., 2005). Although there exist some different developments between *i*LOVECLIM and the LOVECLIM versions, both consist of the following coupled earth system components: the atmosphere (ECBilt), the ocean (CLIO), and vegetation (VECODE) (**Fig. 2**). Each component was originally developed separately and the reader is referred to Goosse et al., 2010 for a detailed description. Furthermore, *i*LOVECLIM more recently includes other optional components including an ice-sheet model (Roche et al., 2014) and a stable water isotopes scheme (Roche, 2013).

2.2.2 ECBilt-VAMPER(S) Coupling Description

The atmospheric component, ECBilt (Opsteegh et al., 1998), which the VAMPER(S) model is specifically coupled to, runs on a spectral grid with a triangular truncation (T21). This translates to a horizontal grid with a resolution of approximately 5.6 ° lat x 5.6 ° lon. The ECBilt-VAMPER(S) semi-coupling is done via the air surface temperature from ECBilt at each timestep (4 hours), which the VAMPER(S) model uses as the ground temperature forcing. The air surface temperature is calculated within ECBilt as a function of the heat balance equation where the major heat fluxes across the air/surface interface are incorporated: sensible heat flux, latent heat flux, shortwave radiation, and longwave radiation. The air surface ~~se~~ temperature is~~s are~~ only communicated to the VAMPER(S) model when the respective grid cell is classified as land with no overlying icesheet (i.e. Greenland/Antarctica at present day). Since ~~the ECBilt air surface temperature is taken to be~~ the VAMPER(S) model ground surface temperature is taken to be the ECBilt air surface temperature, there is no surface offset effect except when there is a snowpack. In this case, ~~the air surface temperature from ECBilt is assumed to be above the snow~~the snow surface temperature is taken to be the air surface temperature . This means the VAMPERS model ground temperature forcing is buffered via the three snowpack layers as discussed in Sect. 2.1.2. Using the ground surface temperature forcing, the VAMPER(S) model then ~~calculates~~ computes the subsurface temperature profile. This calculation, via the implicitly solved heat equation with phase change capability, is fully described in Kitover et al. (2013). As VAMPER is a 1-D model, there is no lateral energy (heat/water) transfer between adjacent grid cells in the subsurface. Permafrost thickness is determined at an annual timestep using a computed average annual temperature profile, where any depth below or equal to 0°C is considered permafrost. Although there is a freezing point depression which may occur as a result of the local pressure or dissolved salts, we are consistent with the common thermal definition of permafrost from the International Permafrost Association: "ground (soil or rock and included ice or organic material) that remains at or below 0°C for at least two consecutive years".

The land surface of ECBilt consists of a single "layer" which represents a volumetric storage capacity to generate surface runoff when full. This system is often referred to as a bucket model in previous text. As of currently, this bucket model, which is the surface hydrology in iLOVECLIM, is not coupled to VAMPERS. It would be a sensible next step to connect the active layer with this bucket model

The results presented in this current work is only a function of performing semi-coupled experiments and are means as an intermediary step to a fully coupled model in order to validate both VAMPERS and its ability to model permafrost extent and thickness. In future experiments, VAMPERS will be fully coupled to ECBilt. In this case then, a~~A~~t the end of each timestep, ~~after~~ VAMPER(S) would calculate~~s the new subsurface temperatures, the~~ the ground heat flux ~~is calculated and~~ and return this value ~~ed~~ to ECBilt (Fig. 3) as one of the variable terms in the surface heat balance equation (among the other fluxes such as sensible heat flux, latent heat flux, etc.) ~~at the air/ground interface~~, which in turn would be~~is~~ used to obtain the air surface temperature for the next time step. ~~(Fig. 3)~~. The equations for this full coupling will be described in a future publication.

2.2.3 Geothermal Heat Flux

The VAMPER(S) model requires a geothermal heat flux as the lower surface boundary. In Kitover et al. (2013), a sensitivity analysis was performed to look at the equilibrium permafrost thickness as a result of varying the geothermal heat flux and found that thickness can increase by about 70 m with every decrease in flux of 10 mW m^{-2}. To obtain the geothermal heat flux for every cell in the ECBilt grid, we used the recent publication of Davies (2013) who determined the median of heat flux estimates per approximately 2° x 2° latitude-longitude grid based on a combination of actual measurements, modeling, and correlation assumptions. However, due to the mismatch of grid resolutions between Davies (2013) and ECBilt, we determined for each ECBilt grid cell, a simple area-weighted average of the Davies (2013) estimates. In other words, each of the Davies grid cells was assigned a weighing factor based on the percentage of overlap with the ECBilt cells. Below is the original map from Davies (2013) and the averaged map applied in the *i*LOVECLIM experiments (**Fig. 4**). A preliminary sensitivity analysis between applying the geothermal heat flux map and applying the continental global average (approx. 60 mW m^{-2}) showed no noticeable difference in permafrost distribution. This result is different, however, than the noticeable sensitivity of geothermal heat flux on permafrost depth.

2.2.4 Porosity

Another variable needed to run the VAMPER(S) model is the porosity values throughout depth, which in these experiments is down to 3000 meters deep. In previous VAMPER studies (Kitover et al., 2013; Kitover et al., 2012), it was always assumed that the land subsurface was sedimentary rock, with a porosity of 0.3, 0.4, or 0.5. However, as shown in Kitover et al. (2013), the porosity, or water content, has a noticeable effect on equilibrium permafrost thickness. That sensitivity test showed about a 50 m difference in permafrost thickness when the porosity values (assuming a saturated subsurface) ranged between 0.3 and 0.5. Therefore, to both narrow our assumptions regarding the subsurface but still maintain the simplification necessary for the coarse horizontal grid, an additional lithological classification scheme was created as an additional VAMPER(S) model parameter. Using the recently published Global Lithological Map Database (GLiM) from Hartmann and Moosdorf (2012), their original seven categories were reclassified into 'Bedrock (Bed)' , (e.g., granitic and metamorphic rock), and 'Sedimentary (Sed)' (e.g., sandstone, limestone) (**Table 3, Fig. 5**). In the case of 'Bed', the subsurface would presumably be quite consolidated/compressed, resulting in a low water content (Almén et al., 1986; Gleeson et al., 2014). 'Bed' was thus assigned a low porosity of 0.1, which based on sources that showed depth profiles of bedrock sites (Schild et al., 2001; Nováková et al., 2012), stayed constant with depth. On the other hand, similar to the case studies from Kitover et al. (2013), a depth porosity function from Athy (1930) was applied for the 'Sed' class, where the surface porosity (Φ) was assumed to be 0.40 and a decay constant (4 x 10^{-4}) in the exponential equation, representing the average for sandy textured soil. Similar to application of the geothermal heat flux map, a preliminary sensitivity analysis between applying the lithology map and applying a constant value (0.4) throughout the globe showed only marginal differences in permafrost distribution. This result is different, however, than the higher sensitivity of porosity on permafrost depth.

3 Validation of preindustrial permafrost thickness distribution

3.1 Experimental Setup

The model experiments are performed over the whole globe semi-coupled, which means that ECBilt passes the air surface temperature values to the VAMPER(S) model (right side of **Fig. 3**) but no data is returned to ECBilt (left side of **Fig. 3**), leaving the climate unaffected from permafrost or changes in permafrost. This configuration, therefore, allows only the examination of the *i*LOVECLIM model to reproduce current permafrost extent and depths as function of the currently established climate of the *i*LOVECLIM model. Two different model runs were made: one without the snow enhancement or any imposed surface offset (ECBilt-VAMPER coupling) and one with the snow enhancement (ECBilt-VAMPERS coupling). These two are first compared in sect. 3.2.1 of the Results & Discussion below.

Because permafrost has a very slow thermal response (Lunardini, 1995) as compared to other components in *i*LOVECLIM, VAMPER(S) is not run in a continuous (semi) coupling with ECBilt. Rather, they are run together continuously for 100 years and then VAMPER(S) runs offline for 900 years using the ECBilt average air surface temperature of the previous 100 years as the forcing. This asynchronous cycle is repeated for thousands of years until approximate equilibrium between the ECBilt temperatures and the VAMPER(S) model is reached. This scheme is illustrated in **Fig. 6** (adapted from a similar figure in McGuffie and Henderson-Sellers (2005)). Equilibrium was determined ~~to be~~ when the lower boundary heat flux approximately matches the annual average ground surface heat flux. This is also of course when the permafrost thickness is stable. Although the model approaches a steady state through the subsurface depth, we acknowledge that in reality, some of the permafrost regions are not at equilibrium since they are responding to recent warming.

3.2 Results and Discussion

In order to verify the performance of the ECBilt-VAMPER(S) coupling within *i*LOVECLIM, a series of equilibrium experiments were performed for the preindustrial (PI) climate (~ 1750 AD). For comparative purposes, we assume the PI state of permafrost is similar enough to the current state of permafrost that we used modern-day data to validate against the PI simulations. The simulated areal extent was compared to present-day extent using the well-known “Circumarctic Map of Permafrost and Ground-Ice Conditions” (Brown et al., 2014). Unlike the model validation done by Lawrence and Slater (2005), and then subsequently critiqued by Burn and Nelson (2006), our simulations attempt to capture the extent of both continuous and discontinuous permafrost. In addition, available borehole data, for sites within the arctic/subarctic, were used to evaluate the simulated thicknesses. Therefore, there are essentially two types of validation approaches: 1) horizontal (spatial extent) and 2) permafrost depth.

3.2.1 Permafrost Distribution Validation

The first validation demonstrates how well the *i*LOVECLIM model reproduces the modern-day permafrost extent by overlaying the simulated results on the map from Brown et al. 2014.

Using a comparison between the different couplings (**Fig. 7**), it is clear that the experiment where the ECBilt- VAMPER semi-coupling (no snow ~~enhancement~~option and no imposed surface offset) is used overestimates permafrost extent while employing the ECBilt -VAMPER**S** version underestimates it. This swing of inaccuracy is at least partially due ~~the result of~~ to simply attempting to match results from a low resolution grid to spatial coverage of much higher resolution. In addition, we expect some inaccuracy since we cannot parameterize the snowpack characteristics and more importantly, the nature of the snowmelt. As opposed to our generalized approach described earlier, high resolution snowmelt models are fitted to observational data by analyzing, for example, the physics of accumulation, areal distribution, and snow-soil interactions. Therefore, it is arguable from **Fig. 7** and the recognized discrepancies in generalizing snow model details, whether the better option is to include ~~the~~ snowpack in VAMPERS or not. ~~since neither 'swing' is very exact.~~ However, as long as the VAMPERS model is doing a reasonable job, we contend it is a better option ~~an improvement~~ over merely applying artificial offsets or assuming none at all since snow plays a critical role in the ground thermal conditions and should be represented. Further, with the snow option~~is enhancement~~t, changing precipitation patterns that are often the byproduct of a shifting climate would otherwise have no effect on the subsurface thermal conditions. In other words, the role of snow cover is likely more noticeable in using the ECBilt-VAMPERS coupling when doing transient experiments. From this point forward, all analysis is done using results from the ECBilt-VAMPERS coupling (i.e. *with* the snow option ~~enhancement~~).

Employing the snow ~~enhancement~~ option in the ECBilt-VAMPERS coupling produces the surface offset that would naturally occur from the snowpack (Goodrich, 1982; Smith and Riseborough, 2002). The simulated global distribution of this offset is shown in **Fig. 8**. It is determined by calculating the difference between the mean annual ground temperature (MAGT) using the ECBilt-VAMPERS coupling and the MAGT using the ECBilt-VAMPER coupling (no snow ~~enhancement~~ option and no imposed offset). Although the maximum mean annual surface offset is about 12 °C, the average among all the grid cells that had snow cover is about 2.7 C, which is close to our original applied offset of 2 °C in Kitover et al., (2013). Values between 1 °C and 6 °C were reported early on by Gold and Lachenbruch (1973). Monitoring studies of the air-ground temperature relationship also fall within this range e.g., Beltrami and Kellman (2003), Bartlett et al., (2005), Grundstein et al., (2005), Zhang (2005). However, larger values of 10 °C have been recorded in Alaska (Lawrence and Slater, 2010).

In addition to the offset imposed by incorporation of a snowpack, there are a number of factors which have been commonly recognized in affecting the surface offset and hence should be part of the air-ground coupling. Depending on the scale of interest, the magnitude of these can vary but a standard list includes surface organic layer, vegetation, overlying water bodies, and wind. It should be recognized that within ECBilt, some of these factors are reflected in the air surface temperature (notably wind and a simplified vegetation scheme) but the others are absent. In addition, coupling the ECBilt surface hydrology to the groundwater storage would affect both the ground thermal regime and hydrological regime. In the first case, subsurface water content affects the thermal properties of the soil. In particular, the conductivity of organics have high variation seasonally. In the second instance, frozen ground is impermeable, allowing little or no subsurface water storage, in turn affecting runoff flowrates and timing.

The permafrost distribution simulated by *i*LOVECLIM can be matched against results from a study comparing a suite of earth system models, namely the Coupled Model Intercomparison Project phase 5 (CMIP5) (Koven et al., 2013). This report gives the simulated preindustrial permafrost areas under a number of different earth system climate models and configurations. Compared to the results from *i*LOVECLIM, some of the other models' simulated permafrost distributions cover more area while some cover less. The maximum is reported as 28.6 x 10^6 km^2 and minimum 2.7 x 10^6 km^2. The simulation by *i*LOVECLIM yields approximately 20.3 x 10^6 km^2 . This is a reasonably comparable estimate considering almost 80 % (14/18) of the model area extents from Koven et al. (2012) fall within 40% (12 – 28 x 10^6

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km^2) of our model estimates. According to discussion by Koven et al., (2012), most of the variation seen among the compared earth system models is primarily attributed to the subsurface modeling techniques, such as water content, using a latent heat term, and differing soil thermal conductivities. Secondary causes are attributed to the air-ground coupling such as incorporation of organics and a snowpack (bulk or multilayer). These conclusions are not different from our own study in that 1) snowpack plays a marked role in permafrost modeling and inclusion/exclusion will impact the results, 2) the air-ground coupling is also a source of potential mismatch (discussed further in section 3.2.2).

3.2.2 Permafrost Thickness Validation

The second validation examines the simulated depth of permafrost using borehole data taken from the Global Terrestrial Network for Permafrost (GTN-P; www.gtnp.org). The scatterplot (**Fig. 9**) shows all the observed borehole measurements mapped in **Fig. 10** versus the corresponding permafrost depth simulated by *i*LOVECLIM. It is clear that there is a larger divergence between modeled and observed depths for the deeper permafrost than for the more shallow observations, where some points are relatively overestimated (> 300 m) and some very underestimated (>700 m). There are a number of reasons to explain the mismatch, which can occur in the borehole data and/or the model data. The first explanation is that the borehole estimates have a given range of uncertainty since measurement techniques and subsequent interpretations are subject to error. Osterkamp and Payne (1981) describe in detail potential errors associated with the freezing point depression, thermal disturbance, and lithology.

The second cause is that we assumed implicitly that the observed permafrost depths are at equilibrium with the current (or PI; preindustrial) climate state. This is probably why there is a striking mismatch at the central Siberian site (66° 26' 2" N, 112° 26' 5" E) (point 1, **Fig. 9**), where the permafrost is estimated from the borehole data to be 1000 m thick while the corresponding modeled value is only about 375 m. It is very likely that, like much of the Siberian permafrost, this permafrost developed from the preceding glacial period (Kondratjeva et l.,1993). Another example concerns western Siberia, (points 2 through 4, **Fig. 9**), which is an area well documented for having relict permafrost (Zemtsov and Shamakhov, 1992; Ananjeva et al., 2003). It is also identified in the "Circumarctic Map of Permafrost and Ground-Ice Conditions" (Brown et al., 2014) and "The Last Permafrost Maximum (LPM) map of the Northern Hemisphere" (Vandenberghe et al., 2014). But it should be noted that not all the relict permafrost in western Siberia is of late Pleistocene origin and may be from earlier cold stages (Zemtsov and Shamakhov, 1992; French, 2007).

Another reason for some discrepancies between modeled and observed data is that high-resolution features in the landscape and topography cannot be captured by *i*LOVECLIM due to the limited spatial resolution and hence, a small set of model parameters. Such factors as vegetation and organic layer, which can vary due to local topography and micro-climatic conditions, have been shown to affect the active layer and ground thermal regime (Shur and Yorgenson, 2007; Fukui et al., 2008; Lewkowicz et al., 2011; Wang et al., 2014). Consequently, given a specific borehole site, some discrepancy in the permafrost thickness estimate will likely occur between our simplified interpretation and that which results from including more complex and local interactions. It is possible, for example, that the observed value for point 5 (720 m) is a function of higher elevation since it is from a borehole site in the Russia Highlands but this relatively local elevation effect may not be a strong enough signal in the *i*LOVECLIM surface temperatures, and hence is underestimated.

The other outlying points (points 6 and 7, **Fig. 9**) occur in Canada but as opposed to the relict sites as mentioned above, *i*LOVECLIM overestimates the permafrost thickness quite noticeably. These discrepancies, both occurring at high latitudes of 80 °N and 76 °N , reveal that VAMPERS is probably not reproducing the subsurface temperatures well for this area. For example, a report for the specific borehole (Gemini E-10; point 6, **Fig. 9**) calculated the geothermal gradient to be approximately 0.04 °C/m (Kutasov and Eppelbaum, 2009) whereas our model result for the corresponding grid space found a gradient of approximately 0.03 °C/m. Although this difference may seem small, it hints at either a necessary increase in the averaged geothermal heat flux used in the model or a change in the subsurface thermal properties (increase in thermal conductivity), which could be altered by an adjustment in the VAMPERS water content.

3.2.3 Climate analysis

Finally, the remaining possibility to explain inaccuracies between the modeled results and the observed results (both in reproducing spatial extent and permafrost thickness) is the *i*LOVECLIM climate. Results of the VAMPER model, above all other parameter settings, are most dependent on the mean annual ground surface temperature, as shown in the sensitivity study from Kitover et al. (2013), so if there exists biases or discrepancies within the forcing, it will be reflected in the semi-coupled output. For this portion of our analysis, we took observed mean annual ground temperature (MAGT) measurements from again the GTN-P (IPY Thermal State of Permafrost Snapshot, IPA 2010) . As a result, we composed a 1:1 comparison between the observed MAGT and the corresponding simulated MAGT at the same approximate depth and location (**Fig. 11**). **Figure 12** shows a map of the selected GTN-P measurements. All the temperature comparisons are within the top thirty meters of the subsurface and therefore reflect the present or very recent climate as opposed to the deeper temperatures (i.e., > 150 m) that, depending on subsurface thermal diffusivity and surface temperature perturbations, can reflect historical temperatures of at least one hundred years ago (Huang et al., 2000) and up to tens of thousands of years (Ter Voorde et al., 2014).

Overall, **Fig. 11** illustrates that ECBilt-VAMPERS does a reasonable job of predicting shallow subsurface temperatures since a majority of the points fall near the 1:1 line. This result, therefore, supports the notion that the preindustrial climate is well represented by *i*LOVECLIM. The points of Kazakhstan and Mongolia, and a few others in Russia, have a warm bias in the forcing (simulated is warmer than observed), which is probably due to an inaccurate representation of elevation temperature changes in *i*LOVECLIM, since many of those sites are at elevations above 1000 m. Even applying the lapse rate for a standard profile (6.5 C / km; McGuffie & Henderson-Sellers, 2013) would presumably make a significant difference on the depth since earlier sensitivity tests (Kitover et al., 2013) showed an average 55 m increase in equilibrium permafrost depth for every 1 °C colder. On the other hand, many of the other points show that predicted subsurface temperatures are on average a few degrees colder than the observed, leading to the most obvious conclusion that a cold bias exists in the *i*LOVECLIM climate.

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Although ~~It should be noted that~~ the cold bias, most obvious for Canada and Alaska, is congruent to the overestimation in permafrost thickness evident from the geographic breakdown illustrated in **Fig. 10**, it~~.~~ ~~However, this~~ has not previously been substantiated in former analyses of LOVECLIM or *i*LOVECLIM so it is more likely that such a discrepancy is due to the air-ground coupling as opposed to simply the air surface temperature forcing. Indeed, there a number of other (sub)surface processes not included in the current ECBilt-VAMPERS coupling which may reduce the apparent cold bias. These effects primarily alter the seasonal behavior of the thermal diffusivity in the subsurface and have been well-documented in observational studies (Williams and Burn, 1996; Woo and Xia, 1996; Fukui et al., 2008). ~~These effects are also identified in~~ Smith and Riseborough (2002) simplified these mechanisms into~~as both~~ the surface offset (air to ground surface) and the thermal offset (ground surface to top of the permafrost). Due to minimal parameterization of the VAMPERS model, these offsets may be somewhat overlooked.

~~It should be noted that the cold bias, most obvious for Canada and Alaska, is congruent to the overestimation in permafrost thickness evident from the geographic breakdown illustrated in **Fig. 10**.~~

For now, the average range of error between observed and predicted is about 2.6 °C. Given that the comparisons are between point-based observations and large grid cell values, meant to represent a relatively large surface area, some variability is expected to occur.

4 Next Steps

The results of this paper demonstrate the ability of ECBilt-VAMPERS semi-coupling within *i*LOVECLIM to model current permafrost distribution and thickness. The next step is to analyze the feedback that permafrost changes have on the climate. This has been of particular interest of the last decade since it is clear that specific feedbacks exists, most notably the release of locked-up carbon in the atmosphere as permafrost degrades (Anisimov, 2007). The initial method behind a full coupling would be to integrate the additional coupling mechanisms, shown in **Fig. 3,** and reanalyze the equilibrium results (since a full coupling would likely lead to an altered equilibrium permafrost state). In addition, the feedback effects would be most visible during millennial-scale transient climate shifts, when major permafrost degradation and/or disappearance is likely to occur.

5 Conclusions

Enhancements have been made to the VAMPER model to make possible the first version of the ECBilt-VAMPERS semi-coupling. The change in timestep to 4 hours was necessary to match the timestep of ECBilt and allow the seasonal effects, notably snow cover and the active layer, to be reflected in the simulation of permafrost. The predicted annual active layer from the stand-alone VAMPER model, under different temperature forcings, compare well with results from the Stefan equation. We also described the snow ~~enhancement~~option, which introduces the thermal insulation effects and changes in the thermal properties of snow over time due to varying snow densities. In addition, we developed two new maps: geothermal heat flux and porosity. Incorporating these parameters at a global scale was an important step in improving the horizontal spatial variability of permafrost thickness/distribution while also maintaining the simplicity and efficiency of ECBilt-VAMPERS.

Using a semi-coupled ECBilt-VAMPER(S) component within *i*LOVECLIM, equilibrium experiments for the PI climate show that when the snow component is included in the VAMPER model, the permafrost extent is noticeably reduced while the average offset of 2.7 °C is comparable to previous reports. We then compared both permafrost thickness estimates and subsurface temperatures to corresponding observed values. Considering that we are comparing point measurements to gridcell-based values, the simulations are quite reasonable. There are some discussion points around the most obvious discrepancies. One is that the relatively coa~~ou~~rse horizontal ECBilt grid will never perfectly match the sensitivity of permafrost occurrence and depth due to local factors. This is also the case in the air-land temperature coupling, where some of the local effects will simply not be present in an EMIC. Similarly, when *i*LOVECLIM does not accurately represent the environmental lapse rate in areas of higher elevation , the occurrence of permafrost in these areas are overlooked by the VAMPERS model. Finally, some of the observed permafrost depths are not a function of the present (PI) climate, but rather a relict presence from previous cold periods. Therefore, when comparing measured to simulated results, some underestimations expectedly occurred. It is only with millennial-scale transient *i*LOVECLIM model runs that we can simulate, for example in areas of West Siberia, how permafrost evolved over periods of major climate change.

6 Code availability

The *i*LOVECLIM (version 1.0) source code is based on the LOVECLIM model version 1.2 whose code is accessible at http://www.elic.ucl.ac.be/modx/elic/index.php?id=289. The developments on the *i*LOVECLIM and VAMPER(S) source code are hosted at https://forge.ipsl.jussieu.fr/ludus but are not publicly available due copyright restrictions. Access can be granted on demand by request to D. M. Roche (didier.roche@lsce.ipsl.fr).

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Table 1. Variable values applied in the Stefan equation.

Variables		
thermal conductivity (k_{mw})	1.7	$W\ m^{-1}\ K^{-1}$
dry density of soil (ρ_m)	1600	$kg\ m^{-3}$
latent heat of fusion (L)	334	$kJ\ kg^{-1}$
total moisture content (W)	0.3	-
unfrozen water conent (W_u)	0	-

Table 2. Calculated maximum annual active layer thickness using both the Stefan Equation and the VAMPER model under different forcing scenarios.

Model Run	Average Annual Ground Surface Temperature	Annual Amplitude	Stefan Equation Active Layer	Vamper Model Active Layer
	(°C)	**(°C)**	**(m)**	**(m)**
1	-6	10	0.7	0.7
2	-4	10	1.0	1.0
3	-2	10	1.2	1.3
5	-6	20	1.6	1.7
6	-4	20	1.7	1.9
7	-2	20	1.9	1.9

Table 3. The original lithological classification from Hartmann and Moosdorf (2012) and the reclassification scheme used for the ECBilt grid.

	Original Litho Class	VAMPER Class
1	Unconsolidated Sediments (SU)	Sed
2	Basic Volcanic Rocks (VB)	Bed
3	Siliciclastic Sedimentary Rocks (SS)	Sed
4	Basic Plutonic Rocks (PB)	Bed
5	Mixed Sedimentary Rocks (SM)	Sed
6	Carbonate Sedimentary Rocks (SC)	Sed
7	Acid Volcanic Rocks (VA)	Bed
8	Metamorphic Rocks (MT)	Bed
9	Acid Plutonic Rocks (PA)	Bed
10	Intermediate Volcanic Rocks (VI)	Bed
11	Water Bodies (WB)	N/A
13	Pyroclastics (PY)	Bed
12	Intermediate Plutonic Rocks (PI)	Bed
15	Evaporites (EV)	Sed
14	No Data (ND)	N/A
16	Ice and Glaciers (IG)	N/A

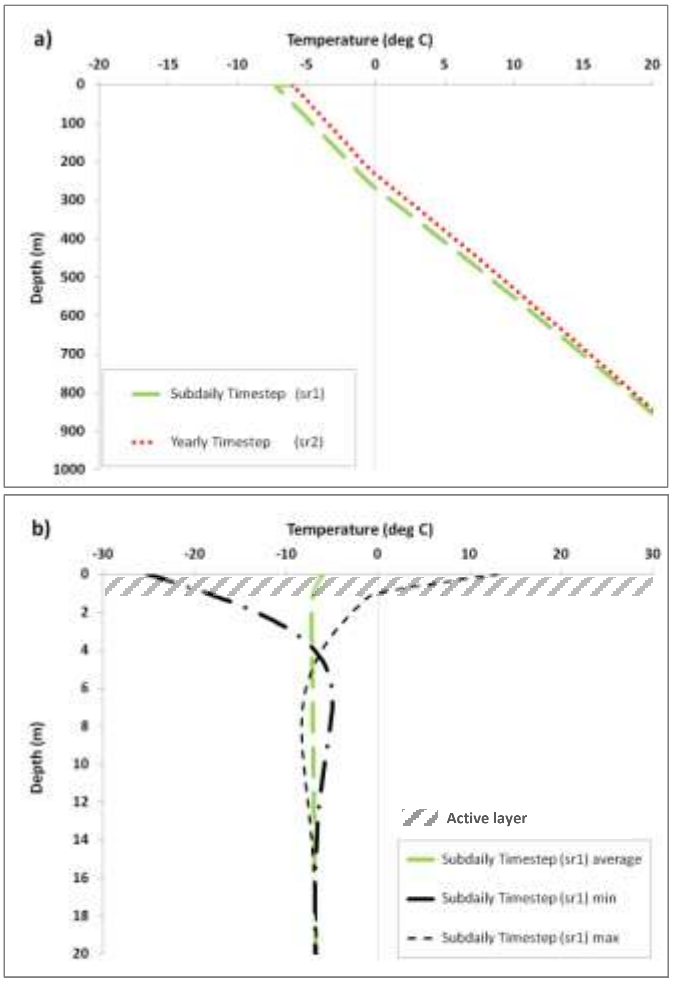

Figure 1. a) Plot comparing VAMPER model results using different timesteps (annual vs. subdaily) but the same annual average temperature forcing of -6 °C. b) Plot showing the sr1 average, min, and max temperature-depth profiles. Also shown in b) is the ~ 1 m active layer, marked as diagonal lines.

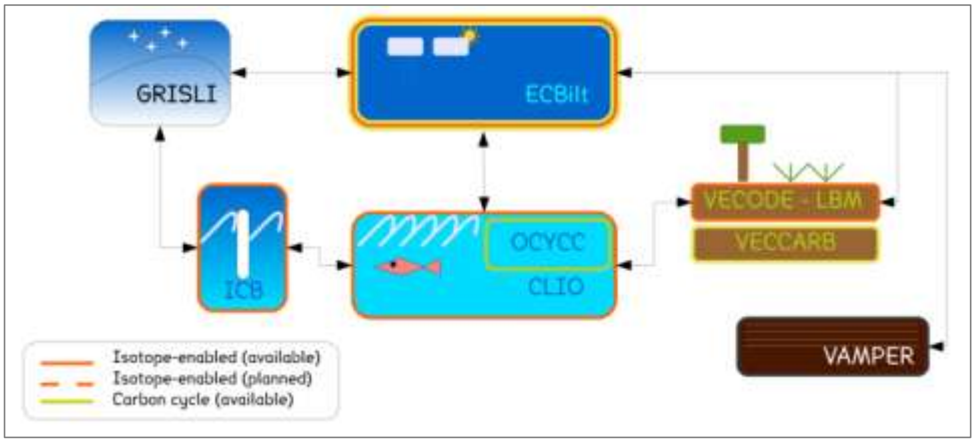

Figure 2. *i*LOVECLIM model component setup.

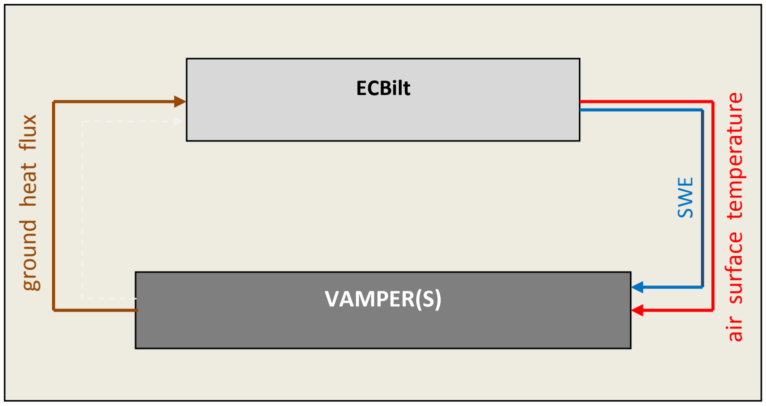

Figure 3. Coupling scheme between ECBilt and the VAMPER(S) model showing the variables (air surface temperature, swe, and ground heat flux) passed between the components at each timestep.

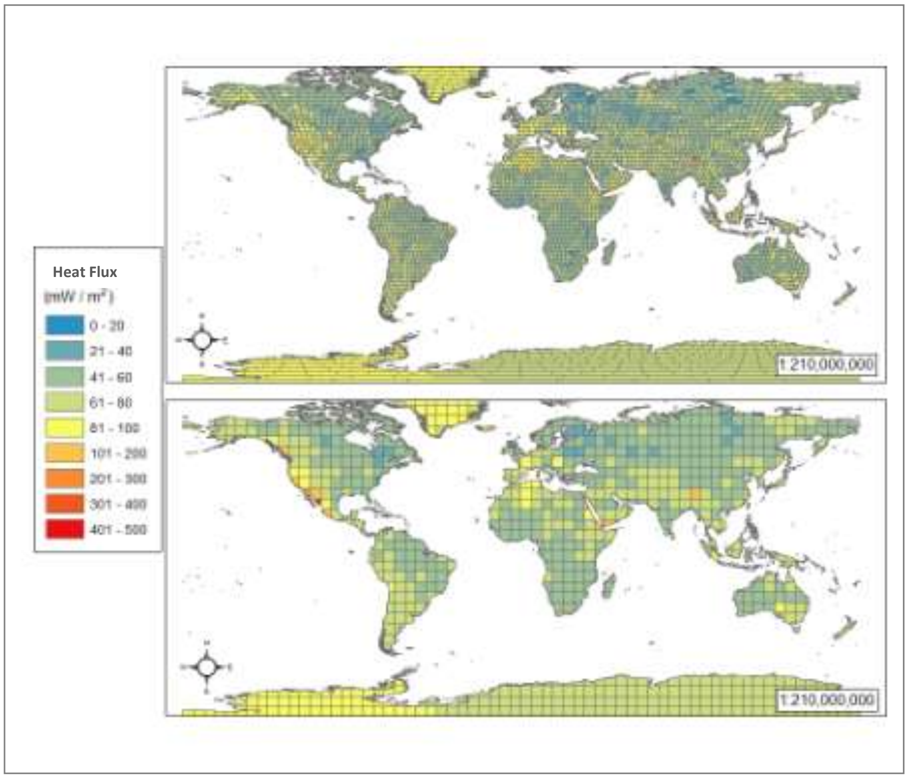

Figure 4. The original geothermal heat flux map (top) from Davies (2013) and the weighted average version (top) for use as the lower boundary value in the *i*LOVECLIM experiments (bottom).

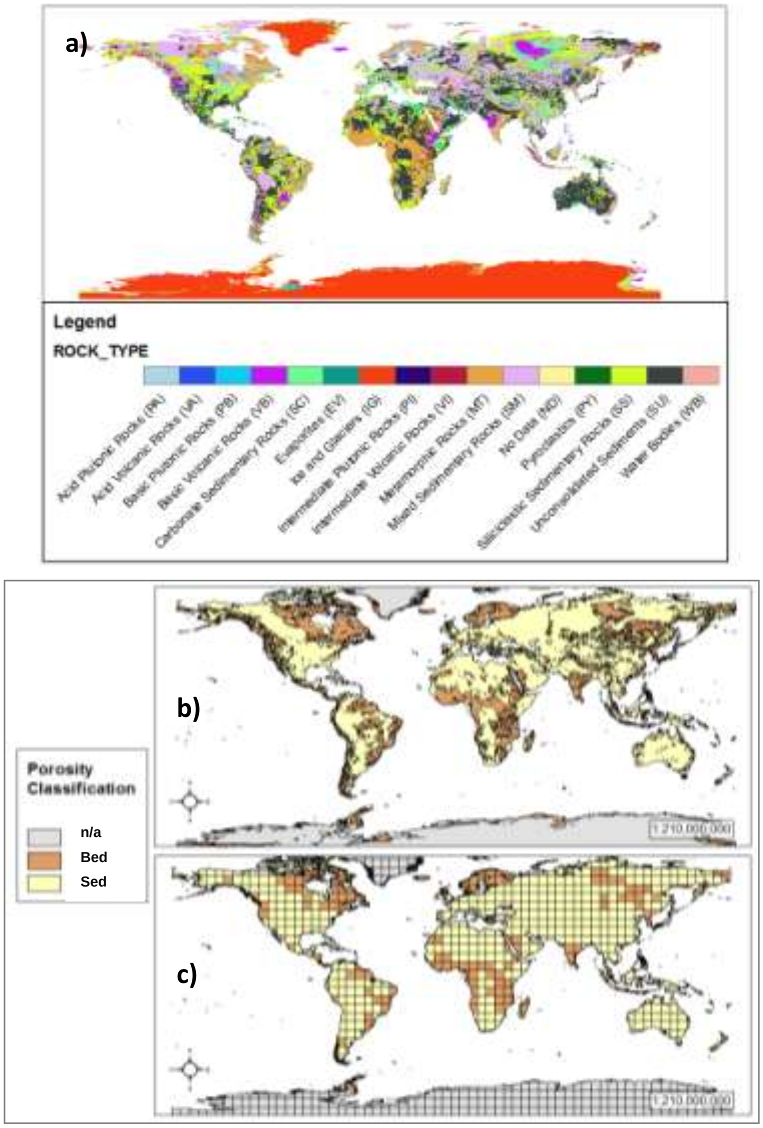

Figure 5. World maps showing a) original map from Hartmann and Moosdorf (2012) b) map of reclassified lithology using Table 2 and c) the version geo-processed to match the ECBilt grid resolution.

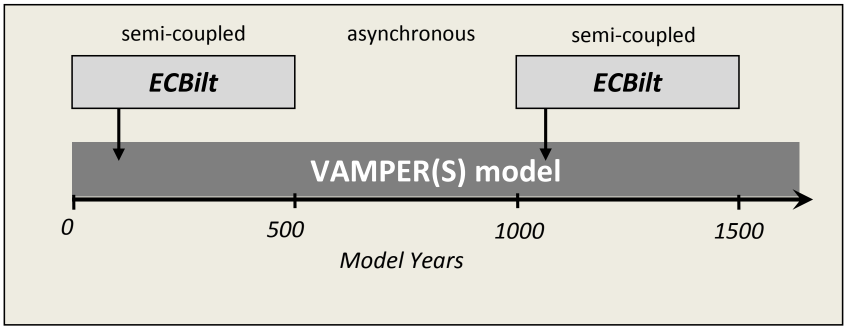

Figure 6. An illustration of asynchronous coupling between VAMPER(S) and ECBilt. The components are run semi-coupled for 100 years while VAMPER(S) is run the entire time. This allows VAMPER(S) to equilibrate with the climate state of *i*LOVECLIM using less computer resources time than a synchronous version.

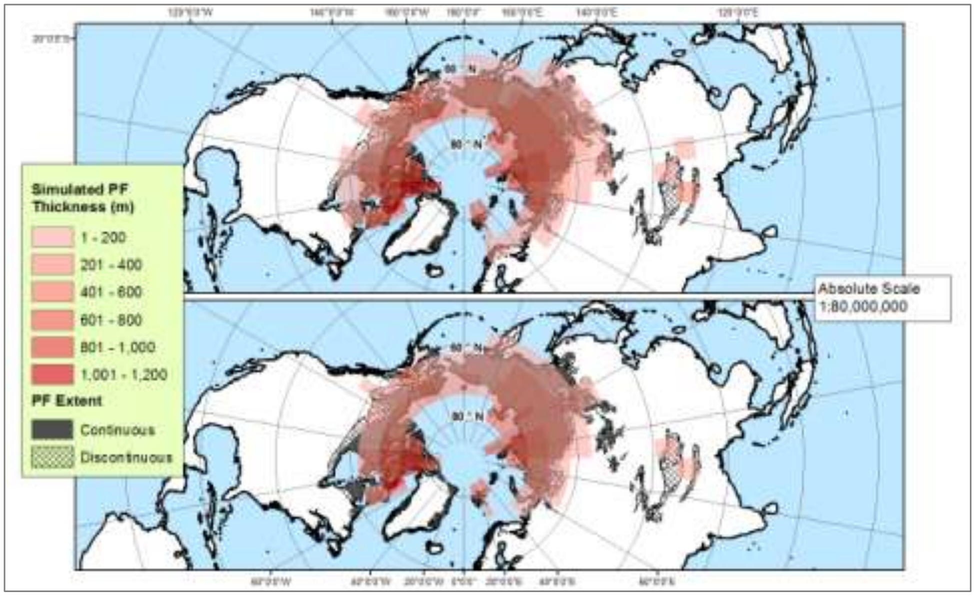

Figure 7. Preindustrial simulation results for permafrost thickness distribution using ECBILT-VAMPER semi-coupling (top) and ECBILT-VAMPER*S* semi-coupling (bottom).

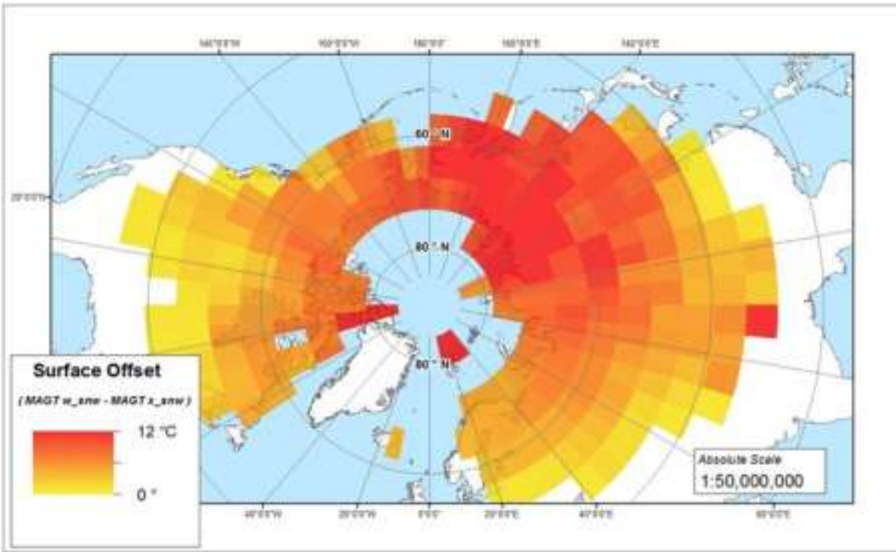

Figure 8. Mean annual surface offset as a result of including the snow ~~enhancement~~ option in the ECBilt-VAMPERS coupling.

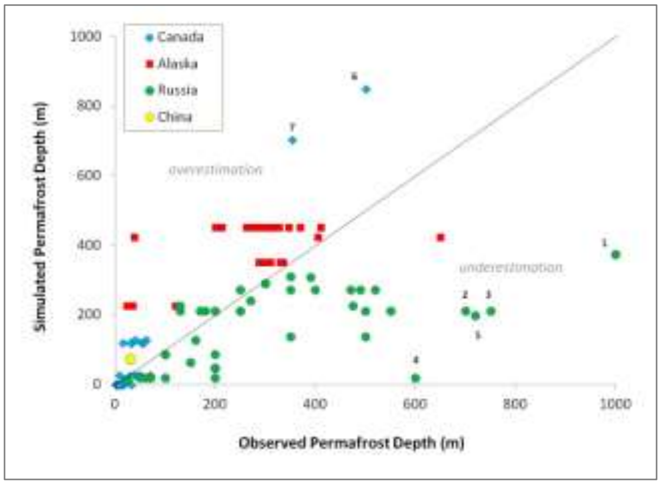

Figure 9. A 1:1 scatterplot comparing simulated thickness results with corresponding permafrost thickness estimates from borehole data. Points 1-7 are outliers mentioned specifically above.

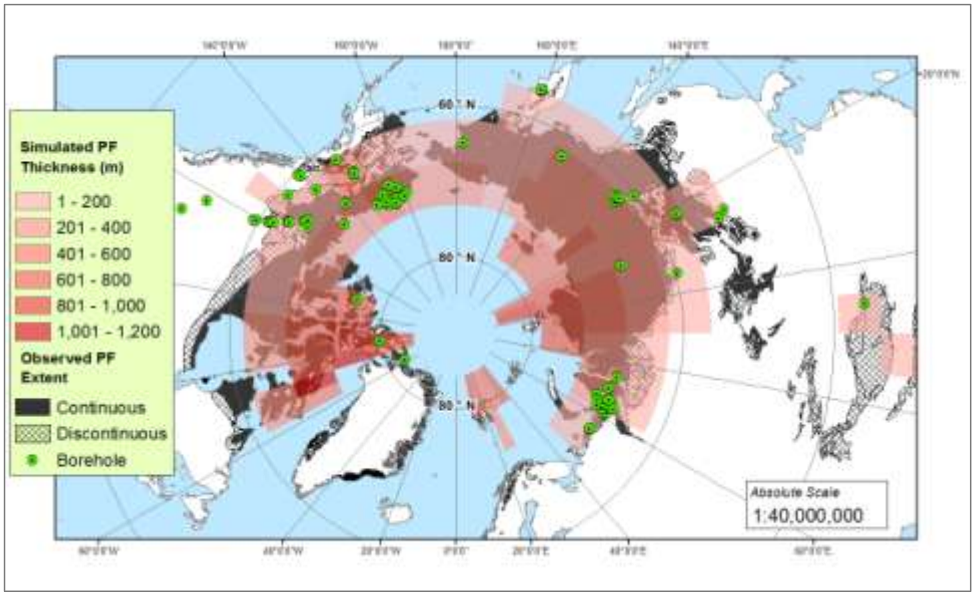

Figure 10. Map of deep GTN-P borehole locations with the simulated permafrost thickness (with snow enhancement) and observed PF extent (Brown et al., 2014).

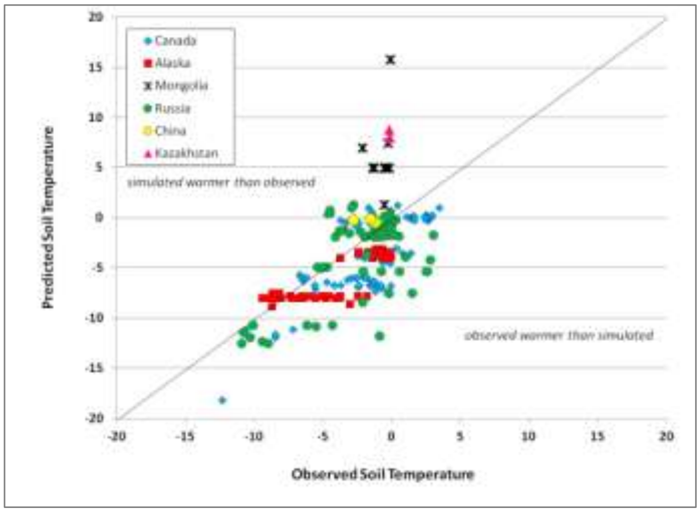

Figure 11. A 1:1 scatterplot comparing simulated mean annual temperatures with corresponding MAGT measurements.

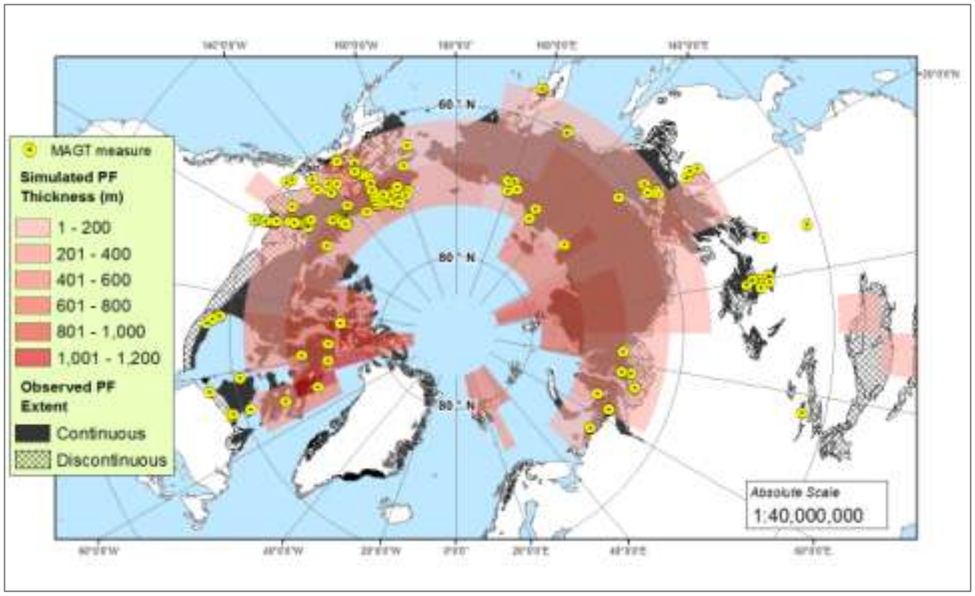

Figure 12. Map showing locations of the MAGT measurements, collected for the IPY 2010 (GTN-P), used in the comparison to corresponding *i*LOVECLIM simulated subsurface temperatures.