Dear Mr. Fyke,

Thank you for the review of the manuscript. We believe we have addressed all of the issues and requests listed below. Your first and foremost concern was use of the terminology ‘coupling’ and ‘semi-coupling’. The argument that our coupling is actually a software coupling is valid. We have thus rewritten the experiment descriptions as simply VAMPERS forced by iLOVECLIM. Coupling is now only referred to as something we will aim to do in the future. This change is recognized in the new title: ‘**Advancement toward coupling of the VAMPER permafrost model within the earth system model *i*LOVECLIM (version 1.0): description and validation’.** We have also combed through the manuscript and removed any subjective wording or vague statements. These changes are identified throughout the manuscript using tracked changes and comments. In addition, we have numbered your specific comments 1 -39 so the corresponding change and number can be clearly marked within a tracked version of the revised manuscript. Again, we appreciate your careful analysis of the manuscript and hope that it will be accepted as part of the GMD iLOVECLIM special issue series.

Topical Editor Initial Decision: Reconsider after major revisions (02 Mar 2015) by Jeremy Fyke
Comments to the Author:
To the authors,

I thank you for replying to the two Reviewer’s comments. In reviewing your responses, I generated a number of requests myself, that I would like to see addressed prior to publication in GMD. Given the number and high-level nature of some of my comments, I classify this as further 'major revisions' that I would like to see robustly addressed.

Also, when replying to these comments (or Reviewer comments in general) if you could specifically note the specific changes you made to all comments (including specific or technical comments) in the Reply to Reviewers, that would be great.

####General comments####

First, and most importantly, I am concerned that despite wide use of the words ‘coupling’ and ’semi-coupling’, it appears to me that VAMPER and iLOVECLIM are not in fact coupled in the physical sense, at all. Suggesting that software coupling (in the sense that VAMPER runs in the same executable as iLOVECLIM) is equivalent to physical coupling or semi-coupling (where there is at least SOME two-way flow of information between VAMPER and iLOVECLIM) could be very misleading to general readers. Ultimately, semantics are very important, because software and physical coupling are extremely different things, and a software-coupled model shouldn’t be regarded in the same family as truly physically-coupled models. I have expanded on this concern in the Specific comments.

Furthermore, generally, I request a very detailed and fine-grained wordsmithing to remove or clarify a number of:

1) vague or grammatically incorrect statements, for example the following direct quotes:
"In fact, Koven et al. (2013) recently reported on the Coupled Model Intercomparison Project phase 5,"
"The modeling run not including the effects of snow cover overestimate the present permafrost extent."
"since,as just mentioned,"
2) subjective or judgement-based words, for example:
"fortunately"
"overall"
"reasonable"
"suitable"
"cumbersome"
"well-known"

####Specific comments####

1. *P1L1: Title: I have some issue with this title, given this manuscript does not actually present a coupled permafrost-climate model (by the author's own admission). I request a title change to accurately reflect that this manuscript describes steps towards full coupling, but not full coupling itself. In addition, the title change should reflect that other perhaps critical processes (namely hydrology) are not included in the model. For example: "Progress towards coupling of the VAMPER permafrost model within the earth system model iLOVECLIM (version 1.0)". This concern is reflected in some of my following comments as well.*

Response: The authors agree that the title should reflect towards coupling or the idea of progression.

Change: We propose to change the title of the manuscript to "Advancement toward coupling of the VAMPER permafrost model within the earth system model *i*LOVECLIM (version 1.0): description and validation:"

2. *P1L8: "has been enhanced for coupling": following from the above comment, I suggest rewording to "has been enhanced in preparation for full coupling".*

Response: The authors agree (also from the general comments) that a physical coupling as the editor describes has not yet been performed between ECBilt and VAMPERS. Therefore it is misleading to present the experiments as "semi-coupled". Rather, the experiments are results which help prepare for future coupling.

Change: We propose to reword, as the editor suggests, “has been enhanced for coupling” to “has been enhanced in preparation for full coupling”.

3. *P1L11: I feel that the term semi-coupled is misleading in the context of this manuscript. The term semi-coupled refers to at least SOME coupling being present (as an arbitrary example, communicating albedo changes but not surface heat fluxes from land to atmosphere). I request a re-terming of ‘semi-coupled’ in this manuscript, to accurately reflect the state of the software being presented. Actually, it appears that practically VAMPERS is completely uncoupled in a physical sense. Rather, it is ‘software-coupled’, in that it simply runs in the same model executable as iLOVECLIM. For example, with some infrastructure changes, I suspect the authors could in theory first run ECBILT-1, then run VAMPERS with ECBILT-1 output, and obtain the exact same results as shown here.*

Response: The authors agree with this assessment by the editor that you could potentially run the experiments in an off-line mode, but that would require saving the 4-hourly data for the forcing, something which is not practical in reality. Because they are run together, the software or executable is indeed coupled. However, we understand that within the modeling world, the general term ‘coupling’ implies physical exchanges between coupled components. Likewise, ‘semi-coupling’ also implies some portion of data passed back and forth. Therefore, to avoid ambiguity, we have removed the term semi-coupling throughout the manuscript.

Change: In order to remove the ambiguity associated with the semi-coupling terminology, the authors propose to remove the term in this instance and throughout the manuscript. When discussing coupling, it will only be referred to in the future sense and “in preparation for”.

4. *P1L35: “In other words, the effects of (changing) permafrost are not fed back to the climate”: please specify for the non-permafrost expert reader here what these effects actually would be (presumably, ground heat flux, which is noted later in the manuscript).*

Response: Since we have removed all reference to semi-coupling, the effects will not be specifically described here. In the model description section (2.2.2), the exchanges between the model components are described in more detail.

Change: In section 2.2.2 where the coupling is described, the effects of coupling are specifically addressed and details are given for the non-permafrost expert reader:

The VAMPER(S) model will be coupled to the atmospheric component, ECBilt, within *i*LOVECLIM. The ECBilt-VAMPER(S) coupling will be done at each timestep (4 hours) where the land surface temperature from ECBilt is passed to VAMPER(S) and the ground heat flux from VAMPER(S) is returned to ECBilt (Fig. 3a). The land 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, longwave radiation, and ground heat flux. The land surface temperature and ground heat flux are only communicated between components when the respective grid cell is classified as land with no overlying icesheet (i.e. Greenland/Antarctica at present day). With this coupling, the effect of changing permafrost conditions may be reflected in the climate via changes in the surface energy balance. If permafrost degrades, the subsurface acts as a thermal sink, absorbing additional energy to accommodate latent heat demands during phase change. However, at the same time, the active layer deepens, also redistributing the (seasonal) energy distribution at the surface.

5. *P2L29: "It should be noted that additional coupling mechanisms are possible between iLOVECLIM components and VAMPER, which include hydrology and the carbon cycle, but are not yet implemented at this time." The effect of these omissions should be explicitly noted as caveats, so that users of the model are aware of these, and also, so that reviewers of future scientific publications based on the model described here can clearly take these caveats into account.*

Response: The authors agree that this an important omission of coupling and should be specifically stated as a caveat. However, as we are no longer referring to the current model experiments as coupled, the sentence was no longer necessary.

Change: The authors propose to delete this sentence in this section of the paper since it is no longer relevant in this part of the manuscript. However, the caveat will be mentioned in the coupling description in section 2.2.2.: "The first phase of the coupling between VAMPER(S) and ECBilt will only include the land surface temperature and the ground heat flux as discussed. It should be mentioned as a caveat that additional coupling mechanisms are possible between *i*LOVECLIM components and VAMPER, which include hydrology and the carbon cycle, but will not be implemented for this first coupling phase."

6. *P3L7: Ensure that the reader doesn't leave with impression that Lawrence and Slater, Dankers, and Schaefer are only global-scale permafrost models (for just one example of additional work, see paper by reviewer Chris Avis: 10.1038/ngeo1160). Generally I think significantly more than 2 lines describing historical efforts in global permafrost-climate modeling are necessary, to put the present work in a historical context.*

Response: We agree that a more detailed list of global-scale permafrost models would put the present work in clearer relation to what has already been done.

Change: We propose to significantly expand the list and description of previous work.

7. *P3L9: Please provide references for previous works that applied one or the other approach.*

Response: Authors agree that references are needed here.

Change: We propose to correct with the following added references:

"…which actively integrate the role of permafrost (including the thermal and/or carbon feedbacks) (Lawrence et al., 2011), and models which look at permafrost in a post-processing perspective (e.g. Buteau et al., 2004, Ling and Zhang, 2004)"

8. *P3L37: By definition, parameterization schemes are not cumbersome, but are meant to be lightweight representations of unresolved physical processes. In fact, models like iLOVECLIM are by their very nature parameterization-heavy (in lieu of explicit simulation of small-scale processes). Thus, this statement is somewhat confusing.*

Response: The sentence can be written to improved in clarity. What we intended to say was that the process of parameterization (i.e. the tuning) can be cumbersome. This process, as McGuffie and Henderson-Sellers (2005) explain in their section 2.5, can be simple in some cases like vegetation but complex in other cases like radiation schemes. But what is particularly difficult in parameterization is matching the scale and timing of the different model components. In any case, we agree with the editor that the term “cumbersome” implies difficulty and complexity when it is meant to actually be a simplification.

Change: We propose to rewrite the sentence as such:

“Consequently, the representation of the soil and subsurface in VAMPER should fit the spatial space of iLOVECLIM, implying that detailed parameterization schemes are not suitable for VAMPER.”

9. *P4L6: “Since we are also interested in this timescale, we originally employed the same reasoning: relying on large-signal paleoclimatic changes”. This statement is somewhat unclear.*

Response: The statement was intended to say that originally the VAMPER model was forced by temperatures which varied or changed over geologic time periods (e.g. millennial) and the sub-annual changes were not part of the forcing.

Change: We propose to rewrite the sentence for improved clarity as such:

“At this timescale, it is not necessary to use a sub-annual timestep. In our earlier work with the VAMPER model (Kitover et al., 2013), we similarly used a yearly timestep.”

10. *P4L13-P4L18: Suggest these few sentences are reworded to increase clarity and flow.*

Response: The authors agree that rewording these sentences would improve the flow and clarity of this introduction paragraph.

Change: We propose to rewrite as follows:

“However, in light of the future coupling between ECBilt and VAMPER, it has become clear that the VAMPER model should run on a 4-hr timestep. Doing this allows VAMPER to match the timescale of the atmosphere, the subsystem to which the VAMPER model will be coupled. Changing to a 4-hour timestep also reduces error in the numerical approximation since the change in thermal properties, which are temperature-dependent, is smoother between each timestep. Since the VAMPER model is somewhat simplified, and hence flexible, the change to a 4-hr timestep required revalidating the model performance. In addition to the change in timestep, we also included a snowpack representation in the VAMPER model. Including this option is meant to simulate the effect of thermal insulation of the ground in winter. *Note that the VAMPER model with the snow enhancement is referred to as the VAMPER**S** model. When referring to both/either versions, the "VAMPER(S)" term is used.*"

11. *P5L3: It is not immediately clear to naive readers that decreasing the time step is the model development that causes appearance of an active layer. It seems the authors sometimes to refer to the same model development as 1) decreasing time step, and 2) simulation of an active layer. It could be beneficial to clearly specify that implementing 1) causes 2) (if this is indeed correct).*

Response: The authors agree that the writing should in fact state that it is the decreased time step which allows simulation of an active layer. This would improved clarity for readers not familiar with permafrost dynamics.

Change: The authors have made this connection in a rewritten paragraph, which serves as the introduction to the section. The rewritten paragraph is as follows:

"In permafrost modeling, an active layer can only be present when the air/ground temperature forcing varies seasonally. Thus, the timestep must be sub-annual. Since a 4-hr time step is now implemented the VAMPER model as expected produces an active layer. It necessary then to check the simulation of this active layer for validation purposes."

12. *P5L23-P5L26 This paragraph seems to belong in the Results section.*

Response: We understand that since it is a "result" it would belong in the results section, later in the paper but we believe that this would disrupt the flow and clear organization of the paper. First the paper only focuses on the VAMPER model itself and the new methods (enhancements) introduced. Here, we discuss the timestep, active layer, and snow scheme. As part of validating the new methods, we show the results of generically (no-site) simulating the active layer, which actually at this point do not have anything to do with iLOVECLIM. Then the manuscript progresses into experiments of VAMPER forced by iLOVECLIM, where the results are not single site but across the Northern Hemisphere. Moving this short paragraph about the active layer into the Results section where the results of the thickness distribution are presented would, in our opinion, not fit.

Change: We propose to leave the placement of this paragraph in its original place.

13. *P5L29: "the surface offset" is unclear to the average reader - suggest a better description of this.*

Response: The authors agree that the term "surface offset" may be unknown to some readers.

Change: We propose to include a simple definition at the first mention of the term, which is in the Introduction. The sentence is rewritten as follows:

“To compensate for this, Kitover et al. (2013) had artificially introduced the effect of snow cover via a surface offset (the difference between land surface temperature and ground temperature) of + 2°C. “

14.P7L1: *“The following is a stepped description of the snow algorithm for the ECBilt-1 VAMPERS semi-coupling”: perhaps reword something like “The following is a stepped description of the snow algorithm to generate a VAMPERS snowpack from ECBilt-1 precipitation”*

Response: The authors agree with the suggested rewording.

Change: We propose to change the sentence as suggested.

15. *Section 2.2.1: Despite iLOVECLIM being described elsewhere, I strongly suggest a brief description of the model components other than ECBilt-1 here (basic physics, resolution, etc.), to make this manuscript more self-describing.*

Response: A brief description of the other model components with corresponding references is provided.

Change: In this section, we propose to mention each component and follow with a brief description. The additional lines added are:

“ECBilt, the atmospheric model (Opsteegh et al., 1998) consists of a dynamical core with three vertical levels at 800, 500, and 200 hPa. It runs on a spectral grid with a triangular truncation (T21), which translates to a horizontal grid with a resolution of approximately 5.6 ° lat x 5.6 ° lon. The CLIO module (Goosse and Fichefet, 1999) is a 3-D ocean general circulation model with a free surface. It has 3° × 3° horizontal resolution and 20 vertical layers. VECODE, the vegetation module (Brovkin et al., 1997), is similar to VAMPER(S) in that it was particularly designed for coupling to a coarse-resolution earth system model. It is a reduced-form dynamic global vegetation model that characterizes the land surface as either trees, grass, or no vegetation (i.e. ‘bare soil’) and is computed at the same resolution as ECBilt. The plant types may be represented fractionally within each gridcell. Each iLOVECLIM model component was originally developed separately and the reader is referred to Goosse et al., 2010 for a detailed description of components and coupling mechanisms. Furthermore, *i*LOVECLIM more recently was extended with other optional components including the dynamical ice-sheet model GRISLI (Roche et al., 2014) and a stable water isotopes scheme (Roche, 2013).”

16. *P7L29: Specify exactly what ‘air surface temperature’ is. Is it equivalent to 2m air temperature, or the temperature right at the boundary layer (however that is simulated in ECBilt-1).*

Response: What we refer to the ‘air surface temperature’ as the lower (bottom) boundary in ECBilt. This variable is then directly used as the (land) surface temperature in the VAMPER model. Therefore, for improved clarity the term ‘air surface temperature’ was changed to ‘land surface temperature’ throughout the manuscript. This change should remove any discrepancy as to what height the air surface temperature is considered to be at.

Change: We propose to change all mention of ‘air surface temperature’ to ‘land surface temperature’. In addition, in the section 3.1 where the experimental setup is described, we explain that it is the lower boundary layer of the atmosphere. There is also now an additional figure 3b which illustrates how these variables are represented between the two models.

17. *P7L37: “In this case, the snow surface temperature is taken to be the air surface temperature .” This is somewhat confusing. For example, a reader would ask “isn’t there still an air surface temperature, even if snow is present? How can snow surface temperature replace air surface temperature?”*

Response: What the authors intended to say is that when snow is present, the temperature of the snow surface (i.e. the top layer of snow) is the same as the current land surface temperature. The land surface temperature is never replaced by the snow temperature.

Change: We propose to reword the sentence for improved clarity as such:

When only VAMPER is employed, i.e. without the snowpack, the VAMPER ground surface temperature is assumed to be the same as the ECBilt land surface temperature. As a result no surface offset occurs. In the case of VAMPERS the snow surface temperature (i.e. at the top of the snow layer) is assumed to be the same as the ECBilt land surface temperature. This means the VAMPERS model ground temperature is buffered via the three snowpack layers as discussed in Sect. 2.1.2. This description is illustrated in Figure 3b.

18. *P8L2: “phase change capability”: echoing reviewer comments, I request that this capability be explicitly described in this particular manuscript, since it is presumably an important aspect of the model.*

Response: Phase change capability means that the VAMPER model is able to simulate freezing/thawing of the subsurface. We agree that this terminology should be explicitly described but is done earlier in the manuscript when the VAMPER model is first described (section 2.1.1).

Change: A new paragraph is written at the end of the VAMPER model general description (section 2.1.1) to explicitly described phase change capability. The paragraph reads as follows:

“The phase change process of freeze/thaw in the subsurface is handled using a modified apparent heat capacity method from Mottaghy and Rath (2006). Their method assumes that phase change occurs continuously over a temperature range, which in our case is approximately between 0 and -2 °C. The apparent heat capacity method includes an additional latent heat term in the general heat diffusivity equation as a way to account for the added energy released (consumed) during freeze (thaw) of the subsurface water content. The latent heat demand during phase change, often referred to as the ‘zero curtain effect’, slows thermal diffusivity rates near the surface as the active layer freezes and thaws but also during permafrost degradation/aggradation. The later is occurring most noticeably during periods of climate change."

19. *P8L11: "This system is often referred to as a bucket model in previous text.": please reference these previous texts.*

Response: Authors will provide this reference.

Change: The following citations were added:

"This system is often referred to as a bucket model in previous text (Goosse et al., 2010)."

20. *P8L12: "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": so does that mean that two land models run simultaneously for a given grid cell: VAMPERS, and the bucket model? And the bucket model is the model that provides feedback to the climate? If so, this is important to note.*

Response: Right now, without any coupling, the answer to your question is yes, there are two separate models: one running hydrology (the bucket model) and one running permafrost. The bucket model is simply how the hydrology is represented and is part of the land surface model. Currently, the future coupling is only intended to transfer temperature and heat fluxes. Eventually, it would be sensible to also transfer hydrology, meaning that the volume of water contained in the "bucket" could also be passed as a water content in the active layer. This is particularly important when the ground is frozen and becomes impermeable, which could affect surface runoff timing. However, all of the implications with connecting the hydrologic portion of ECBilt to the VAMPER model is just speculative at this time and is not relevant to this work. The authors believe that it is only important to mention it as a future coupling option.

Change: We propose to rewrite this paragraph to make more clear that the bucket model is simply part of ECBilt and it is this part which would be the next phase of coupling.

"The land surface of ECBilt consists of a single "layer" which represents a volumetric soil water storage capacity to generate surface runoff when full. This system is referred to as a bucket model in previous text (Goosse et al., 2010). As of current, this hydrology portion of ECBilt, will not be coupled to VAMPERS. However, because the active layer is a regulator of hydrology in arctic and subarctic regions (Hinzman and Kane, 1992; Genxu et al., 2009), a next step would be to expand coupling between VAMPERS and ECBilt by connecting the active layer with this bucket model."

21. *P8L14: "The results presented in this current work is only a function of performing semi-coupled experiments": this is an unclear statement.*

Response: This statement was removed due to comment #3.

Change: No change necessary as the statement was removed per comment #3.

22. *Section 2.2.3 and Section 2.2.4: These seem out of place in the 'Coupling' section; do they rather belong in the description of 'VAMPER model enhancements'?*

Response: The authors placed these enhancements in the coupling section because they are only used when the VAMPER model is coupled or forced by iLOVECLIM (whether we refer to this as model coupling or software coupling). The geothermal heat flux and porosity are maps or in the modeling world, referred to as masks. In this sense, they are more relevant in the coupling section. In addition, they did not cause any changes in the makeup of the actual VAMPER model so describing it as an enhancement in this section, as suggested by the editor, would be out of place.

Change: No change necessary since we propose to keep the descriptions in their original place.

23. *P9L30: "This configuration, therefore, allows only the examination of the iLOVECLIM model to reproduce current permafrost extent and depths as function of the currently established climate of the iLOVECLIM model.". This statement has an unclear meaning, and is perhaps self-obvious?*

Response: The authors agree that this statement is somewhat obvious and unnecessary.

Change: We propose to remove the statement.

24. *P9L38: "until approximate equilibrium between ECBilt temperatures and VAMPER(S) model is reached": the word equilibrium implies coupling. Given that the present setup does not have full coupling, perhaps a better phrase would be "until VAMPER(S) equilibrated under equilibrated ECBilt temperatures".*

Response: Since the term coupling is no longer used in the manuscript, except for referring to it in the future, we agree with the editor that his suggested phrase is better.

Change: We propose to change the phrasing as suggested by the editor. The new sentence reads:

"This asynchronous cycle is repeated for thousands of years until the VAMPER(S) model is equilibriated to the *i*LOVECLIM LGM climate."

25. *P10L19: Suggest replacing "how well the" with "the extent to which the"*

Response: The authors agree this is better wording.

Change: We propose to change the wording as suggested by the editor.

26. *P10L22: Aligning with previous comments: suggest replacing "ECBilt-VAMPER semi-coupling" with "VAMPER driven with ECBilt forcing".*

Response: We agree that the term semi-coupling is no longer fitting and a rewrite is necessary.

Change: We propose to rewrite the sentence as such:

"Using the comparison shown in Figure 7 it is clear that the experiment without the snow option overestimates permafrost extent while employing the VAMPER**S** version underestimates it."

27. *P10L23: "Swing of inaccuracy" is unclear*

Response: We agree that the description "swing of inaccuracy" is a bit unconventional and does not make the point clearly.

Change: We propose to rewrite the description:

"This inaccuracy between both an overestimated result and an underestimated result is at least partially due to attempting to match results from a low resolution grid to spatial coverage of much higher resolution."

28. *P10L23: "This swing of inaccuracy is at least partially due to simply attempting to match results from a low resolution grid to spatial coverage of much higher resolution". I disagree with this statement, since if it were true, I think both VAMPER simulations should show the same bias (since they are both on the same resolution grid).*

Response: A low resolution grid will not provide a consistent bias (there is no effect on climate or actual physics) but rather just a consistent inaccuracy in the display of data.

Change: We propose to rewrite the explanation as such:

"Because the marginal areas of permafrost extent are the most sensitive to climate, they are highly responsive to minor temperature deviations. These deviations, whether a few degrees above or below freezing, determine from a modeling point of view, whether permafrost exists or not. In the case of VAMPER, average annual ground surface temperatures in many of these marginal grid cells fall below freezing while in the case of VAMPERS, the temperatures in these same grid cells now fall above freezing. However, because of the coarse grid, these estimates in either case, look like inaccurate estimates since a single value is representative of a relatively large spatial area. In reality, in these marginal permafrost regions, an area the size of an ECBilt grid cell would have only partial coverage of permafrost."

29. *P10L25: "In addition, we expect some inaccuracy since we cannot parameterize the snowpack characteristics and more importantly, the nature of the snowmelt." But, isn't capturing the first-order nature of snowpack characteristics and/or melt the point of including a snow model in VAMPERS? Please clarify.*

Response: The point of including snow in VAMPERS is to represent the temperature offset between the land surface temperature and the ground temperature that occurs due to snowcover. We have shown to do this by evidence of Figure 7 (decrease in permafrost thickness and distribution) and Figure 8 . However, aside from the expected offset provided by the model, there are a number of factors which can alter the role of snow on the ground thermal regime. These effects should be fitted to match the local landscape characteristics, hence a "parameterization" would be needed. Evolution of the snowcover not captured by the model such as rain on snow events and wind-redistributed snow, change the characteristics of the snow. In turn, model variables such as snow thermal conductivity should be fitted to match observations. And of course, one fitted model with specific snow characteristics does not necessarily fit elsewhere. These meteorological (i.e. wind, atmospheric circulation patterns, frontal activity) and topographical (i.e. elevation, slope, aspect) factors influence how the snow is distributed.

Change: For improved clarity, we propose to expand the original statement to include the explanation as described above:

"In addition, some inaccuracy is expected since we cannot parameterize some of the snowpack characteristics that alter the effect of snow on the ground thermal regime. Although we capture the role of snow cover, which is to impose a reduced thermal diffusivity effect between the air and ground, there are number of snowpack characteristics that we do not include. "

30. *P10L27: "As opposed to our generalized approach described earlier" and "recognized discrepancies in generalizing snow model details,": please specify what exactly these statements refer to.*

Response: Thank you for recognizing the ambiguity and we agree that we should specifically state what these are in reference to.

Change: We propose to refer to the section 2.1.2 and change "generalized approach" to what we specifically name the sub-section in the manuscript, which is snowpack parameterization. In addition, we rewrote the second sentence so it flows better and is more clear. It is rewritten as such:

"As opposed to our generalized snowpack parameterization scheme described in section 2.1.1 , high resolution snow 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 this lack of details and the results shown in **Fig. 7**, whether the better option is to include snowpack in VAMPERS or not."

31. *P10L31: "However, as long as the VAMPERS model is doing a reasonable job, we contend it is a better option 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.": I understand this argument, but think that it could be reworded in a more scientific way. For example, what within what bounds do you define 'reasonable'?*

Response: We will use Figure 8., which shows a map of the average offset produced as a result of including the snow model, to support our conclusion that using the snow component option produces "reasonable" results. The discussion that describes Figure 8 and claims that it is within actual observations gives enough evidence, in our opinion, to support use of the snow option. This paragraph was joined with the preceding paragraph.

Change: We propose to join the following paragraph, which discusses figure 8, with this statement that it is doing a reasonable job. This figure and discussion of naturally (observed) occurring surface offsets substantiate the use of the VAMPERS snow option.

32. *P10L33: "Further, with the snow optiont, changing precipitation patterns that are often the byproduct of a shifting climate would otherwise have no effect on the subsurface thermal conditions." There is a typo, and also, don't you mean "withOUT the snow option"?*

Response: Thank you for pointing out these errors.

Change: We will fix the typo and rewrite as corrected to be "without". In addition these sentences were moved to a new paragraph to separate them from the "reasonability" discussion in comment #31.

33. *P11L1: Again, the 'surface offset' needs to be clearly defined, perhaps each time the statement is used, for non-specialist readers.*

Response: We agree that is was not clearly defined, especially at the initial mention of it.

Change: We added in a simple definition at first mention in the Introduction. After that, we do not find it necessary to repeatedly define the same term throughout the manuscript.

34.*P11L23: This is a great paragraph that should be combined more linearly with the paragraph starting P10L21.*

Response: This is an excellent suggestion, which first gives a perspective of our results within the Intercomparison project.

Change: We propose to accept this suggestion and move the paragraph to the beginning of the section.

35. *P12L3: "(> 300 m) and some very underestimated (>700 m)." Should one of these '>' perhaps go the other way?*

Response: This is actually not an error but admittedly is a bit confusing. We are saying that the overestimations are maximum about 300 m and the underestimations at maximum 700 m.

Change: We propose to rewrite this sentence to improve clarity as such:

"…where the depths at some points are overestimated by over 300 m and at some other points very underestimated by over 700 m."

36. *P13L19: "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 iLOVECLIM." I suggest calculating a regression coefficient, so that you can say something quantitative about the comparison, instead of the subjective statement 'near the 1:1 line'.*

Response: We can include a simple regression coefficient to remove the subjectivity.

Change: We included the regression coefficient as suggested and now the paragraph is rewritten as such:

"Overall, **Fig. 11** illustrates that VAMPERS does a reasonable job of predicting shallow subsurface temperatures since the Pearson correlation is about 0.62."

37. *P13L39: "Due to minimal parameterization": do you perhaps mean 'minimal complexity'?*

Response: We agree that 'minimal complexity' is better stated.

Change: We propose to replace 'minimal parameterization' for 'minimal complexity'.

38. P14L5: Suggest renaming "Next steps" to "Future development"

Response: We agree to the suggestion.

Change. We propose to rename "Next steps" to "Future development".

39. *Figure 3: Is ground heat flux actually passed back to the climate, in the current model? If not, this figure is misleading, since it implies physical coupling. Also, what is the dashed white line?*

Response: In the (future) coupled version, the ground heat flux is indeed passed back. Although since we have now removed any mentioned of a currently coupled model, this figure is only referred to for discussion on future coupling. The dashed white line was an error.

Change: The dashed white line was removed. This figure is carefully referred to in the manuscript when mentioning "full coupling".

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Advancement toward c~~C~~oupling 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 with snow thickness and active layer calculations in preparation for coupling within the *i*LOVECLIM earth system model of intermediate complexity ~~by including snow thickness and active layer calculations~~. ~~.~~ In addition, maps of basal heat flux and lithology were developed within ECBilt, the atmosphere component of *i*LOVECLIM, so that VAMPER may use spatially varying parameters of geothermal heat flux and porosity values. ~~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~~ The enhanced VAMPER model is validated ~~using the~~by comparing the simulated modern day extent of permafrost thickness with observations ~~along with observed permafrost thickness and subsurface temperatures at selected borehole sites~~. To perform the simulations, the VAMPER model is forced by *i*LOVECLIM land surface temperatures. Results show that ~~The~~the simulation ~~modeling run~~ which did not include the ~~ing the effects of~~ snow cover option overestimated the present permafrost extent. However, when the snow component is included, the simulated permafrost extent is ~~overall~~ reduced too much. In analyzing simulated permafrost depths, i~~I~~t was found that most of the modeled thickness values and subsurface temperatures fall within a reasonable range of the corresponding observed values. Discrepancies between simulated and observed 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.

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Comment [D2]: Removed "semi-coupled" per comment no. 3.

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1 Introduction

The **VU Am**sterdam **Per**mafrost (VAMPER) model is a deep 1-d heat conduction model with phase change capability. It has been previously validated for single site experiments such as Barrow, Alaska (Kitover et al., 2012). Subsequently, it has simulated both equilibrium and transient permafrost depth estimates at a number of arctic/subarctic locations (Kitover et al., 2012; Kitover et al., 2013). ~~The model~~ The VAMPER model was built with the intention to couple it within *i*LOVECLIM, an earth system model of intermediate complexity. ~~.~~Using~~With~~ this coupling, ~~it is~~ the ~~ultimate~~ goal is to capture the transient nature of permafrost growth/decay over millennia as a feedback effect during major periods of climate change. To prepare for coupling, a few enhancements have since been made to the VAMPER model. As a next step, we validate these improvements by simulating modern-day permafrost thickness and distribution. The goal of this paper is to describe the enhancements and then analyze the validation experiments for modeling present-day permafrost, with detailed explanation of why mismatches occur between simulated and observed data. ~~However, as a first stepAt 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.~~

Comment [D4]: Removed subjective wording per general comment.

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~~land 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.

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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 and validation 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 snow as optional layers and 2) change in the timestep. The first in particular is an ~~common~~ issue in modeling permafrost since snow cover is a r~~widely recognized~~ecognized influence on the ground thermal regime (Williams and Smith, 1989) and was not an available option 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 (the difference between the

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ECBilt land surface temperature and the VAMPER ground surface temperature) 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 surface 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 the~~se~~ 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 to the ~~in the~~VAMPER model ~~*i*LOVECLIM model~~: geothermal heat flux and porosity~~lithology~~. These are particularly used when VAMPER is run over a horizontal grid, in turn allowing the parameters to vary spatially.

Integrating permafrost into earth system models has become of increased interest since research has acknowledged the effect of climate change on ~~both its sensitivity to climate change~~ permafrost temperatures (Cheng and Wu, 2007), permafrost degradation (Anisimov and Nelson, 1996), and ~~along with~~ carbon stored within the permafrost ~~feedback implications~~(Davidson and Janssens, 1996). ~~In fact, Koven et al. (2013) recently reported on T~~the Coupled Model Intercomparison Project phase 5 (Koven et al., 2013) ~~, which specifically looked~~ analyzed ~~at~~ how different earth system models represent the subsurface thermal dynamics and how well this class of models simulate permafrost and active layer depth. Despite the fact that there is a ~~this study introduced the~~ variety of ~~how~~ modeling methods and configurations for the different global coupled models, ~~els capture permafrost,~~ the ~~overall~~ conclusion was that there is no clear ranking among the~~ir~~ reviewed 15+ model versions. ~~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 the Northern Hemisphere ~~a global~~or globally. ~~scale~~ Simulations are done using either statistical approaches like the frost index method (Anisimov and Nelson, 1996; Stendel and Christensen,2002) or climate models such as Dankers et al., (2011) who used the JULES land surface model and Ekici et al. (2014) who used the JSBACH terrestrial ecosystem model. ~~, namely these are from~~ Other examples include Lawrence and Slater (2005), who used the Community Climate System Model (CCSM) to look at future permafrost extent and associated changes in freshwater discharge to the Arctic Ocean. Schaeffer et al. (2011) used a land surface model (SiBCASA) to simulate reduced future permafrost coverage and subsequent magnitude of the carbon feedback. Similarly, Schneider von Deimling et al.(2012) and Koven et al. (2011) also modeled future estimates of carbon emissions due to thawing permafrost. From a paleoclimate perspective, DeConto et al. (2012) used a version of the GENESIS GCM to model the connection between permafrost degradation and subsequent carbon emission as a driver for the occurrence of the Palaeocene–Eocene Thermal Maximum (PETM). Modeling permafrost changes is also

Comment [D7]: Defined first time the term surface offset is mentioned in manuscript, per comments #13 and #33.

Comment [D8]: Removed and placed in section 2.2.2. as a caveat per comment #5.

Comment [D9]: Remove subjective language an interest from the hydrological perspective. Avis et al. (2011) used a version of the UVic Earth System Climate Model to examine the potential decreasing areal extent of wetlands due to future permafrost thaw.

~~, 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, hydrological, and/or carbon feedbacks) (Lawrence et al., 2011), and models which ~~simply~~ look at permafrost in a post-processing perspective (e.g. Buteau et al., 2004, Ling and Zhang, 2004)~~-~~meaning they are forced by the predicted temperature changes. It is the full coupling with integrated feedbacks which is of our 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. Hence, it is the authors'~~ where the ~~ultimate~~ goal is to fully couple ECBilt and VAMPERS within *i*LOVECLIM. ~~, where~~ T~~t~~he results of the ~~present~~ work presented here serve as an important validation stage toward this goal. 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. Next, two newly developed maps of spatially varying parameters used in the VAMPER experiments are explained. For the validation, t~~T~~he VAMPER model is forced by ECBilt land surface temperatures~~-VAMPERS semi-coupling within the *i*LOVECLIM model~~ ~~is then validated using~~, where the results are compared against a modern-day map of permafrost extent in the northern hemisphere and observed permafrost thickness and subsurface temperatures values in boreholes.

Comment [D10]: Expanded literature review per comment # 6

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2 METHODS

2.1 VAMPER model

2.1.1. General Description

VAMPER is a 1-d permafrost model developed to estimate permafrost thickness and is~~was~~ designed for eventual full coupling with *i*LOVECLIM. Consequently, the representation of the soil and subsurface in VAMPER should fit the spatial space of *i*LOVECLIM, implying that detailed parameterization schemes are not suitable for VAMPER. ~~Because it must fit a relatively coarse earth system model, it is not suitable to undergo cumbersome parameterization schemes.~~VAMPER ~~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.

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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.

The phase change process of freeze/thaw in the subsurface is handled using a modified apparent heat capacity method from Mottaghy and Rath (2006). Their method assumes that phase change occurs continuously over a temperature range, which in our case is approximately between 0 and -2 °C. The apparent heat capacity method includes an additional latent heat term in the heat diffusivity equation as a way to account for the added energy released (consumed) during freeze (thaw) of the subsurface water content. The latent heat demand during phase change, referred to as the 'zero curtain effect', slows thermal diffusivity rates near the surface as the active layer freezes and thaws but also during permafrost degradation/aggradation. ~~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.~~.~~ At this timescale, it is not necessary to use a sub-annual timestep. In our earlier work with the VAMPER model (Kitover et al., 2013)~~.~~, we similarly used a yearly timestep. ~~.~~ ~~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 of the future 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 match the~~more closely follow the response~~ timescale of the atmosphere, the subsystem to which the VAMPER model will be ~~is~~ coupled. Changing to a 4-hour timestep~~, while also allowing~~ also reduces error in the numerical approximation ~~solution to converge~~ since the change in thermal properties, which are temperature-dependent, is smoother between each ~~and hence change on every~~ timestep. ~~Fortunately, being that~~Since the VAMPER model is somewhat simplified, and hence flexible, the change to a 4-hr timestep required revalidating the model performance. In addition to the change in timestep, we also included a snowpack representation in the VAMPER model. Including this option is meant to simulate the effect of thermal insulation of the ground in winter.~~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 VAMPER**S** model. When referring to both/either versions, the "VAMPER(S)" term is used.*

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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. T~~herefore, t~~he 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 to differ since these variables are temperature-dependent (**Fig. 1b**). However, the lower boundary 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 (difference between ground temperature and top of the permafrost) 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**.

Active Layer

In permafrost modeling, an active layer can only be present when the air/ground temperature forcing varies seasonally. Thus, the timestep must be sub-annual. Since a 4-hr ~~a sub-daily~~ time-step is now implemented,~~used,~~ the VAMPER model ~~as expected~~ produces an active layer. It necessary within the framework of model development to then check the simulation of this active layer for validation purposes.

Most dynamical permafrost models that simulate near-surface behavior configure the parameter settings to specifically match locally observed data. ~~Common~~ Some 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.,~~ include for example, Romanovsky and Osterkamp (~~,~~2000),~~;~~ Buteau et al. (~~,~~2004), Ling and Zhang (~~,~~2004)~~;~~, and Zhang et al.~~,~~ (2008), and~~;~~ 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

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$$AL = \sqrt{2\sigma k_{mw}/Q_i} \quad (1)$$

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

$$Q_i = L\rho_m(W - W_u) \quad (2)$$

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** 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 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 produced ~~applied~~ in the VAMPER model.

Comment [D22]: Added simple definition of surface offset as suggested by the editor in comment # 13.

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 is an additional set of necessary functions when coupled with VAMPERS to transfer ECBilt *swe* values into a snowpack thickness (Z) at time *t*:

$$Z^t = \rho_w \, swe^t / \rho_s^t \quad (3)$$

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}) :

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

$$swe^t = swe^{t-1} + swe^{fr} \quad (5)$$

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 metamorphism, constructive metamorphism, 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 ~~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:

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

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 :

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

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

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 layers 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~~to generate a VAMPERS snowpack from ECBilt precipitation:

Comment [D25]: Reworded per comment #14

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~~,~~ ~~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**). ECBilt, the atmospheric model (Opsteegh et al., 1998) consists of a dynamical core with three vertical levels at 800, 500, and 200 hPa. It runs on a spectral grid with a triangular T21 truncation, which translates to a horizontal grid with a resolution of approximately 5.6 ° lat x 5.6 ° lon. The CLIO module (Goosse and Fichefet, 1999) is a 3-D ocean general circulation model with a free surface. It has 3° × 3° horizontal resolution and 20 vertical layers. VECODE, the vegetation module (Brovkin et al., 1997), is similar to VAMPER(S) in that it was particularly designed for coupling to a coarse-resolution earth system model. It is a reduced-form dynamic global vegetation model that characterizes the land surface as either trees, grass, or no vegetation (i.e. ‘bare soil’) and is computed at the same resolution as ECBilt. The plant types may be represented fractionally within each gridcell. Each model component of *i*LOVECLIM was originally developed separately and the reader is referred to Goosse et al., 2010 for a ~~a detailed~~ detailed description of components and coupling mechanisms. Furthermore, *i*LOVECLIM more recently was extended with~~includes~~ other optional components including the~~a~~ dynamical ~~n~~ ice-sheet model GRISLI (Roche et al., 2014) and a stable water isotopes scheme (Roche, 2013).

Comment [D26]: Added brief description of components as suggested in comment # 15

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2.2.2 ECBilt-VAMPER(S) Coupling Description

The VAMPER(S) model will be coupled to the atmospheric component, ECBilt, ~~(Opsteegh et al., 1998)~~within *i*LOVECLIM.~~, 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 will be~~is~~ done at each timestep (4 hours) where ~~via~~ the ~~air surface~~land surface temperature from ECBilt is passed to VAMPER(S) and the ground heat flux from VAMPER(S) is returned to ECBilt (Fig. 3a).~~ at each timestep (4 hours), which the VAMPER(S) model uses as the ground temperature forcing.~~ The ~~air surface~~land 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, and ground heat flux. The ~~air surface~~land surface temperature and ground heat flux are ~~is~~ only communicated ~~to the VAMPER(S) model~~between components when the respective grid cell is classified as land with no overlying icesheet (i.e. Greenland/Antarctica at present day). With this coupling, the effect of changing permafrost conditions may be reflected in the climate via changes in the surface energy balance. If permafrost degrades, the subsurface acts as a thermal sink, absorbing additional energy to accommodate latent heat demands during phase change. However, at the same time, the active layer deepens, also redistributing the (seasonal) energy distribution at the surface.

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Comment [D27]: The paragraph was edited per comment #4 which explains why coupling would capture the effect of changing permafrost.

When only ~~Since the~~ VAMPER is employed, i.e. without the snowpack, the~~(S) model~~ VAMPER ground surface temperature is assumed to be the same as ~~taken to be~~ the ECBilt ~~air surface~~land surface temperature. As a result~~,~~ ~~there is~~ no surface offset occurs.~~effect except when there is a snowpack.~~ In th~~e~~is case of VAMPERS~~,~~ the snow surface temperature (i.e. at the top of the snow layer) is ~~taken to be the~~assumed to be the same as the ~~air surface~~ECBilt land surface temperature~~.~~. This means the VAMPERS model ground temperature ~~forcing~~ is buffered via the three snowpack layers as discussed in Sect. 2.1.2~~.~~. This description is illustrated in Figure 3b. The~~Using the~~ ground surface temperature is the forcing that~~,~~ the VAMPER(S) model then uses to compute~~s~~ 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 in reality 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”.

Comment [D28]: Reworded per comment #17

Comment [D29]: Removed subjective language

The land surface of ECBilt consists of a single “layer” which represents a volumetric soil water storage capacity to generate surface runoff when full. This system is ~~often~~ referred to as a bucket model in previous text (Goosse et al., 2010). As of current~~ly~~, this hydrology portion of ECBilt ~~this bucket model, which is the surface hydrology in *i*LOVECLIM~~, will ~~is~~ not be coupled to VAMPERS. However, because the active layer is a regulator of hydrology in arctic and subarctic regions (Hinzman and Kane, 1992; Genxu et al., 2009), ~~It would be a sensible~~ a next step would be to expand coupling between VAMPERS and ECBilt ~~to~~by connecting the active layer with this bucket model.

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Comment [D31]: Added references per comment #19.

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Comment [D32]: Reworded per comment # 20

The first phase of the coupling between VAMPERS and ECBilt will only include the land surface temperature and the ground heat flux as discussed. It should be mentioned as a caveat -that additional coupling mechanisms are possible between *i*LOVECLIM components and VAMPER, which include hydrology and the carbon cycle, but will not be implemented for the first coupling phase.

~~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, at the end of each timestep, VAMPER(S) would calculate the ground heat flux and return this value 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.) , which in turn would be used to obtain the air surface temperature for the next time step.. The equations for this full coupling will be described in a future publication.~~

Comment [D33]: Paragraph removed via comment # 3.

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 VAMPER(S) ~~iLOVECLIM~~ 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 (Kitover et al., 2013).

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., 2012; 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 (Kitover et al., 2013)~~.~~

3 Validation of preindustrial permafrost thickness distribution

3.1 Experimental Setup

The model experiments are performed over the whole globe ~~semi-coupled~~where the VAMPER model is forced by ~~, which means that~~ ECBilt ~~passes the air~~ ~~surface~~land surface temperatures ~~values~~. These values are the lower boundary layer of the atmosphere and are calculated using a surface heat budget (Goosse et al., 2010). Referring to Figure 3a, this means that ECBilt passes 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. The model experiments also include the spatially varying parameter values of geothermal heat flux and porosity provided by the new maps (described in sections 2.2.3 and 2.2.4) ~~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.

Comment [D34]: This statement was removed since it is unnecessary and was suggested by the editor in comment #23.

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~~forced synchronously by ECBilt. Rather, VAMPER(S) is forced ~~they are run together~~ continuously for 100 years and then ~~VAMPER(S)~~ runs offline for 900 years using the ECBilt average ~~air surface~~land surface temperature of the previous 100 years as the forcing. This asynchronous cycle is repeated for thousands of years until the VAMPER(S) model is equilibrated to the (already) ~~approximate equilibrium between the~~ equilibrated *i*LOVECLIM preindustrial climate.~~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 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.

Comment [D35]: Rewritten to express change to remove “coupling” wording per general comment.

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Comment [D36]: Rewritten per comment #24

Comment [D37]: Removed subjective wording

3.2 Results and Discussion

In order to verify the performance of ~~the ECBilt-~~VAMPER(S) forced by ~~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)~~permafrost distribution and 2) permafrost depth.

Comment [D38]: Removed subjective language

3.2.1 Permafrost Distribution Validation

The first validation demonstrates the extent to which ~~how well the *i*LOVECLIM~~ the VAMPERS model reproduces the modern-day permafrost distribution. ~~extent by overlaying the simulated results on the map from Brown et al. 2014.~~ ~~The permafrost distribution simulated by *i*LOVECLIM~~ The results 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 our study ~~*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~~Our simulation using VAMPERS yields approximately 20.3 x 10^6 km^2. This is a reasonably comparable estimate ~~considering~~ since almost 80 % (14/18) of the model area extents from Koven et al. (2012) fall within ±40%~~all within 40%~~ (12 – 28 x 10^6 km^2) of our model estimate~~s~~. 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).

Comment [D39]: Reworded per comment #25

Comment [D40]: Paragraph was at end of section but now moved to beginning per suggestion in comment #34.

Using the comparison shown in Figure 7, which overlays the simulated results on the map from Brown et al. 2014., ~~a comparison between the different couplings (**Fig. 7**),~~ it is clear that the experiment without the snow option ~~where the ECBilt- VAMPER semi-coupling (no snowoption and no imposed surface offset) is used~~ overestimates permafrost extent while employing the ~~ECBilt-~~ VAMPER**S** version underestimates it. This ~~swing of~~ inaccuracy between both an overestimated result and an underestimated result is at least partially due~~-~~ to ~~simply~~ attempting to match results from a low resolution grid to spatial coverage of much higher resolution. Because the marginal areas of permafrost extent are the most sensitive to climate, they are highly responsive to minor temperature deviations. These deviations, whether a few degrees above or below freezing, determine from a modeling point of view, whether permafrost exists or not. In the case of VAMPER, average annual ground surface temperatures in many of these marginal grid cells fall below freezing while in the case of VAMPERS, the temperatures in these same grid cells now fall above freezing. However, because of the coarse grid, these estimates in either case, look like inaccurate estimates since a single value is representative of a relatively large spatial area. In reality, in these marginal permafrost regions, an area the size of an ECBilt grid cell would have only partial coverage of permafrost.

Comment [D41]: Rewritten per comment #26 and general comment to remove semi-coupling terminology.

Comment [D42]: Rewritten per comment #27

Comment [D43]: Written per comment #28

~~In~~Inaccuracy in model results ~~addition, we expect some inaccuracy~~ is also expected since we cannot parameterize some of the ~~the~~ snowpack characteristics that alter the effect of snow on the ground thermal regime. Although we capture the role of snow cover, which is to impose a reduced thermal diffusivity effect between the air and ground, there are number of snowpack characteristics that we do not include such as rain-on-snow events and wind-induced redistribution. ~~and more importantly, the nature of the snowmelt.~~ As opposed to our generalized snowpack parameterization scheme, ~~approach~~ described in section 2.1.1~~earlier~~, high resolution snow~~melt~~ 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 this lack of details and the results shown in **Fig. 7** ~~and the recognized discrepancies in generalizing snow model details~~, whether the better option is to include a snowpack in VAMPERS or not. However, ~~as long as the~~ we contend that the VAMPERS model is doing a reasonable job since it is producing the surface offset that would naturally occur from the snowpack (Goodrich, 1982; Smith and Riseborough, 2002).~~, we contend it is a better option 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.~~ The simulated global distribution of this surface 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 option and no imposed surface 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 surface 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).

Further, without the snow option~~t~~, changing precipitation patterns that ~~are~~ can be~~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~~will be more noticeable in using the ECBilt-VAMPERS coupling when doing transient experiments. An example of the effect of changing snow conditions on the ground thermal regime come from Lawrence and Slater (2010), who demonstrated through experiments with the Community Land Model that 1) increased snowfall accounted for 10 to 30% of soil warming and 2) a shortened snow season also caused soil warming due to the ground surface's increased uncovered exposure to air temperatures. From this point forward, all analysis is done using results from ~~the ECBilt-~~VAMPERS~~ coupling~~ (i.e. *with* the snow option).

~~Employing the snow 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 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~~

Comment [D44]: Rewritten per comments # 29

Comment [D45]: Rewrote per comment #30

Comment [D46]: This paragraph was moved to substantiate using the snow option and that it is doing a reasonable job as compared to what naturally occurs. In response to comment # 31

Comment [D47]: Removed subjective language

Comment [D48]: Edited per comment #31 and general comment to removed coupling terminology except in mention of future coupling.

~~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 surface 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~~they include~~s~~ 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~~land 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 flow rates and timing.

Comment [D49]: Added in definition of surface offset per comment #33

Comment [D50]: Removed subjective language

~~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 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).~~

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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 the depths at some points are ~~relatively~~ overestimated~~-~~ by over 300 m~~(> 300 m)~~ and at some other points very underestimated by over 700 m.~~(>700 m). T~~There are a number of reasons to explain the mismatch,

Comment [D51]: Rewritten to remove confusion per comment #35.

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 al.,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).

Comment [D52]: Removed subjective language

Comment [D53]: Removed subjective language

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~~ is relatively 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.

Comment [D54]: Removed subjective wording

Comment [D55]: Removed subjective wording

Comment [D56]: Removed subjective language

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(S) 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~~VAMPERS does a reasonable job of predicting shallow subsurface temperatures since the Pearson correlation is about 0.64. ~~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. Although 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 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~~land 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). Smith and Riseborough (2002) simplified these mechanisms into the surface offset (air to ground surface) and the thermal offset (ground surface to top of the permafrost). Due to minimal complexity~~parameterization~~ of the VAMPERS model, these offsets may be somewhat overlooked.

Comment [D57]: Removed subjective language

Comment [D58]: Removed coupling terminology

Comment [D59]: Put in pearson correlation as recommended in comment #36

Comment [D60]: Removed subjective language

Comment [D61]: Replaced parameterization with complexity per comment #37

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 Future Development~~Next Steps~~

Comment [D62]: Renamed as suggested in comment #38

The results of this paper demonstrate the ability of VAMPERS forced by ~~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 activate the~~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 an estimated present-day distribution of permafrost thickness and distribution using ECBilt land surface temperatures within the *i*LOVECLIM equilibriated preindustrial climate as the forcing.~~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 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.

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~~Using a semi-coupled ECBilt-VAMPER(S) component within *i*LOVECLIM, e~~ 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 surface 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 coarse 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 (with

Comment [D63]: Removed subjective language

Comment [D64]: Removed subjective language

Comment [D65]: Removed subjective language the ECBilt-VAMPERS coupling)- 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

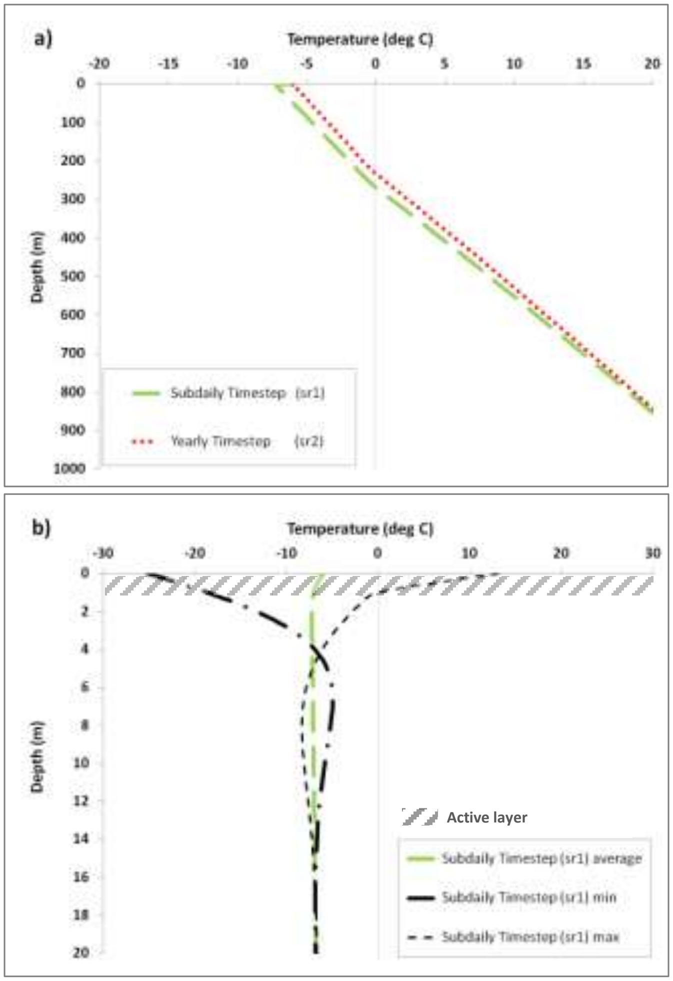

Figure 1. a) Plot comparing VAMPER model results using different timesteps (annual vs. subdaily) but the same annual average temperature forcing of -6 °C. b) Plot showing the sr1 average, min, and max temperature-depth profiles. Also shown in b) is the ~ 1 m active layer, marked as diagonal lines.

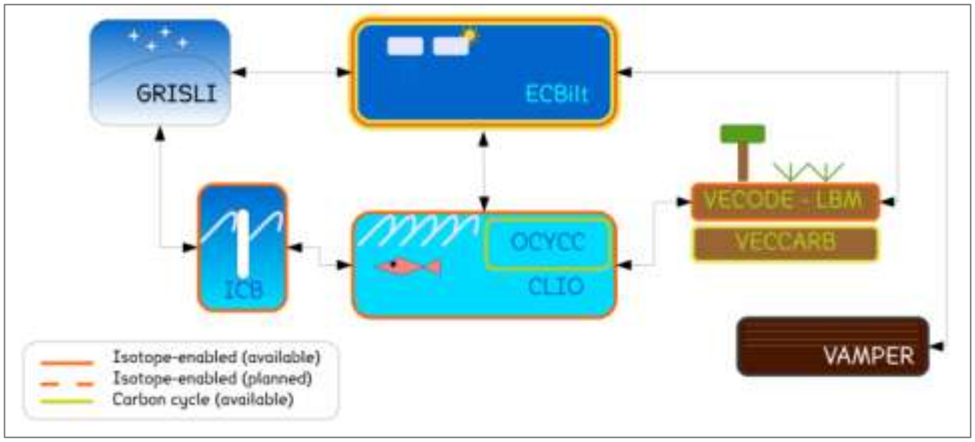

Figure 2. *i*LOVECLIM model component setup.

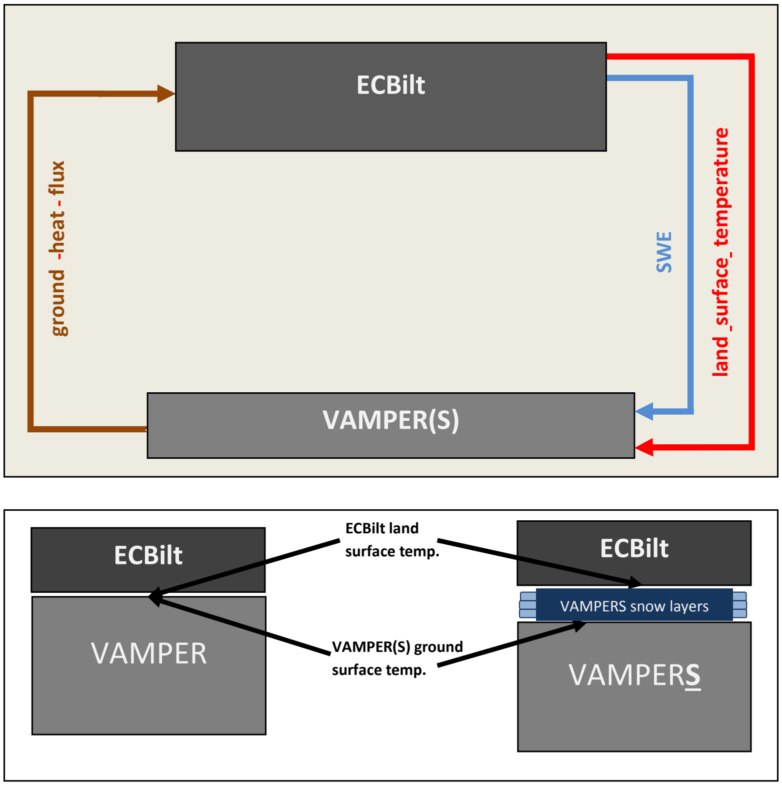

Figure 3 a). Future *i*LOVECLIM c~~C~~oupling scheme between ECBilt and the VAMPER(S) model showing the variables (~~air surface~~land surface temperature, snow water equivalent (swe), and ground heat flux) passed between the components at each timestep. b) Land surface temperature of ECBilt and ground surface temperature of VAMPER(S).

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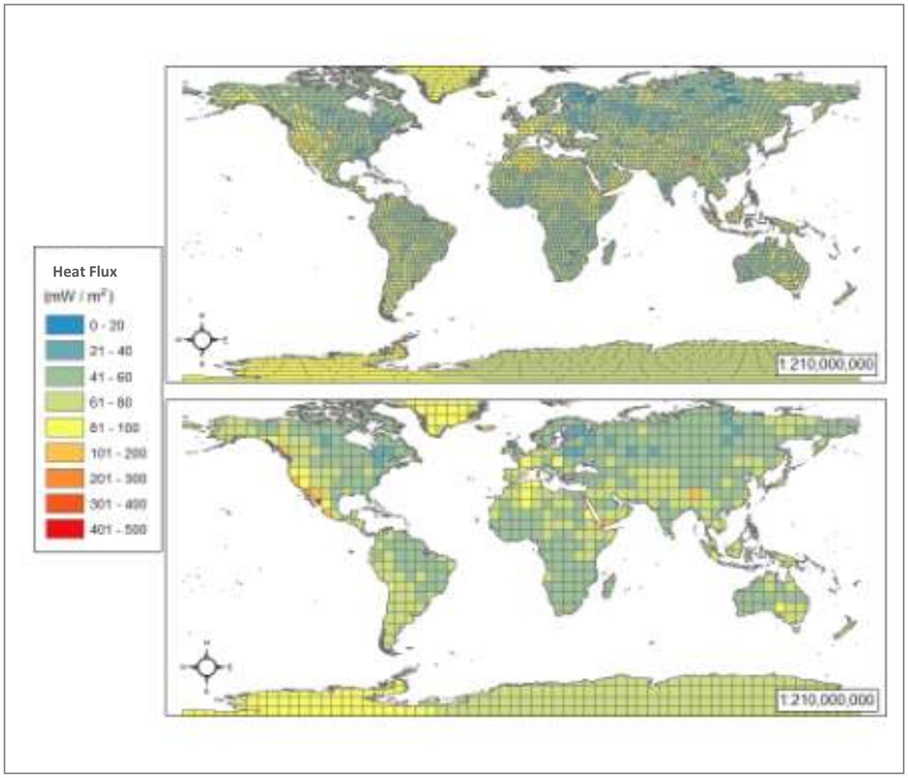

Figure 4. The original geothermal heat flux map (top) from Davies (2013) and the weighted average version (top) for use as the lower boundary value in the *i*LOVECLIM experiments (bottom).

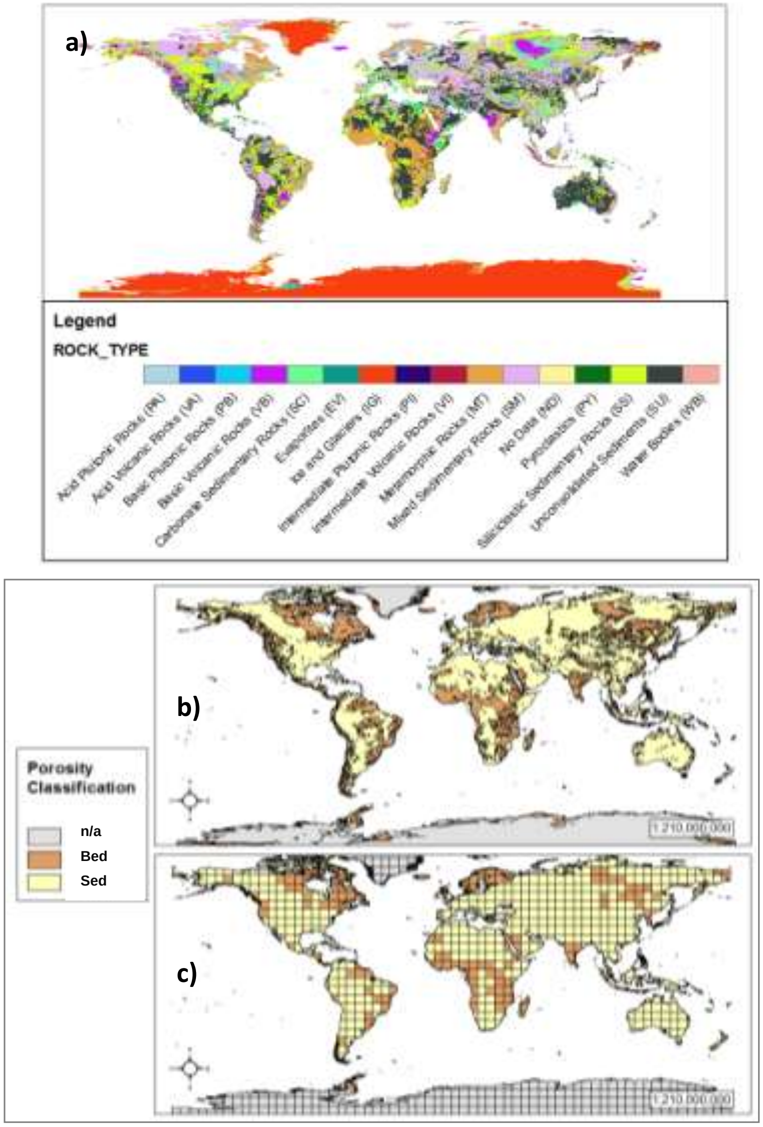

Figure 5. World maps showing a) original map from Hartmann and Moosdorf (2012) b) map of reclassified lithology using Table 2 and c) the version geo-processed to match the ECBilt grid resolution.

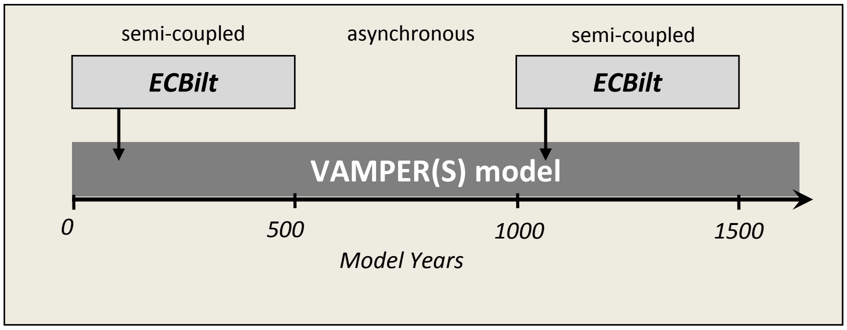

Figure 6. An illustration of asynchronous coupling between VAMPER(S) and ECBilt. The components are run semi-coupled for 100 years while VAMPER(S) is run the entire time. This allows VAMPER(S) to equilibrate with the climate state of *i*LOVECLIM using less computer resources time than a synchronous version.

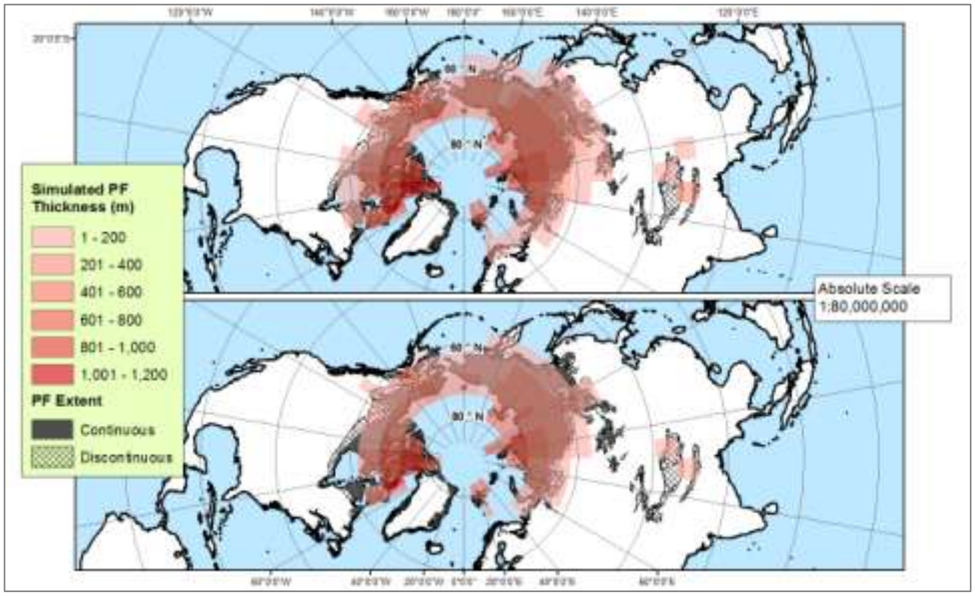

Figure 7. Preindustrial simulation results for permafrost thickness distribution using ECBILT-VAMPER semi-coupling (top) and ECBILT-VAMPER*S* semi-coupling (bottom).

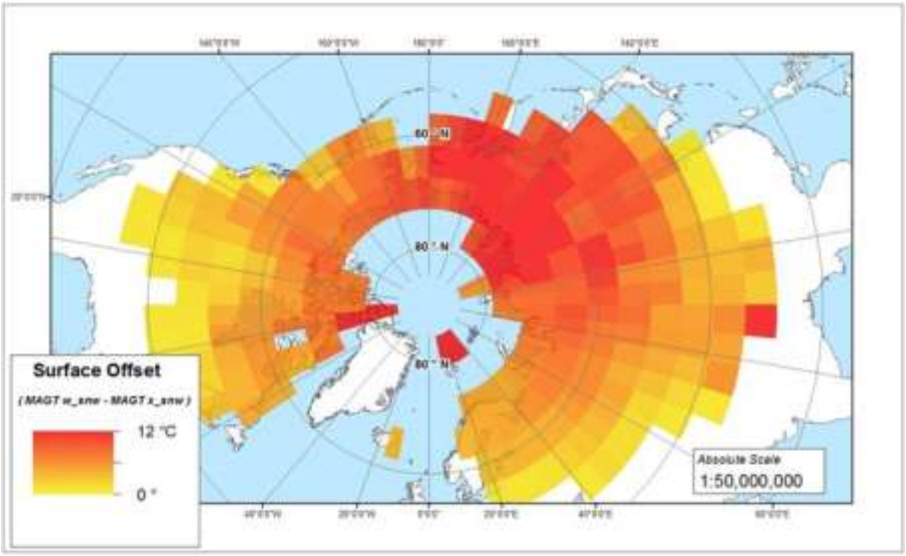

Figure 8. Mean annual surface offset as a result of including the snow option in the ECBilt-VAMPERS coupling.

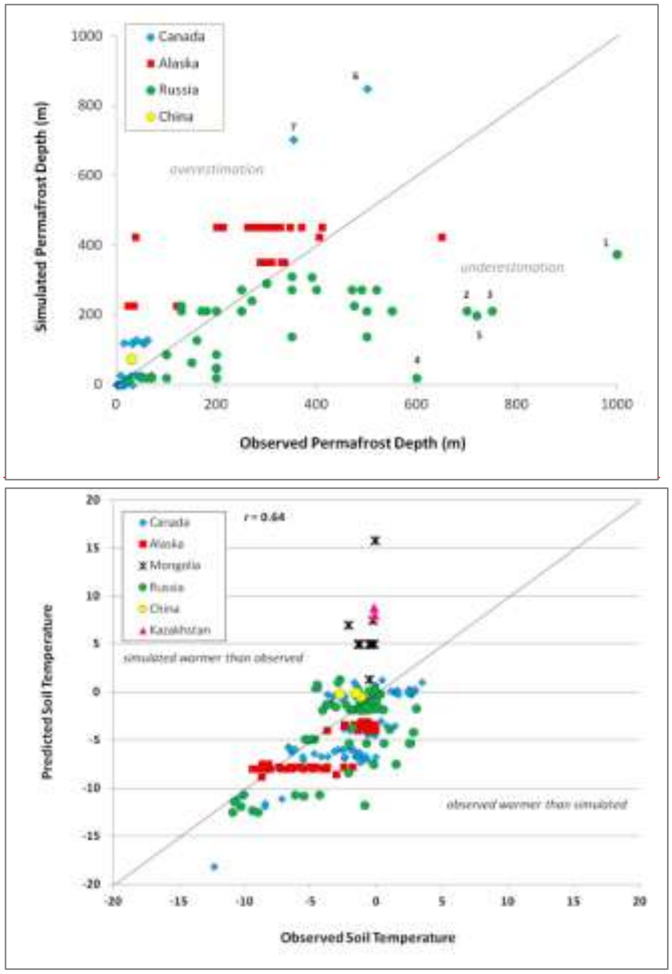

Figure 9. A 1:1 scatterplot comparing simulated thickness results with corresponding permafrost thickness estimates from borehole data. Points 1-7 are outliers mentioned specifically above.

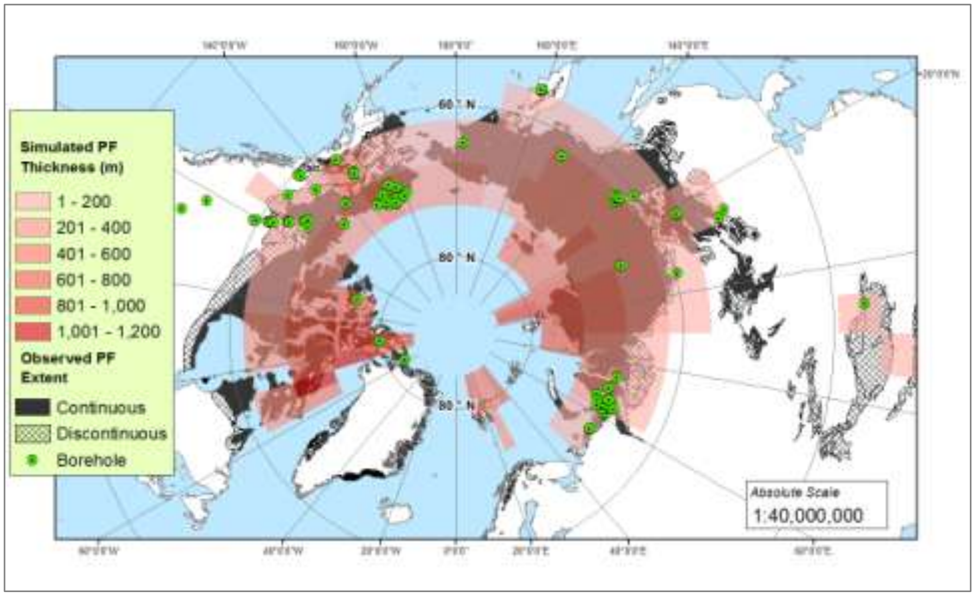

Figure 10. Map of deep GTN-P borehole locations with the simulated permafrost thickness (with snow enhancement) and observed PF extent (Brown et al., 2014).

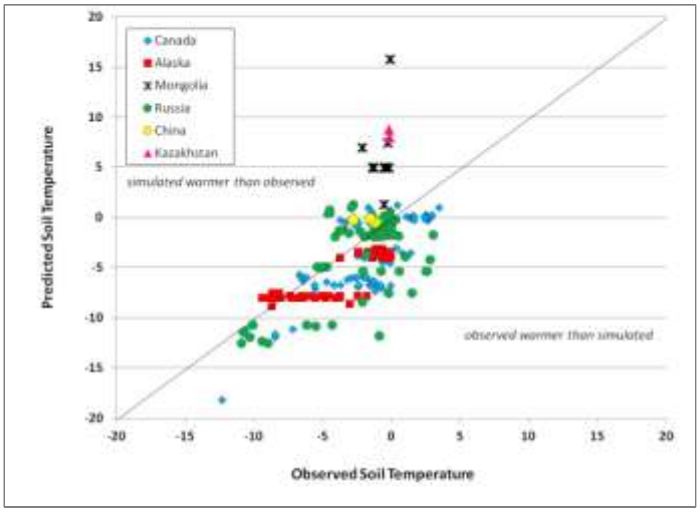

Figure 11. A 1:1 scatterplot comparing simulated mean annual temperatures with corresponding MAGT measurements.

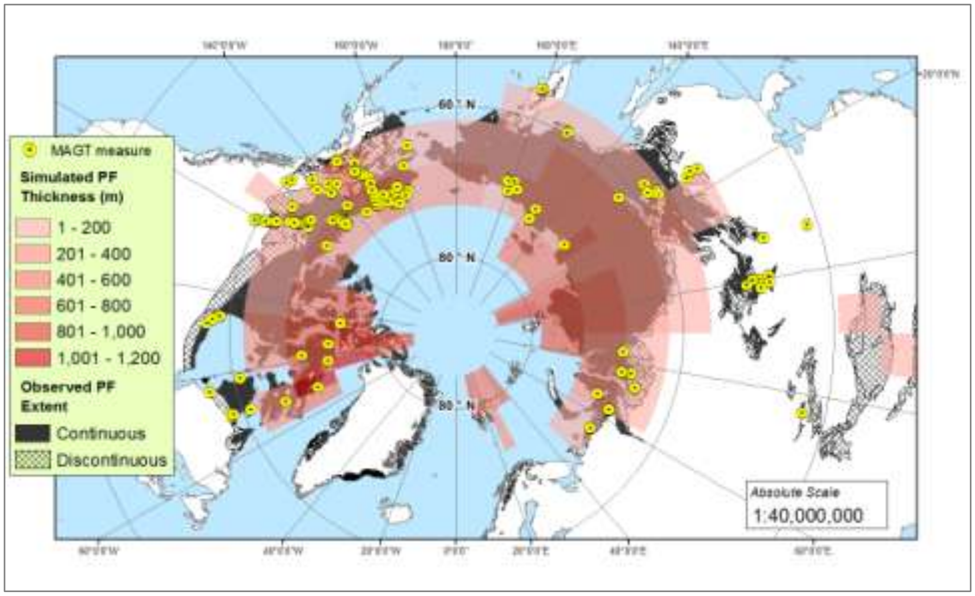

Figure 12. Map showing locations of the MAGT measurements, collected for the IPY 2010 (GTN-P), used in the comparison to corresponding *i*LOVECLIM simulated subsurface temperatures.