Author Response to Reviewer 2

-AC: I thank the reviewer for taking the time to review this paper and for the constructive comments which have helped improve the clarity of the manuscript. Author responses (AC) to the reviewer's comments are provided in blue text below each of the comments.

General comments:

This nice paper describes a new and comprehensive heat-transfer modeling system for permafrost. The model implements a set of heat-transfer physics that are more detailed than in most commonly used large-scale permafrost models. It appears to be highly flexible and therefore applicable to a range of permafrost research problems across a range of spatial scales and timescales. This capacity is nicely demonstrated with three applications that span an impressive array of timescales and research topics (permafrost thermal evolution from 255 ka years ago to present to examine permafrost evolution over ice age cycles; a 60 day detailed simulation of the impact of a borehole drilling operation; and permafrost response to formation of a lake). The model is designed to work for a range of geologic settings as well.

The paper is clear and well-written and the model is described in sufficient detail to really understand how and why the model was constructed as it was. Overall, I find very little to criticize and I find the paper suitable for publication, essentially in its current form. The model should be an excellent resource for the permafrost research community.

-AC: Thank you for the positive comments.

Minor comments:

[1] Maybe I missed it, but I think it would be helpful if the author could explain in a bit more detail what is needed to force the model. Is it just surface temperature?

-AC: CVPM is designed, as much as possible, to be a general-purpose numeral heat-transfer solver. All that is required to force the model are the boundary conditions on the edges of the problem domain. With the current version, either the temperature (Dirichlet condition) or the heat flux (Neumann condition) must be specified on each of the boundaries. These conditions are allowed to vary both spatially and temporally along the edges. For example with a 2-D problem, the temperature can be prescribed on the upper and lateral boundaries while the heat flux is prescribed on the lower boundary. Alternatively, the heat flux can be specified on one or both of the lateral boundaries or the temperature specified on the lower boundary. For the 2-D problem in Section 4.2, the model was forced by prescribed temperatures that varied with depth and time along the borehole wall (inner boundary). Temperatures were also prescribed on the upper boundary while heat fluxes were specified on the outer and lower boundaries. Although the upper, lower, and outer boundary conditions remained fixed, they too could have varied with position and time. For the 2-D problem in Section 4.3, the model was forced on the upper boundary with prescribed temperatures that varied with horizontal distance and time while prescribed heat flux conditions were specified on the other three boundaries. The text in Sections 3 and 4 has been revised to help clarify the boundary conditions. Heat exchange across a boundary by convection (Robin condition) will be included in a future version of CVPM.

[2] Are soil and rock water amounts prescribed and not allowed to change? There isn't any description of soil hydrology so that would suggest that that is the case. If so, then if one wanted to couple this into a large-scale permafrost or Earth System model, it would just replace the heat-transfer solution, and the host model would calculate water flow through the soil and sediment? Would there be any impediments to doing this?

-AC: The current version of CVPM does not allow the rock and soil water amounts to change with time, although this is being considered for a future version. To couple the current version (v1.1) with a large-scale permafrost or Earth System Model, I would recommend coupling CVPM with a hydrologic model that calculates water flow across the surface and with an active-layer model that calculates heat and fluid flow through the active-layer sediments. As the control volume method used by CVPM was originally developed for problems in computational fluid dynamics, CVPM potentially can be modified to include the advective heat and fluid-flow terms. The required modifications would be fairly substantial but it would eliminate the need to couple CVPM to a separate active-layer model in cases where fluid flow within the active layer is deemed important.

[3] Could the CVPM be coupled with a surface energy balance model?

-AC: Yes, CVPM is designed in a modular form to facilitate coupling with surface energy balance and other models.

[4] Along similar lines, the author notes that the CVPM does not represent vegetation, snow, surface water, etc. This makes me wonder how the example simulations were executed. Is the model forced with ground surface temperature, i.e., the temperature from beneath the snow.

-AC: The model is generally forced at the highest level in the ground where advective heat transfer is small compared to the diffusive heat transfer. This level is safely taken at the top of permafrost. During winter in frozen terrain, the upper boundary can be taken a bit higher at the ground–snow interface. During the summer, it can be taken at the base of the active layer (top of permafrost), or at the ground–air interface if the heat flux associated with any fluid flow in the active layer is small. For the examples in Sections 4.1 and 4.2, the upper boundary was taken at the top of permafrost, about 30 cm below the surface. At the scale the model was being run at, the upper 30 cm was completely unresolved in these examples. For the example in Section 4.3, the upper boundary was taken 1.5 m below the surface, corresponding to the lake bed in its deepest section. This allowed the model to be driven by lake-bed temperatures. The model forcing used in the examples is now described in more detail in the manuscript.

[5] Would maybe be helpful to indicate what the timestep is for each of the example applications with a brief description of the implications of the timestep. If, for example, the timestep is annual or longer for the 255kyr simulation, then this obviously implies that these simulations cannot be used to track active layer thickness. If the timestep is shorter than annual, then how does one derive the forcing timeseries, which obviously isn't resolved.

-AC: For the ice-age cycle example in Section 4.1, the computational time step was 20 years. This was deemed sufficient since the focus of this simulation was on exploring the response of permafrost well below the surface, i.e., well below the active layer and any seasonal effects. For the drilling disturbance simulation (Section 4.2), the time step was set to 0.2 days to resolve the rapid temperature changes that occur near the advancing drill bit. For the lake response simulation (Section 4.3), the computational time step was set to 0.1 years. Although the upper boundary condition used to force the model in this case did not include any seasonal effects, a time step this short was required to satisfy the numerical stability condition (Eq. 40) with the fine spatial grid. If the user has a temperature timeseries with subannual variations, there is no impediment to running CVPM with a subannual computational time step. The time step is completely flexible as long as the numerical stability condition (Eq. 40) is satisfied. The time step and its implications for the examples is now described in more detail in the manuscript.