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Hydrology and Earth System Sciences Discussions

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Interactive comment

Interactive comment on "Understanding the Mass, Momentum and Energy Transfer in the Frozen Soil with Three Levels of Model Complexities" *by* Lianyu Yu et al.

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We appreciate very much the editor and reviewers on reading through this manuscript and posting useful comments. We presented the point by point response to the reviewers' comments. The comments are in black fonts and our responses are in blue fonts.

Frozen soil undergoing freeze-thaw cycles has significant impacts on local hydrology, ecosystems, and engineering infrastructure within the context of global warming. However, it is challenging to depict a dynamic thermal equilibrium system of ice, liquid water,

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water vapor and dry air in soil pores, when soil experiences the freeze/thaw process. Through careful design and analyses of numerical simulation experiments, this study may help us understand the contribution of airflow-induced water and heat transport in the frozen ground. I just have a few comments/suggestions that may improve this manuscript, before it can be accepted for publication in HESS.

We really appreciate your helpful comments on improving this manuscript.

Major comments:

1. The authors should clearly state/add the innovative points by this study in the title, abstract, and body text (e.g., objectives, results and discussions, as well as conclusions), by comparing to the listed publications in the references by the same authors. It is obvious that this group has quite a few nice publications on the physics of frozen ground, by describing the contributions/roles of vapor, liquid water and solid ice in the water and heat transports. After my reading of this manuscript, it is more like a sensitive study or a review paper. Please add text to clarify the major difference of this manuscript from previous studies, and demonstrate the new processes/knowledge to the permafrost hydrology community.

Response: The main purpose/motivation of this work is to understand the impact of various representations of soil physical processes on simulating hydrothermal regimes of frozen soils. Usually, such kind of investigation/inter-comparison is implemented via using different models, with different model frameworks, numerical solutions etc. In our study, we used an unified modeling framework, STEMMUS, to investigate the hydrothermal dynamics of frozen soil, considering uncoupled soil moisture and heat transfer (as in most of Land Surface Model), coupled soil moisture and heat transfer (via vapor flow), and further coupled with air transfer (i.e., both vapor and air flow). Such investigation with increasing levels of complexities in representing mass, momentum and energy transfer in frozen soil is the innovation of this study. With the above approach, we can delineate the contributions of each individual process to the soil hydrothermal states, which can be further applied to figure out their roles

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in ecosystem response in cold regions. Furthermore, this study can also provide supports to define how complex the physical processes we should take into account when interpreting the hydrothermal regimes in cold regions.
We added the relevant descriptions in introduction, discussion and conclusion part to highlight this.

2. In Figure (1-3 & 5), the red and blue lines are always overlapped. Is there a better way to show them?

Response: We re-plotted Figure 2-4 & 6 (original Figure 1-3 & 5), making the blue lines discontinuous, to make the difference visible.

3. The difference between CLPD-air and CLPD is that air flow was taken into account. What are the key processes that the air flow affects frozen ground? The difference should be briefly introduced in Section 2.2, for better understanding in this manuscript.

Response: When considering air flow, air flow induced liquid and vapor flow and its corresponding heat flow were activated. While air flow coexists with vapor flow. The presence of air flow considerably affects the vapor transfer processes. The water and heat transfer in frozen soil are thus affected. All these aspects were briefly explained in Sect. 2.2 (Line 110-113).

4. There are many results in this paper, and I think you can add more details in Section 5 (conclusions).

Response: This paper mainly investigated the role of various soil physical processes in representing soil hydrothermal states and explain the underlying mechanisms. We find that the basic coupled model can not well capture the dynamics of soil moisture/temperature. Models with advanced coupled water and heat transfer processes

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largely improved its capability. The underlying reasons were analyzed via looking into the dynamics of heat budgets and subsurface latent heat flux density. We stressed the important role of vapor flow in the total mass and energy heat transfer during frozen periods and also the thermal effect on liquid flow. These physics contribute to a better soil temperature/moisture simulations by ACM (originally as CPLD).
Furthermore, the role of air flow was found only important along with vapor flow. The contribution of airflow to the total water and heat transfer is negligible. However, the consideration of air flow considerably affects the latent heat flux density and the heat transfer process especially during the freezing-thawing transition period.
We further added the description of other non-conductive heat fluxes (liquid/vapor/air induced convective heat fluxes) in conclusions. See Line 314.

5. Literature review about the frozen ground/permafrost hydrology by this manuscript is incomplete. I would like to suggest the authors also referring to the following ones but not limited to them. E.g.,

Qi et al. (2019). Coupled Snow and Frozen Ground Physics Improves Cold Region Hydrological Simulations: An Evaluation at the Upper Yangtze River Basin (Tibetan Plateau). Journal of Geophysical Research: Atmospheres, 124(33): 12985-13004.

Biskaborn et al. (2019).Permafrost is warming at a global scale. Nature communications, 10(1), 264.

Wang et al. (2017). Development of a land surface model with coupled snow and frozen soil physics. Water Resources Research, 53, 5085–5103.

Bao et al. (2016). Development of an enthalpyâĂŘbased frozen soil model and its validation in a cold region in China. Journal of Geophysical Research: Atmospheres, 121(10), 5259-5280.

Iijima, Y., Ohta, T., Kotani, A., Fedorov, A.N., Kodama, Y., & Maximov, T.C. (2014). Sap

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flow changes in relation to permafrost degradation under increasing precipitation in an eastern Siberian larch forest. Ecohydrology, 7(2), 177-187.

Response: We added more in the literature review about the frozen ground/permafrost hydrology. Meanwhile stress the novelty/importance of our study. See Sect. 1 Introduction (Line 3, 7, 22-26, 49-55).
Main changes in manuscript: Line 22-26 "Aiming to efficiently deal with the water phase change between liquid and ice, the enthalpy-based frozen soil model (using enthalpy and total water mass instead of temperature and liquid water content as the prognostic variables) was developed and demonstrated its capability to stably and efficiently simulate soil freeze/thaw process (Li et al., 2010;Bao et al., 2016;Wang et al., 2017)."
Line 49-55 "There are continuous efforts in improving parameterizations and representations of cold region dynamics, including frozen ground (Boone et al., 2000;Luo et al., 2003), vapor diffusion (Karra et al., 2014), thermal diffusion (Bao et al., 2016), coupling water and heat transfer (Wang and Yang, 2018), and three-layer snow physics (Wang et al., 2017;Qi et al., 2019). While to our knowledge, few studies have investigated the role of increasing complexities of soil physical processes (from the basic coupled to the advanced coupled water and heat transfer processes, and then the explicit consideration of air flow) in simulating the thermo-hydrological states in cold regions. "

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Bao, H., Koike, T., Yang, K., Wang, L., Shrestha, M., and Lawford, P.: Development of an enthalpy-based frozen soil model and its validation in a cold region in China, Journal of Geophysical Research: Atmospheres, 121, 5259-5280, 10.1002/2015jd024451, 2016.

Boone, A., Masson, V., Meyers, T., and Noilhan, J.: The Influence of the Inclusion of Soil Freezing on Simulations by a Soil–Vegetation–Atmosphere Transfer Scheme, J Appl Meteorol, 39, 1544-1569, 10.1175/1520-0450(2000)039<1544:tiotio>2.0.co;2, 2000.

Karra, S., Painter, S. L., and Lichtner, P. C.: Three-phase numerical model for subsurface hydrology in permafrost-affected regions (PFLOTRAN-ICE v1.0), Cryosphere, 8, 1935-1950, 10.5194/tc-8-1935-2014, 2014.

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Luo, L., Robock, A., Vinnikov, K. Y., Schlosser, C. A., Slater, A. G., Boone, A., Braden, H., Cox, P., de Rosnay, P., Dickinson, R. E., Dai, Y., Duan, Q., Etchevers, P., Henderson-Sellers, A., Gedney, N., Gusev, Y. M., Habets, F., Kim, J., Kowalczyk, E., Mitchell, K., Nasonova, O. N., Noilhan, J., Pitman, A. J., Schaake, J., Shmakin, A. B., Smirnova, T. G., Wetzel, P., Xue, Y., Yang, Z. L., and Zeng, Q. C.: Effects of frozen soil on soil temperature, spring infiltration, and runoff: Results from the PILPS 2(d) experiment at Valdai, Russia, J Hydrometeorol, 4, 334-351, 10.1175/1525-7541(2003)4<334:EOFSOS>2.0.CO;2, 2003.

Qi, J., Wang, L., Zhou, J., Song, L., Li, X., and Zeng, T.: Coupled Snow and Frozen Ground Physics Improves Cold Region Hydrological Simulations: An Evaluation at the

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upper Yangtze River Basin (Tibetan Plateau), Journal of Geophysical Research: Atmospheres, 124, 12985-13004, 10.1029/2019jd031622, 2019.

Wang, C., and Yang, K.: A New Scheme for Considering Soil Water-Heat Transport Coupling Based on Community Land Model: Model Description and Preliminary Validation, Journal of Advances in Modeling Earth Systems, 10, 927-950, 10.1002/2017ms001148, 2018.

Wang, L., Zhou, J., Qi, J., Sun, L., Yang, K., Tian, L., Lin, Y., Liu, W., Shrestha, M., Xue, Y., Koike, T., Ma, Y., Li, X., Chen, Y., Chen, D., Piao, S., and Lu, H.: Development of a land surface model with coupled snow and frozen soil physics, Water Resour Res, 53, 5085-5103, 10.1002/2017WR020451, 2017.

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Figure captions

Figure 2. Comparison of measured (Obs) and estimated time series of soil temperature at various soil layers using Basic Coupled Model (BCM), Advanced Coupled Model (ACM) and Advanced Coupled Model with Air flow (ACM-AIR).

Figure 3. Comparison of measured (Obs) and model simulated time series of soil moisture at various soil layers using Basic Coupled Model (BCM), Advanced Coupled Model (ACM) and Advanced Coupled Model with Air flow (ACM-AIR).

Figure 4. Comparison of measured (Obs) and model simulated freezing front propagation (FFP) using Basic Coupled Model (BCM), Advanced Coupled Model (ACM) and Advanced Coupled Model with Air flow (ACM-AIR). Note the measured FFP was seen as the development of zero degree isothermal lines from the measured soil temperature field.

Figure 6. Comparison of observed and model simulated (a) mean diurnal variations of surface evapotranspiration and (b) cumulative evapotranspiration (ET) by Basic Coupled Model (BCM), Advanced Coupled Model (ACM), and Advanced Coupled Model with Air flow (ACM-AIR).

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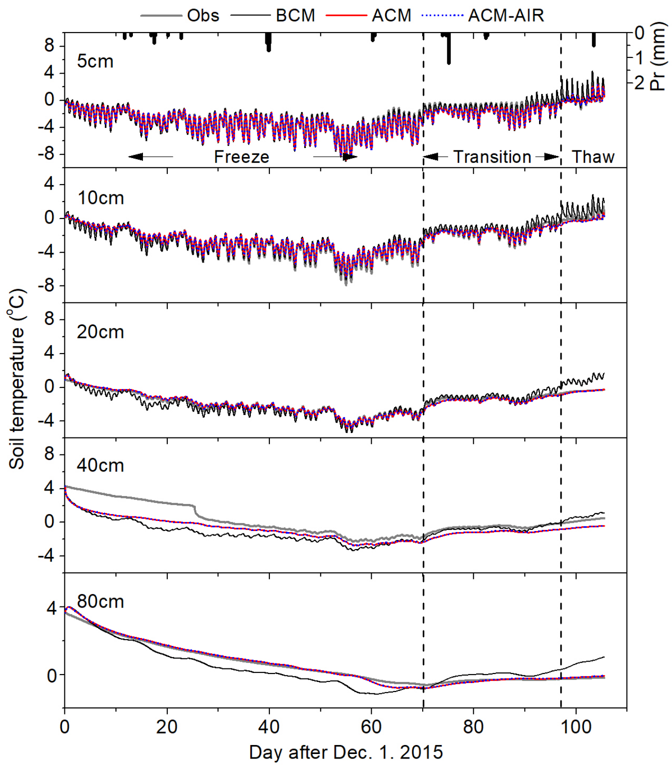

Fig. 1. Figure 2. Comparison of measured (Obs) and estimated time series of soil temperature at various soil layers using BCM, ACM and ACM-AIR.

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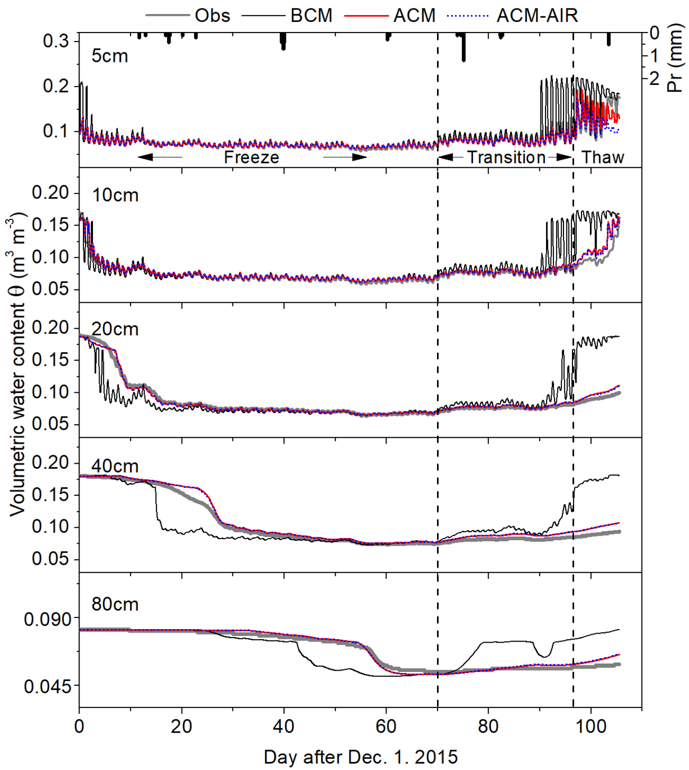

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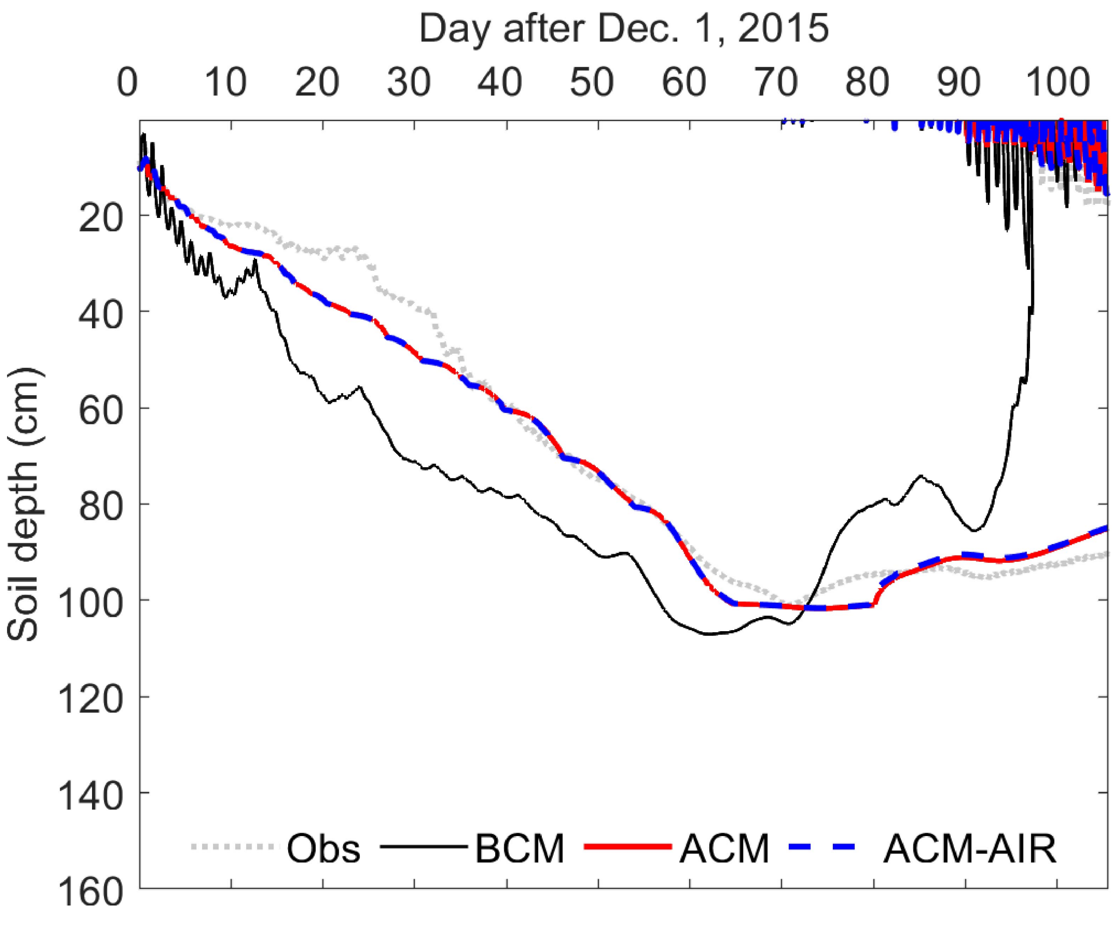

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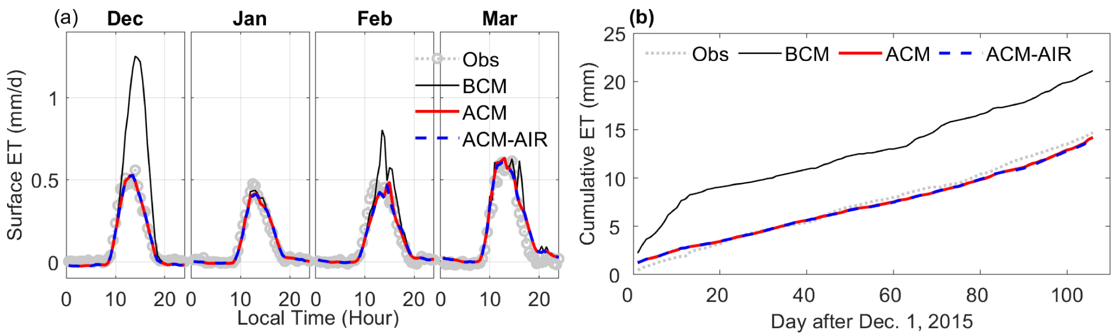

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