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Discussions

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.

General comments:
The considered work deals with the physics of the heat and water transfers in seasonally frozen soils, and in particular with the importance of the descriptions of the

couplings that occur in these transport phenomena, from the basic couplings due freeze/thaw of the pore water (latent heat of solidification/liquefaction, impact of freezing on the hydraulic properties) to finer effects such as those related to heat gradient induced water flow or to the water vapor fluxes, and even to the effect of dry air flow. Thermo-hydrological transfers modeling in seasonally frozen soils is a complex problem with various important implications as it is well explained in the introduction section, and the handling of couplings is one of the major difficulties for their numerical simulations, thus I feel that the scope of the manuscript is appropriate for a submission to HESS. The authors propose a comparative analysis of numerical simulations of ground thermo-hydrological status in a mountain frozen soil field site for which observations are available for a winter season. After a brief description of the considered field site and of the numerical models to be used, the obtained numerical results are presented. Finally the comparison of results obtained with various physical assumptions embedding various level of complexity of the multi-physics couplings involved allows the authors to make a discussion on the trade-off that must be made between the accuracy of the simulations and the complexity of the modeling approach. The goal of the work and its real interest for the study of cold regions hydrology are clearly described, while the proposed methodology is relevant for such a purpose. Nevertheless some critical information are missing in the descriptions of the equations and of the numerical procedures, which damages the completeness of the manuscript, and prevents the reader to assess the range of validity of the conclusions. Moreover the domain of applicability of these conclusions in terms of biogeoclimatic contexts should be better discussed. Thus I suggest a major revision of this manuscript prior to publication. One can find below the specific comments on which are based the previous statement, along with a few technical corrections.

Response: Thanks a lot for your constructive comments. We added the descriptions of the equations and the numerical procedures accordingly in Sect. 2.2. We added the Figure 1 to illustrate the boundary conditions, mesh resolutions, and half-hourly measurements of the driving force during our simulation period (the figure numbers were thus changed). The equations to calculate evapotranspiration were added in the Appendix. We briefly presented the relevant studies to corroborate our results in the Discussion part (Sect. 4.1). Please find our specific response as follows.

Specific comments:

1. Abstract: l22 : 'air-flow induced water (...) transport (...) is negligible': what is the difference with vapor flow, that have been stated as significant in the previous sentence ? Please clarify.

Response: The air flow induced water and heat transport is refer to the water and vapor flow driven by the air pressure gradient, i.e., $\rho_L \frac{\partial}{\partial z}(\frac{K}{\gamma_w}\frac{\partial P_g}{\partial z})$ and $\frac{\partial}{\partial z}(D_{Va}\frac{\partial P_g}{\partial z})$ in Eq. 5 and its corresponding heat flow $-\frac{\partial}{\partial z}(q_a C_a(T-T_r))$ in Eq.6. Its contribution to the total energy transfer is negligible, as the term HFa shown in Figure 7.

Vapor flow is the isothermal and thermal vapor flow driven by the soil matric potential gradient and temperature gradient, i.e., $\frac{\partial}{\partial z}(D_{Vh}\frac{\partial \varphi}{\partial z})$ and $\frac{\partial}{\partial z}(D_{VT}\frac{\partial T}{\partial z})$, respectively. The heat flux driven by the vapor flow refers to $-\frac{\partial}{\partial z}[q_V(L_0 + C_V(T-T_r))]$. From Figure 8, we can find that the relevant latent heat flux density Sh is significant at the upper soil layers, see also (LHF+HFV) term for the heat flow in Figure 7.

We rephrased the text as "The contribution of airflow-induced water and heat transport (driven by the air pressure gradient) to the total mass and energy fluxes is negligible."

2. Methodology 2.2 Mass and energy transport in unsaturated soils l105-109 : The latent heat due to water freeze/thaw introduces necessarily a coupling between heat transport and water transport, since the latent heat term in the thermal equation depends on the water content of the porous medium. The effect of soil ice on soil hydraulic properties induces also a coupling between heat transport and water transport, since the hydraulic properties then depend on the temperature of the porous medium (at least whether the temperature is above or below 0$^{\circ}C$). Thus the name 'uncoupled' is inappropriate for describing the set of equation in the most simple model ('unCPLD' model), and its use is not in line with the common practices in the field of cryohydroge-

ological modeling (e.g.: Grenier et al., 2018). In fact both 'unCPLD' model and 'CPLD' model are coupled thermo-hydrological models, but the latter embeds more coupling effects than the former. Basic coupled model (BCM) versus Advanced coupled model (ACM) might be a better terminology for instance ?

Response: Many thanks for pointing out it. For the simple 'unCPLD' model, there are indeed water and heat coupling mechanisms considered during the frozen period. The coupling between water and heat transport in 'unCPLD' model is achieved by the latent heat term due to phase change and the effect of soil ice on hydraulic properties. The advanced CPLD model taken into account the water and heat coupling mechanisms during both the unfrozen and frozen periods. The vapor flow, which is the function of both soil moisture and temperature, makes the water and heat transfer tightly coupled. The thermal effect on soil matric potential and hydraulic conductivity, from the soil water surface tension and viscous flow effect, have the water flow dependent on the temperature. The convective heat flow in the energy conservation equation, which is due to the liquid/vapor fluxes, makes the heat transport dependent on the soil water flow.

We agree to use the suggested terminology as Basic coupled model (BCM), Advanced coupled model (ACM) and Advanced coupled model with air (ACM-AIR). The changes were made throughout this manuscript.

3. l103 – section 2.2 : a clear presentation of the boundary conditions used for each considered equations in each models is missing. As they are important information for the understanding of the numerical results, they should be added. Numerical convergence studies (meshes resolutions, used time steps, ...) must also be evocated here: in order to compare the results of different models, it is important to control that the truncation errors are comparable between each models (and small compared to the discussed inter-model discrepancies!).

Response: We added the description of the boundary conditions in the Sect. 2.2 as

“Surface boundary for the water transport was set as the flux-type boundary controlled by the atmospheric forcing condition (i.e., evaporation, precipitation) while the specific soil temperature was assigned as the surface boundary of energy conservation equation. The free drainage (zero matric potential gradient) and measured soil temperature were set as the bottom boundary conditions for the water transport and heat transport, respectively. For the air flow, the surface boundary was set as the atmospheric forcing condition and soil air was allowed to escape from the bottom of soil column.”
We added Figure 1 to illustrate the model-used boundary condition, mesh resolutions, and driving forces.
The truncation errors due the numerical solution are related to the node distance and time steps. We added such description in Sect. 2.2 as “The vertical soil discretization was designed finer for the upper soil layers (0.1-2.5cm for 0-40cm, 27 layers) than that for the lower soil layers (5-20cm for 40-160cm, 10 layers). The adaptive time step strategy, with maximum time steps ranging from 1s to 1800s, was utilized for the numerical solution.”
Note that all three models employed the same mesh resolutions and adaptive time step strategies. It indicated that the truncation errors due to numerical solution among three models are comparable. The difference is mainly restricted to the various representations of soil physical processes (e.g., the inclusion of vapor flow and air flow or not). See Line 144.

4. Results l172 and following : The numerical results in terms of computed evapotranspiration depend critically on the way to parameterize evapotranspiration, which is not presented in the paper. Various descriptions could be used here. For instance, and among many others, an empirical one emphasizing the role of vegetation could be find in Orgogozo et al., 2019, or a theoretically derived one in the case of purely evaporative processes could be find in Duval et al., 2004. The mathematical expressions and input data used to compute the evapotranspiration in each model should be described in the manuscript. Without these key information, it is not possible for the reader to interpret

the given results.

Response: We used the Penman Monteith method to calculate the evapotranspiration and added the relevant description in the Sect. 2.2. The different soil physical processes alter the soil thermo-hydrological regimes then affect the actual surface evapotranspiration (see Line 132). The mathematical expressions are presented in Appendix A1.

5. Discussion l244 : The first sentence is wrong: the vapor transfer processes are not the only sources of couplings between thermal and hydrological transfers in porous media when freeze/thaw of the pore water occurs, see also my first comment on section 2. Methodology.

Response: Sorry for the confusion. Here we want to stress the important role of vapor transfer processes. Now rephrased as “Vapor flow, which is dependent on soil matric potential and temperature, links soil water and heat transfer processes.” See Line 255.

6. ll254-l264 : Here is the explanation for the difference of amplitude of diurnal cycle between models. It seems to me that this is the key point of the discussion (evocated already numerous times in the manuscript, e.g;: l141, l147, l163), but somewhat hard to follow. It should be rewritten in a clearer way, may be with explicative schemes ?

Response: Many thanks for pointing out this. We made modifications by specifying the relevant figures and explicative schemes.
Changes in manuscript: "From the energy budget perspective, latent heat fluxes contribute more, due to the vapor phase change (LHF), to the heat balance budget at soil layers above the evaporative front than that below it (see LHF in Figure 7e vs. Figure 7b, corresponding evaporative front shown as Figure 8d vs. Figure 8a). This is consistent with findings by Zhang et al. (2016), who presented that the latent heat of vapor due to phase change is two orders of magnitude less than the heat fluxes

due to conduction during winter time and corresponds to our results of Figure 7b & c during the freezing period. While our results further showed that the latent heat fluxes due to vapor phase change can be considerable during the transition period (Figure 7e & f). The downward latent heat flux from ACM makes the subsurface soil warmer, which reduces the temperature gradient ($\partial T/\partial z$) (Wang and Yang, 2018). This further results in the weaker diurnal fluctuations of HC term in ACM than that in BCM (see HC in Figure 7e vs. Figure 7d). At the soil layers below the evaporative front, the heat flux source from the vapor transfer process (LHF) is negligible (e.g., Figure 7b). The thermal retard effect as the presence of soil ice, expressed as the apparent heat capacity term (Capp), dominates the heat transfer process in frozen soils. By considering the thermal effect on water flow, ACM usually has a larger water capacity value $\partial\theta/\partial\varphi$ than BCM does. As such, the intense thermal impedance effect leads to the results that ACM has a weaker diurnal fluctuation of soil temperature than BCM at subsurface soil layers." See Line 270-285.

7. l274 : 'hydraulic conductivity' increase due to 'airflow from the atmosphere to the soil' ? Please give a short explanation.

Response: After precipitation events, the atmospheric humidity is high. Zeng et al. (2011a) verified that airflow (the air convection between atmosphere and topsoil) can bring the atmospheric moisture into topsoil. Thus the hydraulic conductivity of topsoil layers considerably increased. We rephrase as "since the hydraulic conductivity of topsoil layers increased tremendously due to the increased topsoil moisture by the injected airflow from the moist atmosphere.". See Line 294.

8. l286-290 : The strong point made about evapotranspiration highlights the need to give to the reader all the relevant information about the handling of the evapotranspiration sink terms in each model (see also my comment for the section 3. Results). Please discuss also the transpirative component of evapotranspiration.

Response: We presented the descriptions of evapotranspiration, including the mathematical expressions (Appendix A1) and the relevant text (Line 132). Maqu experimental site is characteristic as seasonal frozen ground where growing the grassland. When soil freezes, grassland steps into the dormancy period. The dormancy period is ended when the integrated root zone soil temperature becomes positive. For our simulation period, soil started thawing only for a few days. The integrated soil temperature was not enough to break the vegetation dormancy. The transpiration thus has a very minimum effect during our simulation period. see Line 138.

9. l296-301 : The domain of applicability of the presented study should be better discussed. For instance, a point is made about the freeze/thaw mechanisms of permafrost while the studied field site is not in a permafrost affected area. The relative importance of the vapor flow, the thermal effect on water flow and the airflow should be more discussed with respect to the biogeoclimatic context (e.g. : more important in climate with long freezing/thawing periods or with long periods with surface temperature oscillating around 0 $^{\circ}C$), and in the context of the existing literature (e.g.: Karra et al., 2014).

Response: This part is for the outlook and applications of our work, which is to understand the freezing/thawing processes. The developed physical process-based model in this study can be applied to other frozen soil conditions. In the discussion, we made some extensions from frozen soils to permafrost. As well known, the active layer of permafrost region undergoes the freezing/thawing processes, which implicates the applicability of our model over the permafrost region. It is to note that the relative importance of the vapor flow, the thermal effect on water flow and airflow might vary among different regions under climate changing context. We discussed it a bit in Sect. 4.1 (Line 286).

10. Technical comments : The English language should be improved, although I am not a native English-speaking person so maybe I am making a mistake on that point.

For instance it seems to me that the vegetation development cannot be 'closed' (l29). As another example I think that 'the best water resources management' or 'a better water resources management' could be used but not 'the better water resources management' (l33). A reread by an English editing service might be helpful.

Response: We made the corresponding changes (Line 29, 34) and have the manuscript English edited.

11. l40 and also in other places (e.g.: l42, l51) : Citations should be re-ordered (2006 before 2010).

Response: We re-ordered the citations by time and checked throughout the whole manuscript.

12. l138 : Fig1. The figure is not clear enough. Firstly it is difficult to decipher the different curves for 5, 10 and 20 cm depth – CPLD curve is nowhere visible (if it si beneath the CPLD-Air curve, make this one discontinuous). The legend should also be clearer for the obs. Secondly I didn't got the 'earlier stepping in / stepping out of the frozen period', may be they should be pointed out in the figure itself.

Response: Thanks a lot. Figure 2 (originally Figure 1) was replotted, with the dotted line for ACM-AIR curve, to make different curves visible. The solid line was used for the observation curve to make the legend clearer. We added the lines to indicate the "Freeze", "Transition", and "Thaw" periods in the Figure 2 to indicate the start/end dates of the frozen period.

13. l147 : Fig2. Same formal remarks that for Fig1.

Response: Figure 3 (original Figure 2) was replotted to highlight the differences.

Reference

Duval, F., Fichot, F., and Quintard, M.: A local thermal non-equilibrium model for two-phase flows with phase-change in porous media, International Journal of Heat and Mass Transfer, 47, 613-639, https://doi.org/10.1016/j.ijheatmasstransfer.2003.07.005, 2004.

Grenier, C., Anbergen, H., Bense, V., Chanzy, Q., Coon, E., Collier, N., Costard, F., Ferry, M., Frampton, A., Frederick, J., Gonçalvès, J., Holmén, J., Jost, A., Kokh, S., Kurylyk, B., McKenzie, J., Molson, J., Mouche, E., Orgogozo, L., Pannetier, R., Rivière, A., Roux, N., Rühaak, W., Scheidegger, J., Selroos, J. O., Therrien, R., Vidstrand, P., and Voss, C.: Groundwater flow and heat transport for systems undergoing freeze-thaw: Intercomparison of numerical simulators for 2D test cases, Adv Water Resour, 114, 196-218, 10.1016/j.advwatres.2018.02.001, 2018.

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.

Orgogozo, L., Prokushkin, A. S., Pokrovsky, O. S., Grenier, C., Quintard, M., Viers, J., and Audry, S.: Water and energy transfer modeling in a permafrost-dominated, forested catchment of Central Siberia: The key role of rooting depth, Permafr Periglac Proc, 30, 75-89, 10.1002/ppp.1995, 2019.

Zeng, Y., Su, Z., Wan, L., and Wen, J.: Numerical analysis of air-water-heat flow in unsaturated soil: Is it necessary to consider airflow in land surface models?, Journal of Geophysical Research: Atmospheres, 116, D20107, 10.1029/2011JD015835, 2011a.

Figure captions

Figure 1. (a) Conceptual illustration of the model setup, the surface/bottom boundary conditions, driving forces, and vertical discretization. (b) Half-hourly measurements of meteorological forcing, including air temperature (T$_{atm}$, $^{\circ}C$), relative humidity (HR$_{atm}$, %), net radiation (Rn, Wm^{-2}), wind speed (U$_{wind}$, ms^{-1}), and atmospheric pressure (P$_{atm}$, kPa), during the simulation period. Note that dimensions are not draw to scale, models were ran at one-dimensional scale.

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).

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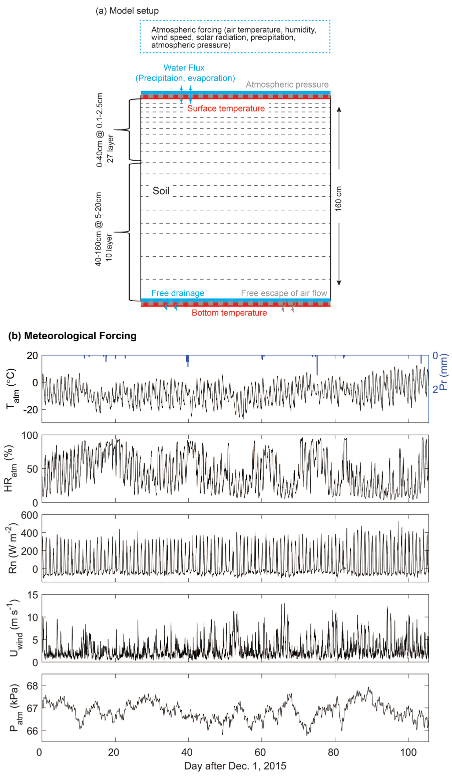

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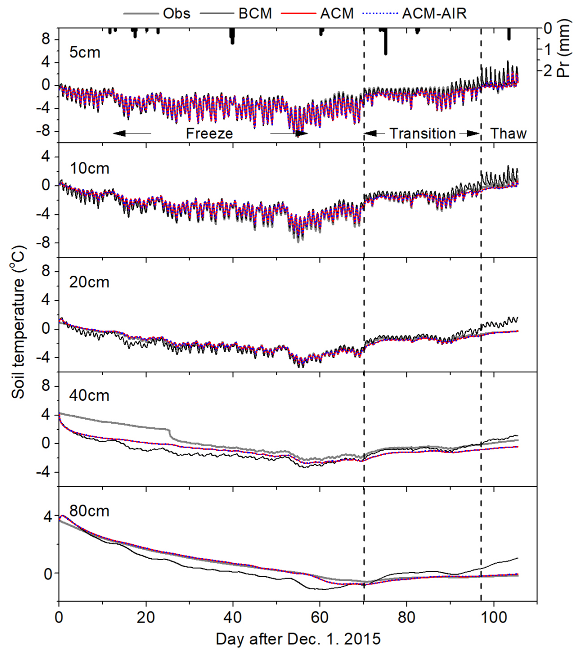
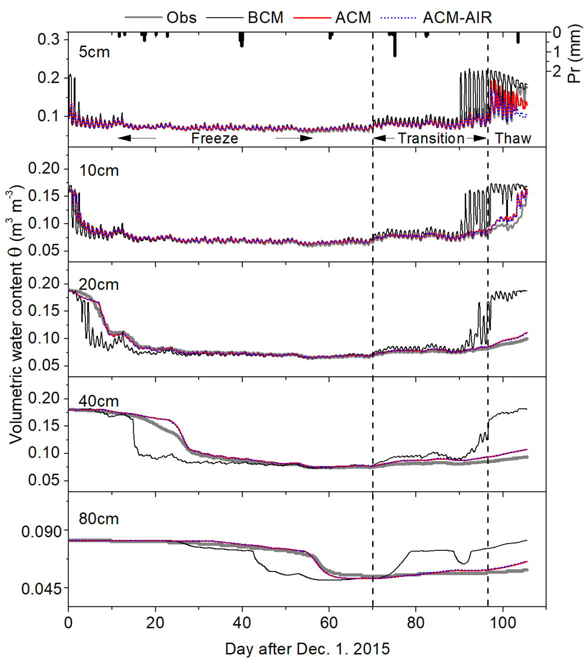


Fig. 2. Comparison of measured (Obs) and estimated time series of soil temperature at various soil layers using BCM, ACM and ACM-AIR.



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