Reply to anonymous Referee #1

The authors thank Referee #1 for the detailed comments below and the decision for minor comments.

In this paper, authors developed new two-dimensional water transport model combining the processes of snow temperature change, snowmelt, refreezing and heterogeneous water transport model. Simulations of preferential flow considering the melt-freeze processes are very important, and this model has a potential to advance modeling studies of heterogeneous water infiltration in the cold snowpack. Components used in this model are basically theories in existence. Water infiltration schemes are almost same with Hirashima et al. (2014). Schemes of temperature and melt-freeze processes are already developed by Illangasekare (1990) and Daanen and Niever (2009). They also simulated interactions between liquid water and snow temperature.

Therefore, analysis of simulation results should show advantage of this combined model and provide informative scientific results (e.g. enhanced accuracy or new simulation which cannot be performed by previous model).

- The components of this model are based on verified theories, but they have never been compiled comprehensively before. Therefore this is a new model with a unique range of capabilities and formulations that presents the importance of coupling heat transfer and water flow through both snow matrix and preferential flow paths. Through the application presented in Section 6, it was shown that preferential flow paths have a significant impact on the warming phase of the snowpack. Section 6 has been enhanced to show the potential of the model to simulate ice layers by varying the heat flux at the surface through time to represent a melt-freeze cycle. This capability is unique amongst snow models and simulates an important natural phenomenon for the first time.

Authors showed many simulation results in sensitivity analysis, but discussions of sensitivity analysis were just confirm processes that were already known qualitatively.

- The sensitivity analysis has been modified and is now discussed more deeply.

Furthermore, model application in section 6 did not apply to real snowpack observation data but only virtual snow stratigraphy. Due to lack of validation using real data, they could not show the accuracy of this model in the analysis quantitatively. Consequently, despite the model is innovative, this study could neither show availability to reproduce the real snowpack nor suggest additional experiment to improve the accuracy of the model sufficiently. Authors are not necessarily required to perform laboratory experiment or field observation by themselves, but in that case, they need to find any literature of real data to compare with the simulation results.

- Aspects of this model's matrix flow have been verified against the detailed model Hydrus 1D and the heat flow equation has been verified against a solver from OpenFoam. However, the authors agree that the model lacks validation against observed data. Therefore, this paper only presents qualitative results and demonstration of outputs that are qualitatively similar to observations such as dye tracing cross-sections and snowpit wetness and temperature profiles. A full validation of the model will be performed in a future study.

If this model has new idea (e.g. new technic to compute quickly) or shows the new simulation that can be performed only by this model (for example, simulation of ice layer formation), this paper may make informative components even if simulation result is not compared with real data. In my opinion, although this model itself seems to be useful, authors should consider the direction of numerical analysis to produce informative scientific results.

- This model has proven to be robust and stable despite the complexity of numerically coupling the heat and mass fluxes. Moreover, the model is proven to conserve mass thanks to the use of the finite volume method to discretize the partial differential equations. A greater discussion of these features is now added to the manuscript.

- The ability of the model to reproduce ice layer formation has been added to the manuscript and demonstrated.

Minor comments from Referee #1:

P3 L9 the model of Hirashima et al. (2014) is not limited to small artificial snow. Although their model neglected melt freeze processes, their model did not neglect multilayer. Simulations in that paper were performed in single layer snow because laboratory experiments were also performed using single layer column. They performed multi layer simulation in following proceedings although validation was not performed. Therefore, it should not be included as advantage in this model. You should replace with following sentence.
"However, their model was limited to isothermal snow samples, neglecting melting at
the surface, and refreezing of liquid water."
1) Hirashima, H., S. Yamaguchi, and Y. Ishii, 2014. Simulation of liquid water infiltration into layered snowpacks using multi-dimensional water transport model. ISSW proceedings, 48-54.
2) Hirashima, H., S. Yamaguchi, and Y. Ishii, 2014, Application of a multi-dimensional water transport model to reproduce the temporal change of runoff amount. ISSW proceedings, 541-546.

- The sentence has been revised and the above conference proceeding citations included in the revised manuscript.

P5 L10 Eq. (8) is not the equation of de Rooji and Cho (1999). Katsushima et al (2013) found that the water entry suction of snow was about 1 cm larger than the estimated value by the equation of Baker and Hillel (2000) (hwe(m)=0.0437d^-1+0.00074). And then, Hirashima et al. (2014) added 0.01 in their equation. Furthermore, rc is half of d, so (1/2rc) is correct, not (2/rc).

- The citation "de Rooij and Cho (1999)" was not used for Eq. 8 but for the equation of air entry pressure in the model (not presented in the manuscript). The sentence P5 L10 has been moved to the end of Section 2.2 to avoid further confusion.
- Equations 7 and 8 have been corrected.

P6 L25 How did you decided to use this boundary condition? What kind of situation were you going to reproduce? (e.g. For laboratory experiment, both right and left hand boundary should be no-flow boundary. For natural snow, both of them should be periodic boundary condition or free drainage boundary.)

- Different boundary conditions can be chosen for the left and right hand boundaries in this model: periodic, both no-flow, and no-flow and free-flow for the left and right boundaries, respectively. The authors chose the third option as an example but we agree that it is more appropriate to use no-flow boundary conditions for the two lateral boundaries in this level case. Section 3.1 has been modified to specify that the lateral boundaries are no-flow boundary conditions for this model application.

P8 L11-12 As mentioned in comment P3L9, Hirashima's model can consider multi snow layer. So it should be replaced with following sentence. "However, their model was limited to an isothermal snowpack. “

- Corrected

P8 L17-25 Both runoff in the graph of Fig.3 are actually impossible. Graph without PFP is simulation result considering water entry suction without heterogeneity. This infiltration condition is different from matrix flow. In reality, the condition with completely homogeneous snow is impossible. Hirashima et al. (2014) showed the simulation of water infiltration in same condition in order to show that considering only water entry suction without heterogeneity is not sufficient to reproduce the preferential flow. The discussion of this impossible phenomenon does not have scientific signification. Graph with PFP also has problem. In the real condition with PFP, it is quite unlikely to occur such a cyclic pulse in red graph. Isn’t it just a fault of this model?

- The purpose of this graph was to show the difference in model outflow between considering the formation of PFP or not. It was not to represent natural conditions.
- The cyclic pulse was not a fault of this model but is explained by the fact that matrix flow feeds PFP through lateral flows, as explained in Jury et al. (2003).
- As it seems that Fig.3 can be misinterpreted (c.f. comments from Referee #2), it has been deleted in the revised manuscript – a table showing relevant information from this simulation is now included.

Reference:

Jury, W., Wang, Z., and Tuli, A. : A conceptual model of unstable flow in unsaturated soil during redistribution, Vadose Zone Journal, 2, 61–67, 2003.

P9-10 Fig. 5 and 6. Irreducible water content, α and n value were determined from the water retention curve in laboratory experiment to optimize the curve. Thus, these values are linked to other parameters each other. Therefore, individual sensitivity experiment with static values of two parameters does not have scientific signification to describe the effect of estimation error. Sensitivity analysis for snow temperature has a potential to show the scientific informative result using this model. However, this result just showed that the low snow temperature leads to delay of runoff by refreezing. It lacks the impact to show advantage of this model.

- The authors agree. The range used for the sensitivity analysis on the irreducible water content has been changed to [0.01,0.04] (range observed by Katsushima et al., 2013). As for the sensitivity analysis on the parameters α and n, it has been replaced by a sensitivity analysis on the three different algorithms available for these parameters: Daanen and Nieber (2009), Yamaguchi et al. (2010) and Yamaguchi et al. (2012).
- The sensitivity analysis on snow initial temperature has now been more deeply discussed.

P10-11 Fig. 7 Applying new numerical model for natural snow is beneficial. However, it was not applied to real data obtained by snowpack observation but to virtual snow layer. If this model applied to real snow using snowpack observations and simulate water infiltration for the duration of interval of two snowpack observations, simulation result can be compared with the real data. If this model can, I expect the reproduction simulation of ice layer formation in the snowpack in this model.

- The formation of ice layer with this model is now shown and discussed.

Overall, although the developed model itself is advanced numerical water transport model, numerical analysis could neither show the advantage nor accuracy of this model. Discussion without any validation by real data could lead erroneous opinion such as the case of runoff in Fig. 3. Furthermore, it is necessary to perform numerical analysis to provide scientific informative result. I believe that if this model is validated using real data and show reproduction simulation of ice layer formation, this model can provide scientific informative results.

- The meaning of “numerical analysis” and its implication for this paper is not clear. The authors now specify on what CPU the model is run and the time it takes to run the simulations. The authors also further discuss the stability, robustness, and mass conservation features of the model.