Response to Reviewer 2 on tc-2020-317

We are thankful to the reviewer for reviewing and commenting our manuscript.

We have copied the specific comments in blue. Our corresponding responses are available in black below each comment, with proposed modifications to the text written in *highlighted italics*.

Best Regards,
Kévin Fourteau on behalf of all co-authors

The stated purpose of the paper is to provide a simplified analysis of the contribution of latent heat to the thermal energy flux in snow, and notably to quantify to what degree heat conduction can or cannot be decoupled from latent heat and vapor transport. This paper is based on theoretical and numerical modeling. They focused on two limiting cases, considering the kinetics of deposition and sublimation of water vapor to be either very fast or very slow. Their stated aim was to quantify the contribution of latent heat to the effective thermal conductivity.

The theoretical analysis leads in to the numerical calculations, and the results of the calculations generally confirm the work of other authors. The authors show that the fast kinetic hypothesis might be suited to snow during temperature gradient metamorphism, however they admit (line 387) that further work remains to be done before a robust assessment can be made about heat and mass transport in snow should be made using the slow kinetic hypothesis, the fast kinetic hypothesis or an intermediate case. In this regard, the narrative in the abstract and in the section entitled 'conclusions' do not seem to clearly convey the actual situation.
As detailed in the specific comments, the comparison with our simulations shows that the fast kinetics assumption is in general agreement with the publicly available experimental data, while the slow kinetics assumption is not. We propose modifications to the text in order to clearly indicate this point.

Moreover, we think it is important to acknowledge that while currently available data suggest the validity of the fast kinetics assumption, this results should be confirmed with new dedicated experiments.

While this investigation involved a significant amount of detailed work, the results confirm results that other authors have obtained; this manuscript does not add new understanding of the subject. It has long been understood that sublimation and condensation are key issues in vapor transport; the calculations in the paper show that, but there is not definitive new knowledge presented. The results of the calculations show differences between the slow kinetic hypothesis and the fast kinetic hypothesis, but the slow case had been shown in other papers, and the work on the kinetic case is inconclusive. The narrative in their stated conclusions and in the abstract seem to overstate the results.
The impression of the reviewer is that our manuscript does not add any new impactful knowledge or contribution to the understanding of heat and mass transport in snow. We however think that the notable contributions of our manuscript are the following:

- We show that the pure conduction part of the effective thermal conductivity cannot be computed independently of vapor transport in the case of fast kinetics. Yet, the state-of-the-art thermal conductivity values are the ones provided by Calonne et al. (2011) and Riche and Schneebeli (2013), which do not include latent heat effects.

- We demonstrate that the infinitely fast kinetics case is equivalent to an inert medium with an increased apparent air thermal conductivity. This allows one to easily compute the effective thermal conductivity with latent heat effect from a 3D microstructure.
- We demonstrate a direct relationship between the effective thermal conductivity and the effective vapor diffusion coefficient in the case of fast kinetics. This allows us to provide clear bounds for the diffusion coefficient, which can be highly valuable for model parametrizations
- We quantify this theoretical results with numerical simulations, providing both effective thermal conductivity and effective diffusion coefficient values under the fast kinetics assumption.
- We compare our numerical results with available experimental data and find a relatively good agreement with the fast kinetics assumption.

Specific Comments

1. The first sentence in the Abstract erroneously states that "it is generally thought that heat conduction and latent heat transport are independent processes. . .", however the claim that people think they are independent is clearly not true, because obviously both are driven by temperature and temperature gradient. This sentence needs to be replaced by some factual statement.

What we meant by "thought to be independent" is the idea that one could be understood and studied without the other. For instance, in most studies, the pure conduction part of thermal conductivity is treated without incorporating the effects latent heat (e.g. Riche and Schneebeli, 2013 or Hamonds and Baker, 2016).

Similarly, while many studies work under the fast kinetics assumption and thus assumes that vapor gradients are governed by temperature gradients, the direct link with thermal conductivity is not explicited (e. g. Pinzer et al., 2012 or Hansen and Folsien, 2015).

For instance, quoting from Hansen and Folsien (2015): *"Specifically, the effective thermal conductivity of snow depends only on the thermal conductivities of ice and humid air, respectively, while the effective diffusion coefficient for snow depends only on the binary coefficient of water vapor in air. Hence, the thermal conductivity and diffusion expressions decouple from one another"*

We will reformulate this first sentence to clarify it:
"Heat transport in snowpacks is understood to occur through the two processes of heat conduction and latent heat transport carried by water vapor, which are generally treated as decoupled from one another. "

In the abstract, the claim made in lines 9-11 are misleading, in particular the abstract omits the finding that further study would be required before robust conclusions about mass and heat transport in snow should be treated by the fast kinetics, slow kinetics, or intermediate hypothesis, as stated later in the paper.

Complementary studies on the validity of the fast kinetics assumption would be welcomed, but the overall body of evidence indicate a good agreement with the fast kinetics assumption

Thus, we do not think that the sentence line 9-11 can be regarded as misleading. Section 4.1 indicates that the fast kinetics approach is able to reproduce the characteristic temperature dependence of the snow thermal conductivity, as well as provide values of the water vapor diffusion coefficient in general agreement with the experiment. The slow kinetics approach on the other hand cannot.

While these results suggest that the fast kinetics approach can represent heat and mass transfer well in snow, they should obviously be confirmed with more data and dedicated experiments. Also, a comparison with relatively fast, but not infinitely fast, kinetics should be performed in case such an intermediary kinetics would be better suited than infinitely fast kinetics. Unfortunately, such intermediary model has not been derived yet and so this comparison is not possible for now.

We thus think that the sentence line 9-11 represents the current state of our knowledge fairly well: at this point fast kinetics appears to reasonably well represent the physical behavior of snow.

We will modify the text **L372** to clearly indicates that the slow kinetics assumption does not reproduce the temperature dependence of the thermal conductivity:
"These measurements, displayed in Figure 7 of Sturm and Johnson (1992), clearly indicate an exponential-like increase of thermal conductivity with temperature, consistent with the fast kinetics hypothesis but not with the slow kinetics hypothesis."

We also propose to modify the concluding sentences of Section 4.1 **L385**:
"All the above reasons suggest that the effective thermal conductivity and diffusion coefficient of water vapor in snow could be well represented under the fast kinetics hypothesis, at least during temperature gradient metamorphism. Further experimental work should be performed to confirm that the fast kinetics assumption generally applies for modeling mass and heat transport in snow and to highlight its potential limitations. Also, the derivation of a theoretical model able to describe heat and mass transfer with arbitrary surface kinetics would allow to investigate intermediary kinetics, in an effort to ultimately select the best modeling assumptions for snow. At the same time, this model could be formulated to explicitly take into account macroscopic convection, as this phenomenon has been observed in sub-artic shallow snowpacks (Trabant and Benson, 1972, Sturm and Johnson, 1991). Its derivation could be achieved using standard homogenization methods, such the as two-scale asymptotic expansion (e.g. Municchi and Icardi, 2020) or volume averaging methods (e.g. Whitaker, 1977)."

2. Continuing on through the early part of the paper, it is evident that the first sentence in the abstract is a chronic problem continuing in the paper. The authors could instead describe their investigations as an effort to identify under what conditions the effective thermal conductivity is mostly controlled by the ice with interstitial air, and when the effective thermal conductivity is mostly controlled by latent heat effects – this is a valid thing to do, without making the claim that the two processes are thought to be independent. Especially the stated aim of the paper in lines 36-37 should be re-cast, in order to eliminate the focus on decoupling the processes, and instead focus on a description of evaluating the relative contributions of the two processes. (An analogy would be to dimensionless numbers in fluid mechanics – the objective is to indicate relative strength between two different mechanisms) The narrative and continued emphasis on decoupling tends to lessen the credibility of the paper for those who appreciate physics.
Our goal is not to decouple the processes of heat conduction and latent transport, but precisely to show that in the case of fast kinetics, these two mechanisms are strongly coupled and cannot be studied without the other. This is exemplified by the difference in the conduction component between the slow and fast kinetics cases.

The first sentence of the abstract will be modified to make our goal clearer (see previous comment). We also propose to modify the formulation of the sentence **L36**:
"The aim of this article is to provide a simplified analysis of the contribution of latent heat to the thermal energy flux in snow, and notably to quantify the coupling between these processes at the macroscopic scale.*"*

3. In reading carefully through the whole paper, while this investigation involved a significant amount of detailed work, definitive new results with impact are lacking; this manuscript does not add new understanding of the subject. It has long been under stood that sublimation and

condensation are key issues in vapor transport. The paper does not have any robust conclusions about whether mass and heat transport in snow should be treated by the fast kinetics, slow kinetics, or intermediate hypothesis.
As explained in the introduction of our response we think that our manuscript add several new results and goes further than simply stating that sublimation/deposition is important for mass transport.

Among other, the simple relationship between the vapor diffusion coefficient and the effective thermal conductivity is completely novel and has far-reaching implications for modelers. It also clearly demonstrates the coupling between heat and mass transport, which was not understood before and which will help modelers better describe these transport processes, which are critical for understanding and reliably quantifying snowpack evolution and energy exchanges issues.

Also, Section 4.1 shows that while the fast kinetics assumption reproduces the observed behavior of snow, the slow kinetics one does not. It indicates that the fast kinetics assumption is a promising hypothesis, and that further work should be dedicated to precisely quantify the surface kinetics at play in snow, and to develop macroscopic models accordingly.

REFERENCES

Calonne, N., Flin, F., Morin, S., Lesaffre, B., du Roscoat, S. R., and Geindreau, C.: Numerical and experimental investigations of the effective
thermal conductivity of snow, Geophys. Res. Lett., 38, L23 501, https://doi.org/10.1029/2011GL049234, 2011.

Hamonds, K. and Baker I.:Investigating the thermophysical properties of the ice–snow interface under a controlled temperature gradient Part II: Analysis, Cold Regions Sci. Tech., 125, 12-20, https://doi.org/10.1016/j.coldregions.2016.01.006, 2016

Hansen, A. C. and Foslien, W. E.: A macroscale mixture theory analysis of deposition and sublimation rates during heat and mass transfer indry snow, The Cryosphere, 9, 1857–1878, https://doi.org/10.5194/tc-9-1857-2015, 2015.

Municchi, F. and Icardi, M.: Macroscopic models for filtration and heterogeneous reactions in porous media, Adv. Water Resour., 141, 103 605, https://doi.org/10.1016/j.advwatres.2020.103605, 2020.

Pinzer, B. R., Schneebeli, M., and Kaempfer, T. U.: Vapor flux and recrystallization during dry snow metamorphism under a steady temperature gradient as observed by time-lapse micro-tomography, The Cryosphere, 6, 1141–1155, https://doi.org/10.5194/tc-6-1141-2012, 2012.

Riche, F. and Schneebeli, M.: Thermal conductivity of snow measured by three independent methods and anisotropy considerations, TheCryosphere, 7, 217–227, https://doi.org/10.5194/tc-7-217-2013, 2013

Sturm, M. and Johnson, J. B.: Natural convection in the subarctic snow cover, J. Geophys. Res. Solid Earth, 96, 11 657–11 671, https://doi.org/10.1029/91JB00895, 1991.

Sturm, M. and Johnson, J. B.: Thermal conductivity measurements of depth hoar, J. Geophys. Res. Solid Earth, 97, 2129–2139, https://doi.org/10.1029/91JB02685, 1992.

Trabant, D. and Benson, C.: Field experiments on the development of depth hoar, Geol. Soc. Am. Mem., 135, 309–322, 1972.

Whitaker, S.: Simultaneous Heat, Mass, and Momentum Transfer in Porous Media: A Theory of Drying, 13, 119–203, https://doi.org/10.1016/S0065-2717(08)70223-5, 1977.