Reviewer Comments on “Impact of water vapor diffusion and latent heat on the effective thermal conductivity of snow” by Fourteau et al.

General Comments

This manuscript presents compelling results of theoretical work and numerical simulations to demonstrate the latent heat effects of water vapor diffusion on the overall thermal conductivity of snow. The authors set up a theoretical model for the energy and vapor transport in snow. The work focuses on the effects of kinetics of sublimation/deposition by analyzing limiting cases of variation of the α parameter (sticking/accommodation coefficient) in the Hertz-Knudsen equation. Slow and fast kinetics are considered as bounds to the overall heat flux, with the bulk of the manuscript exploring the fast kinetics approach (as the slow kinetics approach has been considered in previous cited literature). As a result of the assumptions of their modeling, ultimately, the effects of latent heat from vapor transport can be incorporated into an expression for the conductivity in air, and the overall effective conductivity can be described as comprised of a conduction term and a vapor term, but the importantly authors note that these two terms are interdependent. Their theoretical work results in a linear relationship between the effective thermal conductivity and the normalized diffusion coefficient of water vapor.

Results are presented from numerical simulations using 34 micro-CT snow structures, spanning a range of densities, using the fast and slow kinetics approaches at a range of average temperatures. The complex interdependence of the overall heat transfer due to conduction in air, conduction in ice, and vapor kinetics effects are demonstrated by showing results for slow and fast kinetics and for different densities. The authors demonstrate that conductivity is significantly enhanced in the fast kinetics case at both high and low temperatures, but more so for high temperatures and for low densities. Useful relationships for thermal conductivity and normalized water vapor diffusion coefficient as a function of density are also presented and compared to published results. To assess if the fast kinetics approach is a reasonable model for snow, the authors compare their fast kinetics results to published work (measurements of thermal conductivity and normalized diffusion coefficient) and suggest that the fast kinetics approach may be reasonable model when temperature gradients are present.

Overall, I think that this work presents a strong contribution to the ability to effectively represent and conceptualize heat transfer in snow. Some clarification as to how the theoretical results differ from published work would be useful (see specific comments), but the combination of theoretical and numerical work presents a clear case for the potential of the fast kinetics approach to fairly simply represent complex heat transfer processes in temperature gradient scenarios. The methods implemented are appropriate and rigorous, citing appropriate precedent for both the theoretical and numerical portions of the work. I would appreciate some clarification on determining conditions for which the fast kinetics approach is valid given the assumptions that go into it (see specific comments). I believe that this work is significant and an important step in working from underlying physics to provide relevant information for snow modeling. The presentation of the work is clear and sufficiently structured, with only some minor points where writing could be clarified (as identified in the specific comments). I found the manuscript to be compelling, interesting, and fitting for *The Cryosphere*.

I recommend that this manuscript be accepted with minor revisions.

Specific Comments

Line 11: Consider listing which properties you are referring to here – effective thermal conductivity and water vapor diffusion coefficient, presumably?

Line 44: Please indicate why neglecting convection in the pore space is a reasonable assumption in this case and cite appropriate references.

Lines 62-63: Please elaborate on which mechanisms specifically would invalidate the assumption that thermal conductivity and the vapor diffusion coefficient depend only on physical properties.

Line 92: What constitutes a sufficiently large thermal gradient?

Line 121: Is it the magnitude or the rate of sublimation and deposition? Or is it both? Please clarify.

Line 146: The effective thermal conductivity in the fast kinetics approach does not depend on the macroscopic thermal gradient, but is it true that the thermal gradient must be sufficiently large to assume that the saturation concertation depends on temperature only?

Lines 153-154 (and Equations 16): I think the reader could benefit from more explanation of the $\langle \nabla T_i \rangle$ and $\langle \nabla T_a \rangle$ terms. How are these terms computed in the numerical simulation portion of the work?

Line 170: The text notes that a similar expression to Equation 9 was reported by Jordan (1991) and Sturm and Johnson (1992). Please clarify if their work was based on the same modeling assumptions or how your results differ.

Lines 175-178: I think the explanation here just needs a bit of clarification in the wording. The sentence that starts "This increases the average…" – Is it the *reduced contrast* in conductivity what increases in the average temperature gradient? Or is it just the *increased effective conductivity in the pore space*?

Lines 205-206 (and Figure 2): Does this relationship represent an upper limit because of the fast kinetics assumption? Please clarify.

Line 227: Is there a reason that a thermal gradient of 50 K m^{-1} was chosen? There is a discussion earlier about how the magnitude of the gradient does not affect the ultimate thermal conductivity results, but must be sufficient to warrant the fast kinetics approach.

Line 233: For the c_{sat} equation that follows the Clausius-Clapeyron and ideal gas laws, perhaps include a reference to the Fourteau et al. 2020 paper which contains the c_{sat} equation or include the equation here.

Lines 303-304: Here you reference the absolute difference in thermal conductivity between the fast and slow kinetics. Perhaps the results of the slow kinetics simulations could be included in the Supplement along with the fast kinetics results?

Figure 8: Would it make sense to also include the polynomial fit for slow kinetics from your numerical experiments as well, since this is more directly comparable to the work done by Calonne et al. (2011) and Riche et al. (2013)? I understand the desire to show the difference between the slow and fast kinetics approaches, but showing that your slow kinetics results agree with their work (or explaining why if they do not agree) might be useful.

Line 377: It is not quite clear which "reported experimental values" you are referencing here? The ones from Sokratov and Maeno (2000) which are discussed in the next sentence? Or others? Please clarify.

Line 386: This calls back to previous comments, but again I am curious if there is some limit of the magnitude of thermal gradient that should be considered to employ the fast kinetics approach. I understand that your simulations cannot directly answer that question, but addressing the question at the level of the assumptions that go into the modeling might help this work be implemented more readily.

Line 429: Please clarify the conditions under which this approach is well suited to model snow.

Technical Corrections

Line 3: (and throughout) I think because kinetics is plural, this should read "…case where kinetics *are* fast…". Please revise subject/verb agreement here and throughout the manuscript.

Line 9: consider editing to say "by up to 50%"

Line 21: governs → govern

Line 67: "reduces to a vertical and horizontal" – delete the word "a"

Line 93: imposed to → imposed on

Line 112: details → detail

Line 125: suggest "helps in apprehending"

Line 249: 90 millions of elements → 90 million elements

Line 258: suggest restructuring to clarify this sentence. Maybe removing comma after "causes" is sufficient

Line 282: consistently → consistent

Line 359: applies → apply

Line 420: representativity → representativeness

Line 422: clarify that it us up to 50% more than for the slow kinetics case

Lines 432-433: by detailed snow physics model → in detailed snow physics models