Responses to Reviewer 2 for EGU-2025-3035: "Simulating the effect of natural convection in a tundra snow cover"

October, 2025

1 Answers to general comment, broad comments, and specific comments

Corresponding changes based on the comments from reviewer 1 and 2 and the additional changes in the revised manuscript are highlighted in blue color.

1.0.1 General comment

1. This is a review for "Simulating the effect of natural convection in a tundra snow cover". Overall I really enjoyed this manuscript. Over the past few years I've read the various papers regarding the importance of estimating the near-ground low-density layer, and how difficult this is to simulate. The numerical scientist in me really likes the full-complexity model approach to attempt to bound the behaviour. A "what will this take" type of approach is great to see.

Answer:

We thank the reviewer for their exceptionally thoughtful comments and expertise, and for their enthusiasm toward our manuscript. We are genuinely thrilled that the reviewer enjoyed the work, and your positive feedback strongly encouraged us in the value of this research. We are particularly pleased that our full-complexity model approach to bounding the snowpack behavior is viewed as valuable, as this was the core intent behind our simulation design.

In response to suggestions and to further clarify the bounding nature of our work, we have restructured and extended the Results and Discussion section into distinct subsections. These revisions explicitly frame the two main simulation scenarios:

- The section now begins with a new introductory paragraph that directly compares field measurements with two key model outputs: the Lower Bound simulation (Convection + Compaction) and the SNOWPACK-only diffusion simulation (without compaction).

- The remainder of the section is now divided into two subsections to discuss the bounding scenarios:

  – Lower bound of convection with drifting-snow compaction model: Discusses the scenario where convection is realistically suppressed most of the time by the inclusion of a wind slab. We also note that convection might still be triggered in the early season before hard slabs form, or within the middle of the snowpack in a low-density layer located between two hard slabs, provided the surface is sufficiently cold and the weather is not too windy.

  – Upper bound of convection without drifting-snow compaction model: Discusses the scenario where convection operates freely (which corresponds to the main results presented in the original submission).

This refined organization makes the context and purpose of our approach to bounding convective effects much clearer to the reader.

1.0.2 Broad comments

1. First, this paper absolutely needs a set of research questions to guide the model development. Indeed the goals allude to this around L65. But it needs to be research questions otherwise it's "I ran the model and it did Y". I raise this because I think this paper sells itself a bit short in the discussion and conclusion. These are really valuable insights into a) the difficulty and b) importance of this process. I use models like Snobal and FSM in most of my work because it is computationally fast enough to deploy at a high resolution over millions of km. I'm left a bit unsatisfied as a snow modeller as to the next steps. Indeed you note some, but I mean practical next steps for the community. OpenFOAM is a massive hammer that is not going to be deployed over anything but a small point-scale domain (as done here) due to the computational and IC costs. So, I would really like a discussion on how, by answering these RQs, the authors can advance the more "applied" science. First, it's clear that even though massive computational effort was used, the results are still not correct

(e.g., density profiles). So, how do the authors think these results can inform parameterizations in other less complex models? Is it possible to parametrize around this without the full physics of OpenFOAM? I get very excited with these results as they are a clear step, but they are bespoke. What's next in advancing the snow modelling communities characterization and simulation of these layers?

Answer:

We thank the reviewer for this highly insightful and constructive critique. We strongly agree that the manuscript must clearly articulate its contribution to the applied snow modeling community and provide a clear, step by step path forward. We have addressed this broad critique through the following revisions in the manuscript:

1) Explicit Research Questions (RQs): We have revised the Introduction (around L65) to establish two core Research Questions (RQs), which now guide the entire narrative as:

"In this paper, we focus on two core research questions: To what extent does two-dimensional natural convection, simulated by the full SNOWPACK-OpenFOAM model, modify the one-dimensional temperature and density profiles of an Arctic tundra snow cover compared to standard diffusion-only models? and How do realistic snow physics, specifically wind slab formation (drifting-snow compaction), influence the occurrence and overall impact of natural convection in Arctic tundra snowpacks, thereby defining a lower bound for convective effects?."

2) Advancing Applied Science: Parameterization and Density Fidelity: the reviewer raises the critical question of how these bespoke, high-complexity results can inform scalable 1D models and why the density profiles still show error.

- We address the density profile error directly in the Results and Discussion section (end of the third paragraph). An important, yet negative result is that our setup is still unable to produce snow density profiles, which are close to observation. This could be due to effects of vegetation and heterogeneity discussed in Jafari and Lehning (2023) or some other physics not fully understood. This motivates further research, which is beyond the scope of the current paper, however.

- Parameterization Strategy (Conclusions): We detail our strategy in the Conclusions section in the last paragraph, clarifying the difficulties and proposing a practical solution as:

"We acknowledge that a simple parameterization based on classical dimensionless numbers (like the Rayleigh number, Ra) for the entire snow column is problematic. Snow properties (the snow porosity, the effective thermal conductivity, and the intrinsic permeability) vary dramatically and constantly, making it difficult to define a single, representative Ra for a one dimensional model. The practical step forward is to use the high-fidelity SNOWPACK-OpenFOAM solution as a "truth set." We will extract the resulting effective convective vapor flux as a function of local one dimensional snow properties (density, grain type, the snow element temperature difference as ΔT) within snow layers. This generated data can then be used to calibrate or tune to find a new parameter as the water vapor diffusion enhancement factors (α_v) to be employed in one dimensional models, which is the most feasible way to integrate these complex two dimensional results into large-scale simulations."

2. Second, this paper needs a tighten w.r.t how some of the sections are presented. I guess it should have been obvious early on, but it wasn't that this was a 2D (x,y) model instead of a 1D col model with the processes added. I mean, it's obvious as I write this, but when I was reading the paper it didn't immediately jump at me. I think that there ought to be a small schematic just showing the (numerical) experimental setup in the main text to lead the reader through what is obvious to the authors (perhaps an opportunity to graphically detail the layer coupling?). I found the equation at l135 to come out of no where, and either walking the reader through this more or cutting it would be my suggestion.

   Answer:

   Thank you for these excellent suggestions on improving the manuscript's clarity. We agree that the dual-dimensionality of the coupled model and the necessity of the modified energy equation need clearer introduction. We have addressed the request for a clearer representation of the 1D/2D domains by enhancing Figure 1 (which shows the coupling procedure). The revised Figure 1 now includes a schematic that explicitly illustrates the 1D column (SNOWPACK) domain and the 2D domain (OpenFOAM), visually detailing the layer-by-layer coupling and the flow of information between the models. This makes the dual-dimensionality obvious earlier in the paper.

   Regarding justification for Equation at L135, we recognize that the energy equation appeared without sufficient context. We have chosen to keep the equation because it is mathematically essential for reproducibility of our numerical setup. As we noted in the original manuscript ("...except for the changes due to presence of water and the heat source/sink term from shortwave radiation absorption..."), this equation is the corrected energy balance specific to our coupled solver (SNOWPACKFoam). It differs from the standard convective solver used in idealized snowpack studies by Jafari et al. (2022) because it has been explicitly adjusted to account for the continuous mass and energy adjustments required during the SNOWPACK-OpenFOAM coupling. Keeping this modified energy equation allows researchers to accurately reproduce the numerical setups, whereas momentum and continuity equations remain standard and are referenced only by citation.

1.0.3 Specific comments- w/c = word choice

1. L1: "straightforward" OpenFOAM is almost never considered simple!

   Answer:

   Thank you for catching this confusing terminology. We fully agree that describing anything related to OpenFOAM as "straightforward" is misleading and undersells the complexity of the effort. The term was intended to refer to our direct numerical solution approach for convection, not the complexity of using the OpenFOAM platform itself.

   We have replaced "straightforward" with "direct" in the manuscript (L1 in the original draft) to accurately reflect the nature of our solution method while avoiding the implication of simplicity.

2. L3 convection of what?

   Answer:

   Thanks. We changed to "convection of water vapor" in the revised manuscript.

3. L4 "feeds" w/c

   Answer:

   Thanks. We replaced "feeds" with "transfers". The revised sentence will read as "OpenFOAM simulates convection in two dimensions based on

SNOWPACK snow profiles and transfers the convective vapor fluxes back to SNOWPACK."

4. L5 “numerical observed“ -> simulated?

   Answer:

   Thanks. We changed "numerical observed" to "simulated" in the revised manuscript.

5. L5 “coupler” remove? w./c -> model?

   Answer:

   Thanks. We replaced "coupler" to "coupling" in stead in the revised manuscript.

6. L6 “only if [..] surface layers” perhaps remove

   Answer:

   Thanks for the suggestion. We removed the entire line of "only if we neglect wind slab formation for surface layers." in the revised manuscript.

7. L7 “downward” w/c -> vertical?

   Answer:

   Thanks. We changed it to "vertical" in the revised manuscript.

8. L9 “in the SNOWPACK” insert “non-coupled” or similar to clarify

   Answer:

   Thanks for the suggestion. We added "non-coupled" in L9 and we have in the revised manuscript as "...respectively makes a consistent representation in the non-coupled SNOWPACK one-dimensional profile difficult".

9. L11 “this effect” what effect? be specific

   Answer:

   Thanks. In L11, We replaced "this effect" to "convective water vapor transport" in the revised manuscript.

10. L12 “and its interaction[...]” within snowpack or the surface wind model?

    Answer:

    Thanks for the suggestion. We added "within snowpack" at the end of L12 in the revised manuscript as "... and its interaction with snow settling and metamorphism within snowpack."

11. L17 “i.e” -> i.e.,

    Answer:

    Thanks. Done."

12. L22 “finite” as opposed to infinite distances?

    Answer:

    Thanks. Yes."

13. L22 “and changes in”

    Answer:

    Thanks. Done."

14. L24 “significant” w/c as significant implies statistical significance

    Answer:

    Thanks. We replaced “significant” with "statistically significant" in L24 in the revised manuscript."

15. L25 “convection” within the snowpack

    Answer:

    Thanks. We added "within the snowpack" at the L25 in the revised manuscript."

16. L27 “convection of water vapour” a small blurb about what this is might be helpful

    Answer:

    Thank you for this constructive suggestion. We agree that adding a concise physical description of water vapor convection in snow will enhance clarity for the broader readership. We have inserted a short explanatory phrase around L27 to describe the process as a buoyancy-driven movement of air and vapor:

    We added a clause defining the process, such as: "... However, convection of water vapor, the buoyant movement of air and moisture driven by temperature and air density gradients, is not captured in conventional snow models leading to large errors in simulated snow prop....."

17. L28 “convectional” do the authors mean conventional?

    Answer:

    Thanks. Yes now it is corrected to "conventional" in the revised manuscript.

18. L29 “Subarctic” -> subarctic

    Answer:

    Thanks. We have changed "Subarctic" to "subarctic" everywhere in the revised manuscript.

19. L34 love the ecological tie in. super important

    Answer:

Thank you for this encouraging comment. We are glad that the ecological connection resonated with you, as we believe it is essential to emphasize the real-world significance of accurate snow modeling beyond pure physics. We will retain this sentence as is.

20. L38 “SNOWPACK, as a [...]” remove as

    Answer:

    Thanks. Done.

21. L48 “direct” for the snow modeller not versed in numerical methods you might contextualize direct versus alternatives.

    Answer:

    Thanks. The term "direct" in our original sentence refers to the fact that our model uses a Direct Numerical Solution (DNS) method for solving the coupled flow and transport equations.

    We have revised the surrounding text in the manuscript to provide context for the broad readers. The revised sentence now reads: "The convection model used in this paper is a direct numerical solution (DNS) that solves the full set of coupled mass and energy transport equations, offering a high-fidelity alternative to traditional parameterizations. This model shows an error level between 3% to 10% (Jafari et al., 2022).""

22. L48 “accuracy between [...]” versus what?

    Answer:

    Thanks. We changed it to "This model shows an error level between 3% to 10% compared to the numerical benchmark (Jafari et al., 2022)." in the revised manuscript.

23. L50 I find this sentance awkward and difficult to fully comprehend. It doesn’t lead well into the next sentence either, so it’s not super clear what the authors wish to convey.

    Answer:

Thanks. We remove the part as "It is important to explicitly state a key ....which are tailored to Alpine conditions." in the revised manuscript.

24. L52 remove ", such as those [...] Island"

    Answer:

    Thanks. Done.

25. L53, L54 "no physically accurate" ... "rough approximation" suggests it's at least partially physically accurate ??

    Answer:

    Thanks. As also suggested by reviewer 1, We added "partially physically accurate" and we have the revised L53 and the rest of paragraph as:

    "Arctic snowpacks are substantially influenced by wind compaction—a process for which no physically accurate, widely accepted model exists. The current parameterizations, including those proposed by Gouttevin et al. (2018) and recent studies by Keenan et al. (2021); Wever et al. (2023) for drifting-snow compaction, offer only a rough approximation (partially physically accurate). Including wind compaction in the simulation results in a high-density surface layer that suppresses the formation of convection cells, rendering natural convection less active."

26. L55 "natural convection" as opposed to?

    Answer:

    Thanks for the clarification request. We use "natural convection" to explicitly distinguish our modeled process from "forced convection" (i.e., wind pumping), which is the other major form of air movement in snow. Thus, we have added "driven by buoyancy forces" after "natural convection".

27. L61 "is not possible" why?

    Answer:

    Thanks for asking for this clarification. We agree that this point, while intuitive to 2D/3D solver users, must be explicitly stated for the broader snow modeling community.

We clarify that modeling natural convection is not possible in 1D snow models because natural convection is fundamentally a 2D or 3D phenomenon (it requires lateral dimensions to form flow cells).

We have revised the surrounding text in the Introduction (around L61) to explicitly state the justification. The revised sentence now reads:

"Modeling convection in one-dimensional snow models is not possible as one-dimensional models cannot capture the spontaneous formation and lateral flow fields of two dimensional convection cells..."

28. L70 turn these into research questions that will guide and support this manuscript but also inform the next steps

    Answer:

    Thanks. As answered in the first broad comment, we have added few lines for the research questions in the revised manuscript as:

    "In this paper, we focus on two core research questions: To what extent does two-dimensional natural convection, simulated by the full SNOWPACK-OpenFOAM model, modify the one-dimensional temperature and density profiles of an Arctic tundra snow cover compared to standard diffusion-only models? and How do realistic snow physics, specifically wind slab formation (drifting-snow compaction), influence the occurrence and overall impact of natural convection in Arctic tundra snowpacks, thereby defining a lower bound for convective effects?.

29. L72 strong disagree that this is a straightforward approach.

    Answer:

    Thanks. As answered earlier in the first specific comment, we changed "straightforward" to "direct" in the revised manuscript.

30. L80 maybe it's difficult to do but I think a figure illustrating this section would be helpful.

Answer:

Thanks. As answered earlier in the second broad comment, we revised figure 1 and it now includes a schematic that explicitly illustrates the 1D column (SNOWPACK) domain and the 2D domain (OpenFOAM), visually detailing the coupling and the flow of information between the models.

31. L81 "internal elements" w.c -> computational elements?.

    Answer:

    Thanks. Done.

32. L91 OF=OpenFoam, SN=Snowpack needs to be in the text

    Answer:

    Thanks. We have revised the entire relevant item to improve readability and added an explicit definition, stating: "Please note that the subscript OF and SN refer to OpenFOAM and SNOWPACK, respectively."

33. L105,120 could be shorter and tighter.

    Answer:

    Thanks. We shortened the entire paragraph in the revised manuscript as:

    "Currently, OpenFOAM provides only the laterally-averaged snow density change rate (due to vapor transport) to SNOWPACK. Future work will enhance this by incorporating the laterally-averaged temperature profiles from OpenFOAM back into SNOWPACK's initial conditions and using the density change rate directly in SNOWPACK's metamorphism calculation. It is theoretically possible to use multiple parallel SNOWPACK columns across the OpenFOAM domain to capture lateral heterogeneity. However, the resulting differences in compaction and snow height would create surface discontinuities, complicating the current dynamic mesh strategy. Numerically, this challenge can be addressed by using separate, disconnected meshes for each SNOWPACK domain, though careful attention would be required for defining boundary conditions and information exchange across these discontinuities."

34. L105 “only feedback” I think this shoudl be re written in the vernacular of couplers e.g., flux exchange between the models etc

    Answer:

    Thanks. We removed "feedback" in the revised manuscript.

35. L135 This eq comes out no where I found, and it’s complex enough to need a lot of time to read

    Answer:

    Thanks. As mentioned in the answer for second broad comment, we have chosen to keep the equation because it is mathematically essential for reproducibility of our numerical setup in the revised manuscript.

36. L135 “presented as” is confusing. was this modified from Jafari 2022 into this? or something else?

    Answer:

    Thanks for highlighting the potential confusion. We confirm that the energy equations presented are indeed modifications of the full energy equations found in Jafari et al. (2022).

    The revised text now reads: "The heat transfer equations for the ice-water mixture and the gas phase are similar to those presented in Jafari et al. (2022), but have been modified to account for the presence of water and the heat source/sink term from shortwave radiation absorption. The resulting modified energy equations for the gas phase and ice-water mixture, essential for the reproducibility of our coupled solver, are presented as:"

37. L138 Jv is missing definition

    Answer:

    Thanks. We have added the definition as "J_v is the diffusive water vapor flux" in the revised manuscript.

38. L164 Courant of 5. This feels a bit adhoc of a choice. How sensitive are the results to this choice?

    Answer:

    Thanks. The choice is governed by the highly transient nature of the coupled problem, where the thermal boundary conditions change every 15 minutes due to SNOWPACK. While our previous steady-state convection analysis (e.g., Jafari et al., 2022) showed that results are insensitive to Courant values up to 200, such high values compromise stability and accuracy in a highly dynamic, coupled system.

39. L164 PIMPLE = ?

    Answer:

    Thanks. We added a small explanation in L164 where PIMPLE is mentioned as "Note that it is possible to use the PIMPLE algorithm (a hybrid pressure-velocity coupling algorithm for solving incompressible flows) for higher values of the maximum Courant number in OpenFOAM..." in the revised manuscript.

40. L167 "faster" It might be faster but is the result right? Providing the wrong answer faster isn't interesting. I think your text suggests it's fine w.r.t error, but this can be tightened up a lot.

    Answer:

    The term "faster" refers to the computational efficiency gained by using OpenFOAM's PIMPLE algorithm and adaptive time stepping (Courant number). For quasi-steady problems with fixed thermal boundaries, higher Courant numbers can achieve speed without sacrificing accuracy. However, in our case, we have highly dynamic thermal boundary conditions (driven by SNOWPACK). For such transient problems, stability and accuracy necessitate lower Courant numbers. We emphasize that the overall computational gain comes from optimizing the stability of the coupled solution by choosing lower Courant numbers, which indirectly makes the simulation as fast as possible while maintaining a stable and accurate result.

41. L175 "computer runtime" suggest you use the HPC vernacular of "wall clock" or similar. You need to distinguish between core hours and wall

clock either way.

Answer:

L175 has been revised as follows:

"We found that (1) the simulation required approximately 21 hours of wall-clock time using four MPI processes (i.e., about 84 core-hours in total), whereas the 'flow-freezing' approach reduced this to about 5 hours of wall-clock time, and (2) the averaged cumulative density changes exhibited acceptably small differences."

42. L177 "small differences" define small, e.g., $<$??

    Answer:

    Thanks. As also suggested by reviwer 1, we mentioned the values for the differences in the revised manuscript as "...exhibited acceptably small differences as shown later in figure 27 the maximum difference in snow density is only between 5 and 10 kg m^{-3}..."

43. L205 Above I note that explaining what this convection process is would help the reader. e.g., including the info from here would be good. "It's a process that is dependent upon thermal gradients and high density,. . . ."

    Answer:

    Thanks. We have added an explanation for the convection in the revised manuscript as "...Canadian High Arctic, conditions to trigger convection (the buoyant movement of air and moisture driven by temperature and air density gradients) are at least partially fulfilled".

44. L2XX these plots are really nice"

    Answer:

    Thank you for the very kind feedback! We are truly thrilled that you enjoyed the plots and found them informative.

45. L2XX I wonder if fig 3 and 4 could be made a 4 pane single plot?

    Answer:

    Thank you for this excellent suggestion. We agree that consolidating the figures will improve the manuscript's flow and visual efficiency. We have implemented this change in the revised manuscript by merging the related figures:

    1) Figure 3 and Figure 4 (original manuscript) have been merged into a single, comprehensive plot detailing the cumulative density change across scenarios.

    2) Figure 5 and Figure 6 (original manuscript) have also been merged into one figure, which presents the snow density change rate due to vapor transport.

46. L239 Figure 7 caption, define H and $\rho_{s,cum}$ If it's the same snow height as fig 5,6, please use the same y axis label

    Answer:

    Thank you for pointing out the necessity for clearer figure definitions and standardized axes. We have implemented the following revisions:

    1) We added the definitions for the key variables ($\Delta\rho_{s,cum}$ and ρ_s) in the caption, which now reads as:

    "Comparison between diffusion from SNOWPACK simulation (without drifting-snow compaction) and convection from SNOWPACK-OpenFOAM simulation (without drifting-snow compaction) for cumulative snow density change ($\Delta\rho_{s,cum}$) and snow density (ρ_s) profiles on 12 April 2015..."

    2) We standardized the y-axis label to "snow height [cm]" to ensure consistency across all relevant figures (Figures 2 and 6).

    3)We note that measured snow density profiles were removed from this specific figure. The detailed comparison with measurements for both the SNOWPACK and SNOWPACK-OpenFOAM simulations (including drifting-snow compaction) is now placed and discussed earlier in the "Results and Discussion" section to improve narrative flow.

47. FIgure 8, 9 need axis labels

Answer:

Thanks. Done.

48. L286-9 great result

Answer:

Thank you for the positive feedback! We are pleased that you found these results insightful and appreciate the encouragement.

49. L309 “benchmark” w/c/ observations?

Answer:

Thanks. This benchmark is a numerical benchmark and not observations. We change it to "numerical benchmark" in the revised manuscript.

50. L333 It would be great to have a simple concluding sentence somewhere in here where you can attribute X% uncertain to ignoring this process. A nice quotable sentence for other papers to cite, to really hit home ignoring this, even if not perfect, is costing X% in uncertainty”

Answer:

Thank you for the excellent suggestion to include both key uncertainties. We have revised the concluding sentence to be concise and highly citable, quantifying the impact on both density and temperature:

The finalized, quotable sentence at the end of last paragraph in the Conclusion section reads as follows:

"In summary, the substantial two-dimensional variations observed, up to 90 kg m^{-3} (115%) in localized snow density and up to 5 K (30%) in temperature, demonstrate that ignoring the two-dimensional nature of natural convection introduces over 100% uncertainty in localized density prediction and up to 30% uncertainty in snow temperature in conventional one-dimensional models, underscoring the necessity of addressing this process."

51. L335 Open science and data section?

Answer:

Thanks. It is now added in the revised manuscript.

References

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