Review for „Snow Structure Modulates the Isotopic Imprint of Sublimation“ by Dar et al. submitted to The Cryosphere

General comments:

The experimental study by Dar et al. addresses the often-overlooked, complex physical process of snow sublimation and the isotopic fractionation process associated with it. As this process has relevance in several cryospheric research domains such as boundary layer meteorology, hydrology, paleoclimatology and polar and alpine snow studies, the presented, well-written manuscript fits well within the scope of The Cryosphere journal. The study uses an elaborated climate controlled "container-laboratory" wind tunnel set-up to experimentally investigate the isotopic changes occurring during sublimation of snow. Similar studies have been performed in the past and the fundamental findings of the Dar et al. study confirm previous results of increasing primary and decreasing secondary isotope signals in snow under sublimation. A significantly new aspect in the presented study is the test for sensitivity of sublimation-fractionation signals to snow (micro)structure. The results suggest that snow structure notably influences the magnitude of a sublimation-imprint in the snow, with lower density (higher porosity) snow showing stronger changes in the isotopic composition during a 24-hour time window compared to higher density (lower porosity) snow. In their set of eight experiments, the snow structure seems to be the dominant control for snow isotope change, even more important than sublimation strength (cumulative mass loss), which is a new and important result. Strikingly, this porosity-control does not seem to hold for the artificially produced snow which the authors argue is due to insufficiently detailed knowledge of the microstructure differences between snow samples. However, as the artificially produced snow does show nature-resembling characteristics ("plate-like and columnar crystals", L. 139) this result significantly reduces the credibility for a snow-structure control on sublimation imprints in my eyes. Instead, I am missing alternative explanation attempts for why the artificially produced snow does not follow the behavior of natural snow, which could reconcile all observations. For example, the authors should investigate whether the substantially different initial isotopic composition between FS/OS and LS could be the reason for the diverging behaviour. The modeling framework applied in the study (L. 499) also supports this argument of initial isotopic composition differences as main contributor between FS and LS differences.

The study also includes an attempt at modeling the observed snow isotope changes using the Craig-Gordon model, a numerical model developed for isotopic fractionation during the evaporation of (a well-mixed) water body. As in previously published studies, the model overpredicts the fractionation signal for snow sublimation. Since two important parameters, the isotopic composition of the vapor overlying the snow sample and the snow surface temperature were not measured, the authors can not model the change in snow isotope signal per sample. Instead, the authors make use of the three synchronously sublimating snow samples and calculate the difference in snow isotope change between two snow samples as this allows for the analytical cancellation of the isotopic composition of ambient vapor. Acknowledging that this approach allows some attempt at modeling, I am unsure whether this (rather cumbersome) modeling framework is a valuable addition to the study as it does not yield any new insights beyond that the Craig-Gordon model does overestimate fractionation when applied to snow. Considering that model variable uncertainties are high, such as the variable “n” which is arbitrarily set, and the important variable RH (normalized to surface temperature) is highly uncertain as surface temperature was not measured, I am doubtful whether the model results are useful as they are presented in the current manuscript version. As an alternative, the authors could decide to adapt the Craig-Gordon model to snow conditions by including some “snow structure” variable in an attempt to improve model-observation matching.

The study is interesting and worth to be published in The Cryosphere after some major modifications are taken under consideration.

Please elaborate on the following topics:

- Can the strong difference in initial snow isotopic composition between FS/OS and LS be the reason for the different sublimation imprint? See discussion on disequilibrium in e.g. (Aemisegger et al., 2015; Wahl et al., 2024)

- Discuss the physical process that imprints isotopic fractionation during sublimation in the remaining snow. In my view, snow metamorphism (which is strongly linked to snow microstructure) is the process which enables the imprint of sublimation into the snow under the assumption that the metamorphism rate is higher or comparable to the sublimation rate. Your results confirm this hypothesis and also link well with the findings from (Harris Stuart et al., 2023). The highest signal change is recorded when fresh snow with highly dendritic snow crystals undergoes strong metamorphism under moderate sublimation. However, if sublimation rate and flow increases, sublimated molecules are “removed” quicker and metamorphism rate is too low to incorporate the signal. Since the snow samples are subject to a huge temperature gradient, the metamorphism rate in the presented experiments is abnormally high (temperature gradients of 500-100 K/m are already considered “strong”) see (Dick et al., 2026). Thus, please include a temperature gradient metamorphism explanation and definition in the introduction and compare the T-gradients of these experiments with T-gradients observed in nature and associated recrystallization rates.

Additionally, it looks as if you have several competing processes happening at the same time and their balance modulates whether you can see a sublimation imprint, or not (see L. 415). Please incorporate a comparison of sublimation rate to metamorphism/ recrystallization rate for each experiment. Also discuss the physical link between snow metamorphism and surface sublimation e.g. in paragraph 574-579. See also (Harris Stuart et al., 2023; Ollivier et al., 2025; Wahl et al., 2024)

- Consider removing the Craig Gordon model to focus on the experimental insights of your study or adjust the model to include some kind of modification that reflects the snow structure evolution. The pure finding that the Craig&Gordon approach is not suitable to model snow isotope evolution is not new (Dietrich et al., 2023; Ollivier et al., 2025; Wahl et al., 2022) and since a few key variables were not measured in your experiments (surface temperature, ambient vapor) the model results are also subject to high uncertainties beyond just the model framework alone.

Specific comments:

- abstract: Include quantitative results in the abstract as descriptive terms like “high airflow”, “smallest isotopic change”, “porosity range” etc can be interpreted very differently depending on the background of the reader. Include the concrete numbers of your experiments.

- Methods: Include an initial paragraph in which you shortly outline the general set up and protocol followed in the experiments before you describe the individual components in detail. For example describe that the three petri dishes were filled shortly before the experiments, then placed in the wind tunnel next to each other, etc…

- Methods: Include a description of the time components in your methods section. Within which time window were the experiments performed? Were the petri dishes prepared all at once, or only shortly before placing them inside the wind tunnel. You refer to “fresh snow” throughout the manuscript but considering that each of the 8 experiments is running for 24 hours, the experiments were probably conducted over a period of 2 weeks or more. Was laboratory snow produced several times throughout this period, or only once and stored? All of these aspects are relevant for the snow structure.

- Fig 1: Include more details on the wind tunnel including dimensions. What are the black and white rectangles representing? Add labels to subplots. Add a reference that describes this C3 container in detail.

- Sec. 2.2.: Add a description of the snow microstructure following (Fierz et al., 2009) which does not require any sophisticated instrumentation. For example, old snow usually consists of larger grains whereas you describe it as “small rounded grains”. Please include some quantitative metrics here to make it less descriptive.

L. 180 ff: Give more quantitative details on the experimental conditions inside the wind tunnel using actual measured metrics. What does “generally uniform” mean? Give values for observed variability in temperature and humidity in each location and between locations inside the wind tunnel. Specify if the Fig 2 error bars are a measure of spatial or temporal variability.

- Are the relative humidity values given in the manuscript reported with respect to water or ice? Since this is influencing your VPD and the Craig and Gordon model results, it is important to use the one with respect to ice (Anderson, 1994; Murphy and Koop, 2005)

- L. 201: Give an estimate of the total uncertainty on the individual sample isotope value. “Instrumental accuracy” is only one source of uncertainty, additional you need to consider uncertainties in standards, instrument drift, repeatability of the instrument etc.. (Sodemann et al., 2023). Optimally you would report the total uncertainty of a "blind standard" that was measured alongside the samples to judge uncertainty. Since you are only reporting relative differences, you could also report the maximum observed standard deviation within the 4 injections that were used to calculate the final value as a minimal uncertainty value.

- L. 206 and Fig 4: I recommend removing one mass ratio metric. Since the two metrics do not show significantly different outcomes (L. 368-371) remove one to streamline the manuscript.

- Fig. 5: One has to notice that FS of Exp 1 and 2 are crucially defining the linear regression results. Please add a statement on the robustness of these linear trends when removing these 2 out of 24 datapoints?

- L. 437: The snow surface temperature is the driving end-member for both the "in-snow" VPD and the "above-snow" VPD (Fig S3) but since you have not measured it these calculations seem arbitrary. Instead consider estimating the sublimation rate with the mass lost, and the metamorphism rate with the T-gradient and some reasonable Specific Surface Area (SSA) based on density and grain shape characteristic. (Domine et al., 2007; Legagneux et al., 2002)

- L. 619 and 623-630 and 821: To me the argument about the missing history of snow structural evolution is not very convincing as the controlling variables will be microphysical properties such as SSA, tortuosity etc which are present at the initial experiment state and a previous or past structure status will not influence the evolution of the snow structure which is present at the beginning of the experiment. The argument that density/porosity are not sufficient to describe the present microphysical properties is convincing, even though one would assume FS and LS should have similar characteristics compared to FS and OS and thus can not explain the LS anomaly either.

- Fig. 7: I suggest removing the "lab snow behaves anomalously" from the figure as I do not think it is the fact that this snow is produced in the lab, but that it has a certain characteristic that is different from the "natural snow" which can not be identified with the measurement techniques available. Several other studies have successfully used laboratory-produced snow to study snow processes.

- L. 777-779: This sentence (in the way it is formulated) is misleading. The melting and refreezing process in itself is a fractionating process which is why the snowmelt isotopic composition is enriched compared to the bulk isotopic composition (Taylor et al., 2001). Please rephrase so that it becomes clear that meltwater isotopic composition is the sum of melting & refreezing and sublimation fractionation processes.

- L. 784-789: Although I agree that the presented study points to structural control on the sublimation-fractionation magnitude, I would argue that, for hydrological applications, other variables such as internal snowpack isotope variability, catchment scale variability and melt-fractionation processes will contribute higher uncertainties to hydrological modeling results than snow structure control on the sublimation effect. Besides, the Ala-Aho 2017 “single calibration parameter” would incorporate all of the fractionation-influencing processes in the one fitted parameter.

Technical corrections:

- add subplot labels in all of your figures, also in the supplementary Material
- L. 163: What does representative sub-sample mean? How many were collected and how did you ensure “representativity”?
- L. 176: give a range of Temperature-gradients (unit K/m) in your experiments and include it in the data table (S T1)
- L. 235: It is clear that the snow sample is not a “well-mixed reservoir” which is also why you included the “time stepping” Craig-Gordon model. Please reformulate.
- L. 258: replace “vapor removed” with “sublimated snow” or similar

L. 284: replace “residual enrichment” with “relative model error” or so which makes it clearer (since depending on which sample is the reference you can also have negative differences).
- L. 294: Include “To” at the beginning of line.
- L. 314: replace “produced” and “yielded” with “lost” or similar
- Fig.3 : Include error bars on d, e, and f and add second axis on b with densities, since this is the metric that was measured.
- L. 383: include reference to Fig.5 here.
- L. 428: convert to Temperature gradient (unit K/m) estimates
- L. 505: I do not understand the meaning of this sentence, Please reformulate.
- L. 554, 555: cite (Casado et al., 2021; Harris Stuart et al., 2023) here
- L. 570: cite (Wahl et al., 2024) here
- L. 762: Cite (Harris Stuart et al., 2023) here
- L. 767: Exchange the (Wahl et al., 2022) citation with (Dietrich et al., 2023) and rephrase sentence accordingly

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