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.

We thank the reviewer for the constructive assessment of our manuscript. The reviewer's comments are reproduced in blue, while our responses are provided in black.

The revised manuscript places the influence of snow structure within the broader context of sublimation, initial snow–vapour isotopic disequilibrium, temperature-gradient metamorphism, and internal isotope redistribution.

We have removed the Craig–Gordon modelling and refocused the manuscript on the experimental results. We have also strengthened the quantitative description of the experimental conditions and their spatiotemporal variability. In addition, we clarified the sample preparation, and storage procedures. Finally, we incorporated two additional experiments as an independent constraint on internal isotope redistribution and atmospheric sublimation (Appendix A).

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)

The differences in initial snow–vapour isotopic disequilibrium could have contributed to the contrasting sublimation responses of the natural snow samples (FS and OS) and the laboratory-produced snow (LS). Across EXP1–8, the mean initial $\delta^{18}O$ difference was approximately 10.1‰ between FS and LS and 8.4‰ between OS and LS, whereas FS and OS differed by only approximately 1.7‰. Because the isotopic composition of the interacting atmospheric vapour was not measured, we cannot quantify how much these differences in initial isotopic state contributed to the observed response.

However, the differences in isotopic response do not simply follow the magnitude of the initial isotopic differences. FS showed greater $\delta^{18}O$ enrichment than LS in all eight experiments, with FS–LS enrichment differences ranging from +0.22 to +2.49‰ and averaging +1.04‰. In contrast, the OS–LS enrichment differences were much smaller, ranging from −0.20 to +0.80‰ and averaging only +0.20‰, despite the large initial $\delta^{18}O$ difference between OS and LS. At the same time, FS and OS had much more similar initial isotopic compositions, yet FS showed greater $\delta^{18}O$ enrichment than OS in all eight experiments, with differences ranging from +0.22 to +1.86‰ and averaging +0.84‰.

We therefore consider initial snow–vapour isotopic disequilibrium a plausible and potentially important contributor to the observed differences. However, the pairwise comparisons show that the magnitude of the initial isotopic contrast alone does not explain the magnitude of the subsequent isotopic response. We have revised the discussion accordingly.

- 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)

We have expanded the Introduction to define temperature-gradient metamorphism (TGM) and revised the Discussion to clarify its physical connection to surface sublimation, drawing on Harris Stuart et al. (2023), Wahl et al. (2024), and Ollivier et al. (2025). Under TGM, sublimation from relatively warm ice surfaces, vapour transport through the pore space, and deposition on colder surfaces produce internal ice turnover and microstructural evolution. Surface sublimation occurs simultaneously but removes vapour from the snow to the atmosphere. We therefore interpret the retained isotope signal as reflecting the combined influence of internal sublimation–transport–deposition and atmospheric vapour removal.

We added Figure R1 comparing imposed thermal forcing, measured net sublimation rate, and isotope response across EXP1–10. An experiment-specific metamorphism-to-sublimation rate ratio cannot be determined from the available measurements. Atmospheric mass loss quantifies net removal from the sample, while recrystallization includes simultaneous internal ice loss and growth. Quantifying gross turnover would require time-resolved microstructural observations, supported by internal snow-temperature measurements. We therefore compare the measured quantities and provide laboratory and field context while leaving the relative rates unresolved.

In our experiments nominal base-to-air gradients ranged from approximately 55 to 1000 K $m^{-1}$. These values were calculated from the base-plate and tunnel-air temperatures across the nominal 2 cm snow depth. Internal snow temperatures were not measured, so the magnitude and vertical distribution of the internal gradients remain uncertain. Previous laboratory studies show faceting and depth-hoar development at 10–100 K $m^{-1}$ and internal ice turnover of up to 60% per day at 50 K $m^{-1}$ (Dick et al., 2026; Pinzer et al., 2012). Comparable rapid evolution occurs in natural near-surface snow: Fukuzawa and Akitaya (1993) measured a mean gradient of 159 K $m^{-1}$ with crystal-size growth of $1.65 \times 10^{-9}$ m $s^{-1}$ and depth-hoar development over two nights. Their complementary laboratory experiments also demonstrated rapid crystal growth under gradients of 100–300 K $m^{-1}$. Our nominal forcing therefore overlaps conditions supporting rapid metamorphism and extends considerably above these examples, supporting the plausibility of appreciable microstructural evolution during our approximately 24 h experiments.

EXP9 and EXP10 included three exposed and three covered samples under zero and high forced airflow, respectively. The upper and lower 1 cm were analysed separately to examine vertical isotope structure. Within approximately 24 h, covered lower-layer $\delta^2H$ increased by 0.79‰ in zero-airflow EXP9 and 0.98‰ in high-airflow EXP10, while upper-layer $\delta^2H$ changed by −1.28‰ and −0.08‰, respectively. The resulting upper-minus-lower contrasts were −2.07‰ and −1.06‰, showing that the vertical pattern consistent with internal redistribution persisted in covered snow under both

experimental airflow regimes. This pattern agrees with the direction of redistribution described by Sturm and Benson (1997), who reported basal $\delta^2H$ enrichment of 12–30‰ relative to equivalent snow layers on elevated tables and upper-layer depletion of 10–30‰ in seasonal subarctic snow. In our exposed samples, upper-layer $\delta^2H$ enrichment decreased from 11.14‰ in EXP9 to 6.33‰ in EXP10, while lower-layer enrichment decreased from 1.86‰ to 1.34‰. Thus, high-airflow EXP10 produced approximately 43% less upper-layer enrichment despite greater atmospheric mass loss, following the EXP1–8 pattern of weaker isotopic modification under stronger airflow.

- 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.

We have removed the Craig–Gordon analysis from the revised manuscript because key boundary conditions, particularly snow-surface temperature and ambient vapour isotopic composition, were not measured.

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.

We have therefore revised the Abstract to include quantitative information on the experimental conditions.

- 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...

We have added details that summarizes the overall experimental protocol and the individual components of the setup. For each experiment, 12 Petri dishes were then filled sequentially from the stored snow materials and placed directly on the temperature-controlled base (Figure R2). Once all dishes were positioned, the upper wind-tunnel section was installed, and the experiment was initiated. The 12-dish design allowed samples to be collected at different stages during each run. Sampling at each stage was completed in less than 1 min to minimize disturbance of the experimental conditions. The revised manuscript now also presents the intermediate isotope measurements to illustrate temporal evolution, while the initial-to-final change remains the primary metric used for quantitative comparison among experiments and snow types.

- 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.

The three snow materials were obtained once before the experimental series and the same stored material was used throughout all eight experiments. Fresh natural snow and old natural snow were collected once, and the laboratory snow was produced once before the campaign. Between experiments, all three snow types were stored in airtight, insulated containers to minimize exchange with the surrounding air and limit alteration during storage. The Petri dishes were not prepared in advance; they were filled shortly before each experiment.

- 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.

We have revised Figure 1 and its caption to provide additional details and added labels to the individual subpanels.

Regarding the requested reference, a dedicated technical study describing the C3 facility in detail is currently being prepared and is not yet available for citation. We have therefore expanded the description of the experimental facility in Section 2.1 to provide the necessary information within the present manuscript.

- 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.

We have revised Section 2.2 using the terminology of Fierz et al. (2009), where supported by our observations. Fresh natural snow (FS) is described as predominantly dendritic precipitation particles, while laboratory-produced snow (LS) is described as consisting predominantly of columnar and plate-like ice crystals. Old natural snow (OS) was collected from the basal part of the seasonal snowpack and is described as an aged, metamorphosed snow layer.

We agree that our previous description of OS as consisting of “small rounded grains” was inappropriate. The term “small” was subjective and was not supported by systematic grain-size measurements, so this wording has been removed.

The three snow materials were collected or produced once before the experimental series and stored between experiments. Grain-size and morphology analyses were not repeated before each individual experiment. Consequently, possible microstructural evolution during storage cannot be quantified, and a detailed experiment-specific classification following Fierz et al. (2009) cannot be assigned retrospectively. To provide quantitative structural information, we rely on the measured bulk densities and porosities for all three snow types.

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.

We have revised the presentation of the experimental conditions to provide quantitative information on both temporal and spatial variability within the wind tunnel.

Revised Figure R3 shows the mean temperature and relative humidity measured separately at the inlet, midpoint, and outlet during each experiment. The error bars in Figure R3 represent ±1 SD of the temporal variability measured at each individual sensor location over the duration of the experiment. The surrounding-container measurements are shown separately.

We additionally added Figure R4 to quantify temporal and spatial variability explicitly. Tunnel temporal variability was calculated as the standard deviation through time of the mean of the inlet, midpoint, and outlet measurements. Tunnel spatial variability was calculated as the standard deviation among the experiment-mean values at the three sensor positions.

Across EXP1–EXP10, tunnel temperature temporal variability ranged from 0.39 to 3.01 °C and spatial variability from 0.10 to 1.19 °C. Relative-humidity temporal variability ranged from 2.70 to 11.78 percentage points and spatial variability from 0.58 to 4.35 percentage points.

- 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)

Yes. Relative humidity is reported with respect to ice, and we have clarified this in the revised Methods and updated the notation throughout.

- 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.

Samples were analysed in five analytical runs. TAP and VIRO reference standards were measured repeatedly throughout each run and used for normalization to VSMOW2 and to monitor calibration stability. Each sample was injected seven times; the first three injections were discarded, and the mean of the remaining four was reported.

Analytical uncertainty was estimated from the uncertainties of the independently characterized reference standards and measurement repeatability. The mean standard uncertainties of TAP and VIRO were 0.12‰ for $\delta^{18}O$ and 0.57‰ for $\delta^{2}H$. The maximum standard deviation among the four retained injections was 0.12‰ for $\delta^{18}O$ and 0.90 ‰ for $\delta^{2}H$. Combining the stated reference-standard uncertainties and the maximum within-sample injection SDs in quadrature yielded uncertainty estimates of 0.17‰ for $\delta^{18}O$ and 1.07‰ for $\delta^{2}H$.

Instrument drift was monitored through repeated TAP and VIRO measurements throughout the analytical runs, with calibration updated accordingly. The maximum residual deviations of the calibrated standards from their assigned values were 0.092‰ for $\delta^{18}O$ and 0.959‰ for $\delta^{2}H$.

- 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.

We have moved one of the normalization metrics to the Supplementary Material.

- 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?

We evaluated the influence of the FS observations from EXP1 and EXP2 using a sensitivity analysis. Figure 5 contains 24 observations in total, but it presents separate regressions for individual snow types (n = 8 each), the combined natural-snow dataset (FS + OS; n = 16), and all snow types combined (LS + FS + OS; n = 24). We therefore assessed the FS-only and combined natural-snow relationships separately.

EXP1 and EXP2 contain the highest-porosity FS observations. Removing them narrows the FS porosity range from approximately 0.71–0.81 to 0.71–0.74, T. This narrow porosity range limits the ability to resolve a relationship.

For the combined natural-snow dataset (FS + OS), after removing the two FS observations the relationships with absolute isotopic change weakened but remained statistically significant: $\Delta\delta^{18}O$, $r = 0.76$, $p = 0.0017$; $\Delta\delta^{2}H$, $r = 0.71$, $p = 0.0041$; and $\Delta$d-excess, $r = -0.60$, $p = 0.0232$. The two observations therefore strengthen, but do not solely determine, the associations between porosity and absolute isotopic change across the natural-snow dataset.

The mass-normalized relationships were less robust. In the complete natural-snow dataset (FS + OS; n = 16), porosity was significantly related to $\Delta\delta^{18}O$ per gram ($r = 0.539$, $p = 0.0311$) and $\Delta$d-excess per gram ($r = -0.648$, $p = 0.0066$), whereas its relationship with $\Delta\delta^{2}H$ per gram was not significant ($r = 0.417$, $p = 0.108$). After excluding FS from EXP1 and EXP2 (n = 14), none of these relationships remained significant: $\Delta\delta^{18}O$ per gram, $r = 0.232$, $p = 0.424$; $\Delta\delta^{2}H$ per gram, $r = 0.231$, $p = 0.427$; and $\Delta$d-excess per gram, $r = -0.193$, $p = 0.508$.

We have revised the manuscript accordingly.

- 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)

We agree that the previous separation of “in-snow” and “above-snow” VPD is poorly constrained because snow-surface temperature was not measured. We have therefore removed the VPD-based analysis.

Net sublimation rates are calculated directly from the measured mass loss and ranged from approximately 0.11 to 0.88 g $h^{-1}$ across EXP1–8.

We also considered the reviewer's suggestion to estimate metamorphism rates from the imposed thermal forcing and literature-based SSA values following Domine et al. (2007) and Legagneux et al. (2002). However, we do not consider an experiment-specific metamorphism rate sufficiently constrained by our measurements. The internal snow-temperature profile was not measured, so the base-to-air temperature difference provides only a boundary-gradient proxy. In addition, SSA was not measured directly, and grain size and morphology were not characterized immediately before each experiment. Because the snow materials were stored between experiments, possible microstructural evolution during storage also cannot be quantified.

We therefore do not assign literature-based SSA values to individual experiments or calculate a metamorphism/recrystallization rate. Instead, as described in our response to the major comment on temperature-gradient metamorphism, we compare the measured net sublimation rate, imposed thermal forcing, and isotopic response across experiments. This comparison is summarized in Figure R1 and is further constrained by EXP9–10, where covered and exposed samples provide an additional constraint on the relative contributions of internal redistribution and atmospheric mass loss.

Metamorphism is therefore discussed as a concurrent process involving internal sublimation, vapour transport and deposition, while its rate is not quantified because the required internal temperature and time-resolved microstructural measurements were not available.

- 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.

We agree that the microphysical state at the beginning of the experiment is more relevant than the previous structural history of the snow, and we have removed the latter argument from the revised manuscript.

We also agree that bulk density and porosity alone are insufficient to explain the different LS response. Although FS and LS had relatively similar bulk porosities, they likely differed in crystal morphology, and potentially in SSA, tortuosity, pore connectivity, and permeability, none of which were measured directly. We therefore cannot assume that similar bulk porosity implies similar microphysical transport properties.

In addition, LS differed strongly in initial $\delta^{18}O$ from both FS and OS, by approximately 10.1‰ and 8.4‰, respectively, so differences in snow–vapour isotopic disequilibrium may have contributed to its response. However, this cannot explain the full pattern. OS and LS also had a large initial isotopic difference, yet their subsequent $\delta^{18}O$ enrichment differed by only about 0.20‰ on average. Conversely, FS and OS had much more similar initial isotopic compositions, but FS enriched more strongly than OS in all eight experiments, by about 0.84‰ on average.

We therefore no longer attribute the LS behaviour to snow structural history. Instead, we interpret it as potentially reflecting the combined influence of initial isotopic state and unresolved microphysical

properties that are not captured by bulk density or porosity alone. Because ambient vapour isotopic composition and properties such as SSA, tortuosity, and pore connectivity were not measured, their individual contributions cannot be separated.

- 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.

We have removed the statement "lab snow behaves anomalously" from Fig. 7 and the corresponding discussion. Our results show that laboratory-produced snow exhibited a different isotopic response from FS and OS that cannot be attributed to a single measured property.

As discussed in response to the related major comment, LS differed from the natural snow samples in both initial isotopic composition and potentially in unresolved microphysical properties such as SSA, tortuosity, pore connectivity, and permeability, which were not measured directly. Bulk porosity alone did not explain the observed differences, and the ambient vapour isotopic composition was not measured, so the contribution of initial snow–vapour disequilibrium also cannot be quantified independently.

We therefore revised Fig. 7 and the text to describe LS simply as showing a weaker or distinct isotopic response under the experimental conditions, without attributing that behaviour to its laboratory origin.

- 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.

We have rephrased this section to acknowledge that meltwater isotopic composition reflects the combined effects of fractionation during melting and refreezing (Taylor et al., 2001) and sublimation-induced fractionation, rather than attributing meltwater isotopic enrichment solely to sublimation.

- 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.

Our experiments show snow-type-dependent and porosity-associated differences in isotopic modification, but they do not establish that this effect is a dominant source of uncertainty in catchment-scale isotope modelling. Internal snowpack isotope variability, spatial variability across a catchment, and isotope effects associated with melt and refreezing can all introduce substantial additional variability. We have therefore revised this section to present snow-structure effects as an additional process contributing to post-depositional isotope modification, without implying that they dominate hydrological-model uncertainty. We also agree that the calibrated fractionation parameter

used by Ala-Aho et al. (2017) can effectively integrate several fractionation processes into a single empirical parameter. Our results do not challenge the usefulness of such an approach. They indicate that the effective sublimation-related fractionation represented by such a parameter may vary with snow state and environmental conditions.

Technical corrections:

- add subplot labels in all of your figures, also in the supplementary Material

We have made this change in the revised manuscript.

- L. 163: What does representative sub-sample mean? How many were collected and how did you ensure "representativity"?

For each experiment, one initial isotope sample was collected for each snow type immediately before the Petri dishes were filled. The sample was taken from the same stored snow batch used to fill the four dishes of that snow type and was used as the initial isotopic reference for those dishes. We did not independently quantify within-batch isotopic heterogeneity. We have revised the Methods accordingly.

- L. 176: give a range of Temperature-gradients (unit K/m) in your experiments and include it in the data
We have made this change in the revised manuscript.

- 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.

We have removed this section

- L. 258: replace "vapor removed" with "sublimated snow" or similar

We have removed this section.

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).

We have removed this.

- L. 294: Include "To" at the beginning of line.

We have made this change in the revised manuscript.

- L. 314: replace "produced" and "yielded" with "lost" or similar

We have made this change in the revised manuscript.

- 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.

We have made this change in the revised manuscript.

- L. 383: include reference to Fig.5 here

We have made this change in the revised manuscript.

- L. 428: convert to Temperature gradient (unit K/m) estimates

We have made this change in the revised manuscript.

- L. 505: I do not understand the meaning of this sentence, Please reformulate.

We rephrased the sentence

- L. 554, 555: cite (Casado et al., 2021; Harris Stuart et al., 2023) here

Added

- L. 570: cite (Wahl et al., 2024) here

Added

- L. 762: Cite (Harris Stuart et al., 2023) here

Added

- L. 767: Exchange the (Wahl et al., 2022) citation with (Dietrich et al., 2023) and rephrase sentence accordingly

We have made this change in the revised manuscript.

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**Appendix A. Additional covered–exposed experiments**

EXP9 and EXP10 were follow-up process experiments conducted after completion of the main EXP1–EXP8 series to provide additional constraints on internal isotope redistribution and surface atmospheric exchange. At that stage, the remaining available snow consisted of a mixture of fresh and laboratory-produced snow rather than a single defined snow type. Consequently, EXP9 and EXP10 were not part of the original snow-type comparison and were analysed separately from EXP1–8. They were not included in the original submission but are included here because they provide an additional process constraint on the mechanisms discussed in the revised manuscript.

For each experiment, six Petri dishes were prepared from the mixed snow. Three dishes were left exposed to the wind-tunnel atmosphere, while three were covered with Petri-dish lids. The lids were not airtight and therefore strongly reduced, but did not completely prevent, vapour exchange with the overlying air. EXP9 was conducted under zero airflow, whereas EXP10 was conducted under high airflow.

At the end of each experiment, the remaining snow in each Petri dish was sampled separately from the upper 1 cm and lower 1 cm of the approximately 2 cm snow layer. These depth-resolved samples were analysed for $\delta^{18}O$ and $\delta^{2}H$, with d-excess calculated from the measured isotope values. Changes were evaluated relative to the initial isotopic composition of the mixed snow used in each experiment. This

comparison assumes that the snow was vertically isotopically homogeneous at the start of EXP9 and EXP10.

Both experiments were subjected to very strong imposed thermal forcing. he temperature-controlled aluminium base plate was maintained near −1 °C while the overlying tunnel air was much colder, giving boundary-gradient proxies of ~920 K $m^{-1}$ in EXP9 and ~1000 K $m^{-1}$ in EXP10. These values describe the imposed base–air thermal forcing and should not be interpreted as measured internal snow-temperature gradients.

The covered–exposed design was used to assess whether isotope redistribution within the snow persisted when direct atmospheric sublimation was strongly reduced. Covering decreased net mass loss by more than 90% in both experiments. Despite this reduction, isotopic differences developed between the top and bottom 1 cm of the covered snow. In contrast, the exposed samples showed clear enrichment of $\delta^{18}O$ and $\delta^{2}H$ in the top 1 cm together with lower d-excess. The isotope response in the exposed top layer was stronger in zero-airflow EXP9 than in high-airflow EXP10, despite greater mass loss in EXP10.

These experiments therefore provide an additional constraint consistent with internal isotope redistribution persisting when atmospheric mass loss is suppressed, while the additional enrichment in exposed samples is consistent with a surface-sublimation imprint superimposed on internal redistribution.

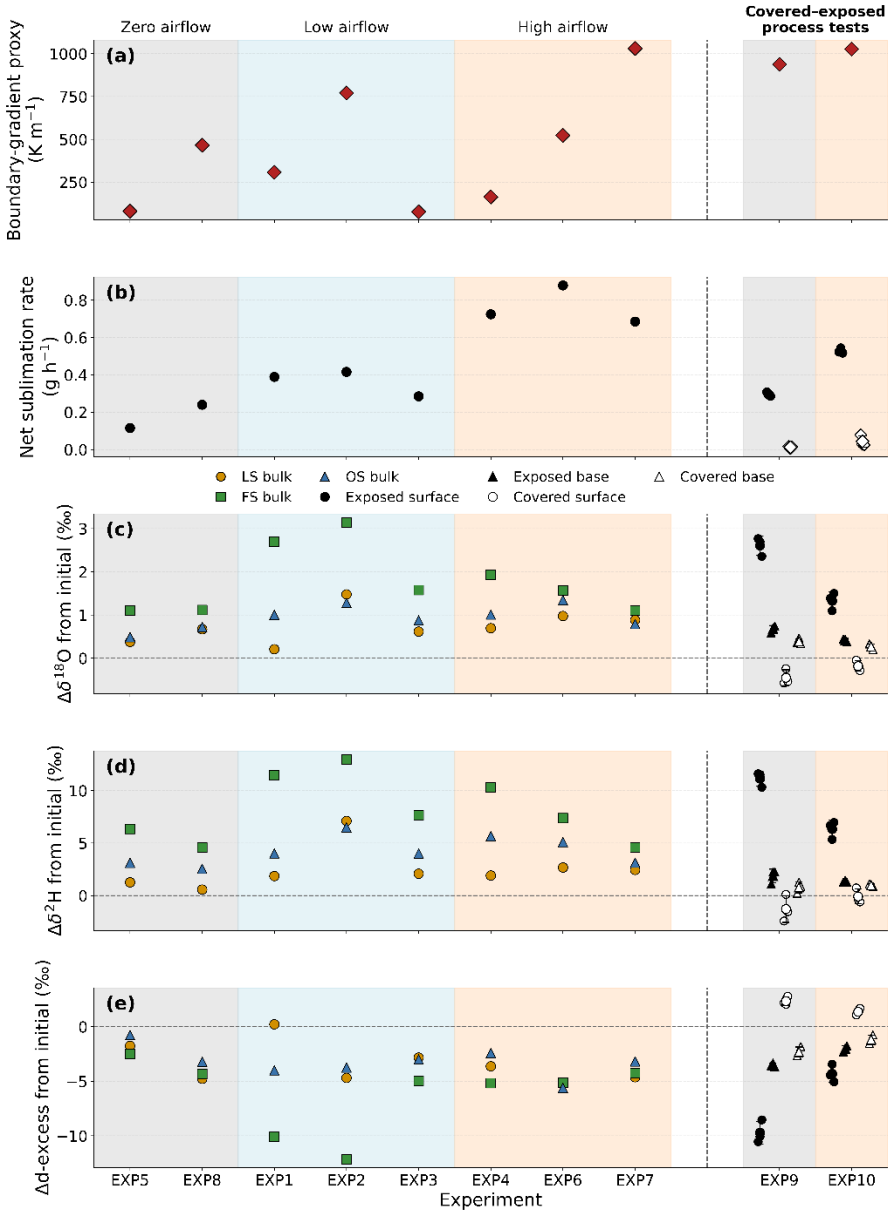



**Figure R1 (a) Imposed temperature-gradient proxy, calculated from the temperature difference between the base and mean tunnel air over the 2-cm snow depth. (b) Net sublimation rate derived from measured mass loss. For EXP9–10, individual exposed and covered replicates are shown together with mean ± SD. (c–e) Changes in $\delta^{18}O$, $\delta^{2}H$, and d-excess relative to the measured initial composition. For EXP1–8, symbols show final bulk minus initial composition for laboratory snow (LS), fresh snow (FS), and old snow (OS). For EXP9–10, symbols show upper- and lower-1-cm isotopic compositions relative to the initial snow for exposed and covered treatments; individual replicates and mean ± SD are shown. Interpretation of EXP9–10 relative to the initial composition assumes that the snow was vertically isotopically homogeneous at the start of each experiment. Background shading denotes zero-, low-, and high-airflow conditions; EXP9 and EXP10 are covered–exposed process experiments conducted under zero and high airflow, respectively.**

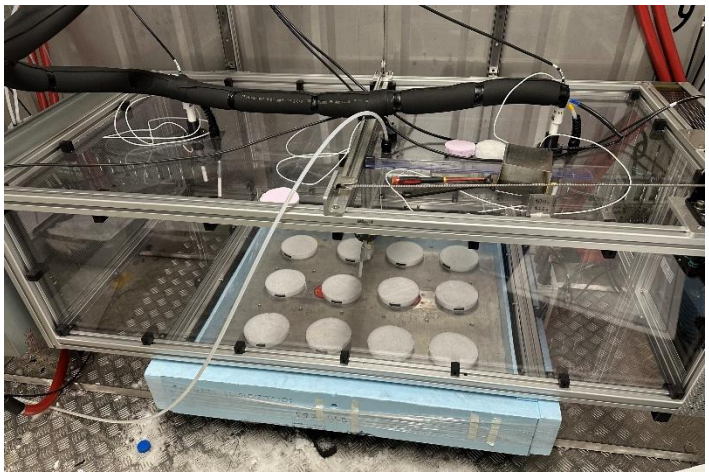


**Figure R2 Photograph of the wind-tunnel setup before initiation of an experiment. Twelve Petri dishes (four per snow type) were arranged on the temperature-controlled aluminium base plate inside the wind tunnel. The dishes were filled shortly before each experiment after the target thermal conditions had been established.**

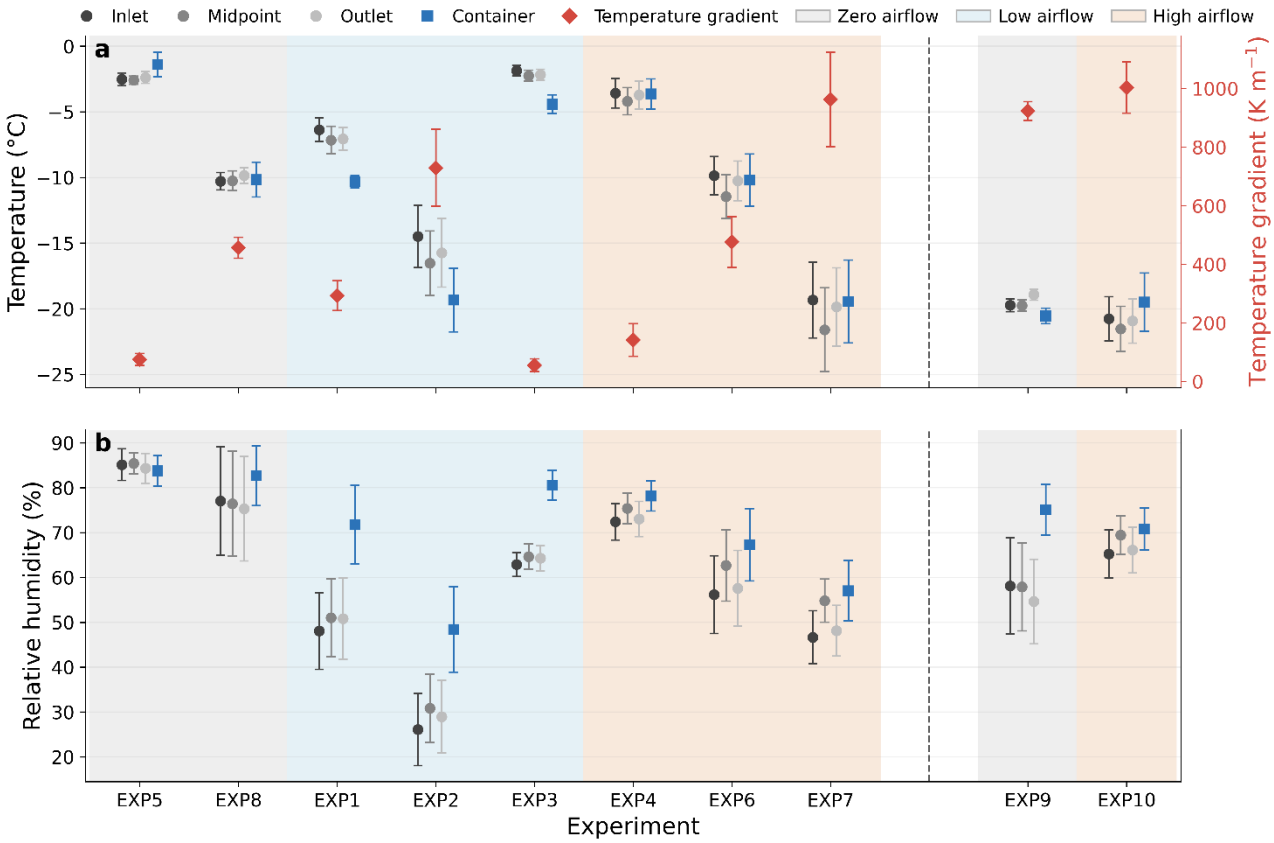



**Figure R3. Atmospheric and thermal conditions during EXP1–EXP10. The upper panel shows mean air temperature measured at the wind-tunnel inlet, midpoint, and outlet, together with the mean temperature in the surrounding container. The lower panel shows the corresponding relative humidity. Error bars indicate ±1 SD of temporal variability over each experiment. Background shading groups experiments by airflow regime: zero airflow (0 m/s), low airflow (0.7 m/s), and high airflow (~3 m/s). Red diamonds in the upper panel show the nominal temperature-gradient magnitude calculated from the difference between the −1 °C base-plate temperature and mean tunnel air temperature across the 2 cm snow depth; error bars reflect combined spatial and temporal variability in tunnel air temperature.**

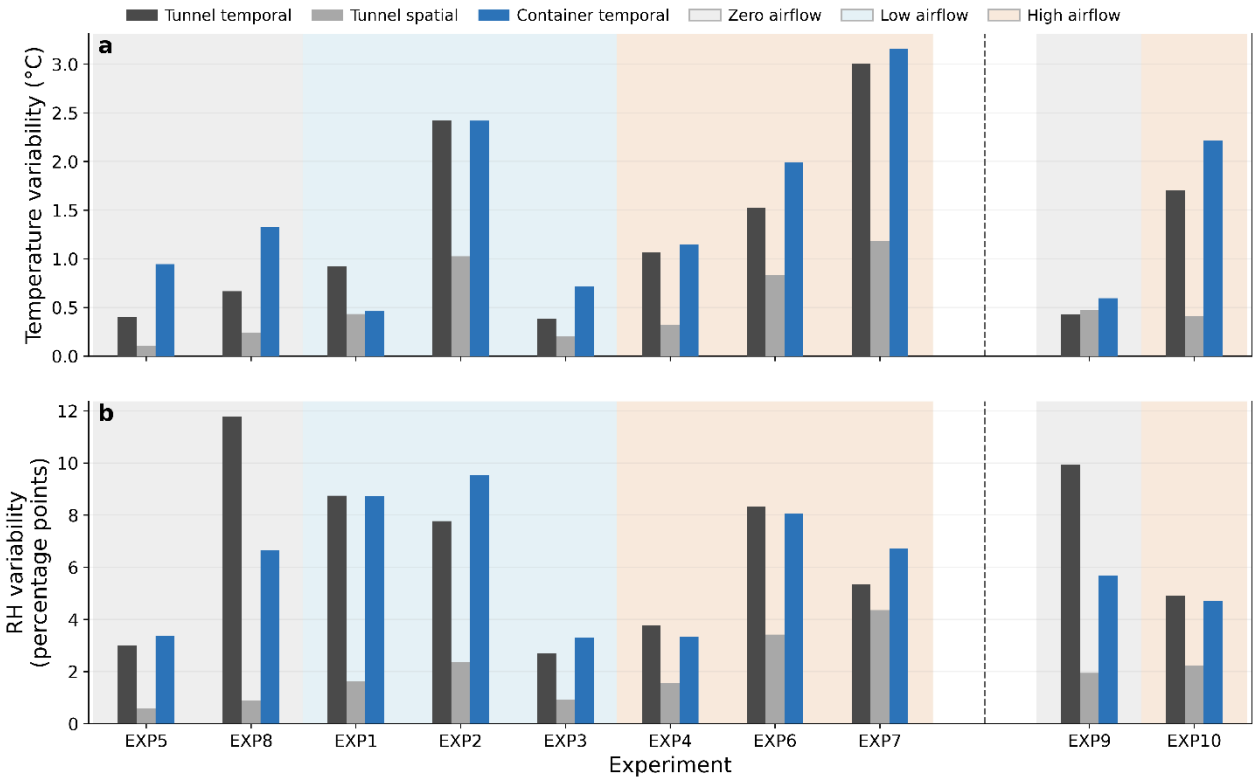



**Figure R4 Spatial and temporal variability in temperature and relative humidity during EXP1–EXP10. The upper panel shows temperature variability and the lower panel shows relative-humidity variability. Tunnel temporal variability was calculated as the standard deviation through time of the mean of the inlet, midpoint, and outlet sensors. Tunnel spatial variability was calculated as the standard deviation among the experiment-mean values of the three tunnel sensor positions. Container temporal variability represents the standard deviation through time measured by the single sensor in the surrounding container; spatial variability is therefore not available for the container. Background shading groups the experiments by airflow regime.**