Review of EGU-2025-2724: "Isotopic Stratification and Non-Equilibrium Processes in a Sub-Arctic Snowpack"

We thank the reviewer for the careful reading and constructive comments. Below, reviewer comments are shown in *italics*, and our responses are given in **blue text**.

Major comment:

I'm a bit concerned about the correctness of the measurement looking at the data in Figure 2 and 3. Your temperature measurement inside the snowpack (Figure 2) shows a minimum of around -4 degrees (corresponding to a saturation vapor concentration of around 4300 ppmv) but your concentration measurements with the Picarro (Figure 3) show a minimum of around 2700 ppmv. This would indicate that you have a relative humidity of only 65% inside the pore space of the snow pack which is not possible. Do you have an explanation for this? The same for the ambient measurement, you measured the lowest temperature at 1.5m of around -20 degrees (corresponding to a saturation vapor concentration of around 1500 ppmv) but your lowest measured concentration was around 2500 ppmv. This would indicate that your ambient air was sometimes oversaturated. Or could it be that your Picarro sucked in ice/water particles or is the Campbell Scientific AP200 intake also used for the isotope vapor? Maybe you could provide a picture of the system in the supplement materials.

You claimed that the pore spaces of the snowpack was at saturation but I could not find any evidence in the data. Therefore, it seems like that either your setup was not leak-tight or there is an offset in the humidity measurement of your Picarro.

Response to major comment:

Our response is structured in three steps: first confirming that the system was leak-tight, then validating Picarro humidity against an independent RH sensor for ambient air, and finally explaining why undersaturation in the pore space is physically plausible.

Leak tightness of the sampling system was verified prior to measurements using a **pressure hold test**. Each sampling line was connected to a dry air cylinder, pressurized, and then isolated by closing the cylinder valve. With the line sealed, the internal pressure was monitored for 30 minutes while sequentially selecting each line via the multiplexer. The pressure remained stable throughout these tests, confirming that the sampling lines were leak-proof.

The Campbell Scientific AP200 inlet was indeed used for isotope vapor sampling, but the system was equipped with heated and insulated lines and terminated in downward-facing sintered frits (2.54 mm diameter, 10 µm pore size) to prevent entrainment of ice/water particles. This configuration minimizes the risk of *sucked in ice particles*. The picture of the setup is included now.

We verified the ambient air measurements against a co-located RH sensor at 1.5 m height within a radiation shield. Converting the Picarro L2130-i H_2O concentrations to relative humidity over ice using the Goff–Gratch formulation shows very good agreement with the independent RH sensor (R^2 = 0.91, RMSE = 5.3 %RH, mean bias = −2.2 %RH; Fig. 1a). A direct comparison in absolute humidity (ppmv) likewise demonstrates excellent consistency between the CRDS and the sensor (R^2 = 0.99, RMSE = 214 ppmv, mean bias = −116 ppmv; Fig. 1b). These validations confirm that there is no significant offset in the Picarro humidity measurement.

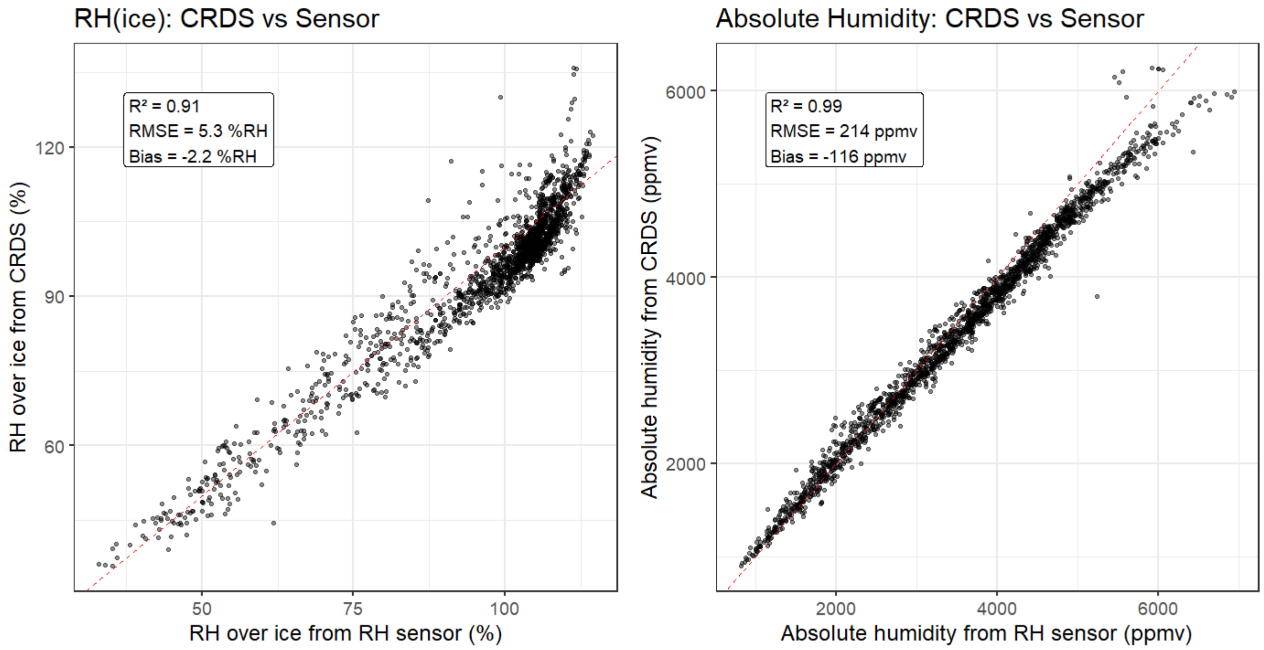

Figure 1 Comparison of humidity measurements from the Picarro L2130-i CRDS and a co-located independent RH sensor at 1.5 m height. (a) Relative humidity with respect to ice (RHice) derived from CRDS H_2O concentrations versus RHice from the RH sensor, converted from RH over liquid using the Goff–Gratch formulation. (b) Absolute humidity (ppmv) from the CRDS versus the sensor (converted from RHice and ambient temperature/pressure). The red dashed line indicates the 1:1 relationship. Statistics shown are coefficient of determination (R^2), root mean square error (RMSE), and mean bias (CRDS minus sensor). Both comparisons demonstrate very good agreement, confirming the absence of a systematic offset in the CRDS humidity measurements.

You are right to question our earlier statement that the snowpack pore space was saturated. That claim was based on buried RH sensors that were not heated. Since unheated RH sensors in snow are prone to frost deposition and tend to report near-constant values close to 100%, we do not rely on these measurements to assert saturation. We have removed this statement from the manuscript. The apparent undersaturation inside the snowpack is real rather than an artifact: laboratory and modelling studies have shown that deep snow layers can indeed be undersaturated relative to ice due to limited sublimation kinetics (e.g., Ebner et al., 2017; Bouvet et al., 2024). Our pore-space measurements therefore likely captured genuine undersaturation, however the saturation we observed was larger in magnitude than reported in those studies.

Importantly, prior studies of gas transport in snowpacks demonstrate that ventilation by barometric and wind-driven pressure fluctuations is an established process that operates on sub-hourly timescales. For example, Massman (1995) combined field data and modeling to show that turbulent pressure fluctuations penetrating a 2 m snowpack enhanced CO_2 fluxes by 19–31% above diffusion alone. In follow-up modeling, Massman (1997) showed that barometric and turbulence-driven oscillations can penetrate meters into the snowpack and drive advective velocities on the order of 10^{-4} m s^{-1}, with short-term fluxes deviating by up to ±25% from diffusion. Graham and Risk (2018) later confirmed in field observations that CO_2 concentrations inside a seasonal snowpack can drop by hundreds of ppm within hours during windy episodes, directly evidencing the timescale of ventilation events. These studies focused on CO_2 and other trace gases, which do not equilibrate with ice surfaces, but the physics of air exchange is the same for all pore-space gases. The key implication for our work is that pore air can be replaced by ambient air far faster than molecular diffusion or sublimation can re-establish local vapor equilibrium with ice. For H_2O vapor, this means that ventilation can continually import drier ambient air, maintaining undersaturation inside the snowpack. Thus, while CO_2 studies demonstrate the transport mechanism, our measurements show the water vapor consequence: persistent deviations of pore humidity from ice saturation are a physically plausible outcome of rapid ventilation.

In our original submission we had only considered wind-driven ventilation as the mechanism of pore-space exchange. Following the reviewer's comment and our re-analysis, we now explicitly include barometric pumping of ambient air into the snowpack as an additional process. As a baseline, we first evaluated diffusion timescales (Figure 2). Purely diffusive equilibration of pore-space vapor with the surrounding snow requires 3–12 hours depending on depth and snow conditions. This sets a relatively slow reference against which pressure-driven processes can be compared. By contrast, our new calculations of the pressure forcing required for ventilation (Figure 3) show that barometric pressure variations routinely exceed this threshold at both 5 and 15 cm, often by more than an order of magnitude. Wind-driven forcing alone only intermittently reaches the required ΔP, but when it does, it acts in concert with barometric oscillations to further enhance exchange.

Together, these results demonstrate that ventilation is physically feasible across much of the record, primarily through barometric pumping. This means that pore air was frequently mixed with intruding ambient air on sub-hourly timescales, far faster than diffusive equilibration could occur. Such a separation of timescales explains why persistent undersaturation developed in the pore space: intrusions of drier ambient air occurred more rapidly than sublimation from ice surfaces could replenish vapor toward saturation.

Diffusion timescales (Figure 2, Calculation procedure in Appendix A1).
The diffusion timescale provides a baseline reference for the characteristic time it takes water vapor molecules to traverse a given snow depth by molecular diffusion. This is critical because if natural forcings (wind or barometric pressure changes) act on shorter timescales than diffusion, then ventilation can outpace diffusive exchange and drive pore-space conditions away from equilibrium. Conversely, if natural forcings are slower than diffusion, then pore vapor has enough time to equilibrate, and deviations are less likely to persist. At the 5 cm basal intake, diffusion times were consistently longer than at 15 cm, because the effective path length to the surface was greater (L=snow depth−0.05m vs L = snow depth - 0.15m). Early in the season, diffusion times were ~5-6 hours at 5 cm compared to ~3-4 hours at 15 cm. As the snowpack accumulated diffusion times increased reaching ~12 hours at 5 cm and ~9-11 hours at 15 cm. Step increases in the curves coincide with snowfall events that increased snow depth, since t_diff grows with the square of the diffusion path length. The shaded bands reflect the uncertainty in tortuosity (τ = 1.1–1.4). This parameter affects the absolute magnitude of t_diff but does not change the overall seasonal pattern.

Why RH_ice < 100% is physically plausible in our record:

Reviewer raised the concern that our pore-space vapor concentrations imply relative humidities below ice saturation, which would seem contradictory to the expectation of fully saturated snowpack air. Here we explain why such undersaturation is physically plausible in our measurements.

Figure 3 compares the pressure gradients required to ventilate the snowpack pore space with the magnitudes of two natural forcing mechanisms: wind pumping and barometric oscillations. The analysis was conducted for lag times of 15, 30, and 60 minutes, which were chosen to represent short to intermediate exchange timescales relevant to pore–surface ventilation. These windows were derived from the underlying 5-minute observations of wind speed and barometric pressure, and are consistent with the temporal averaging applied to the isotopic dataset, which was aggregated to hourly resolution (see Methods in the original manuscript). By testing multiple lag lengths, the analysis brackets both transient and sustained forcing events that could influence vapor exchange in the snowpack.

Required ΔP (left column, Calculation procedure in Appendix A2):
The shaded brown envelopes represent the range of pressure differences needed to ventilate the snowpack, a range of realistic seasonal snow properties: Permeability: 10^{-11} to 10^{-7} m^2, Porosity (ϕ): 0.55 to 0.80 (Calonne et al., 2012). Tortuosity (τ): 1.1 to 1.4 (Lieblappen et al., 2020). On the log scale, the required values mostly fall between 10^{-2} and 10^{1} Pa. Shorter lag times (15 min) demand higher gradients, reaching up to ~10 Pa (10^{1} Pa), while longer lag times (60 min) require much less, often close to 10^{-2}–10^{-1} Pa. Seasonal changes shift the envelopes slightly, but lag time is the dominant control: as the equilibration window lengthens, progressively smaller pressure perturbations are sufficient.

Wind forcing (middle column, Calculation procedure in Appendix A3):
Dynamic pressure from wind events produces values that typically fall between 10^{-1} and 1 Pa, occasionally spiking toward 10 Pa during strong gusts. Compared to the required range, this means wind forcing can occasionally overlap with the ΔP needed for 15–30 min ventilation windows, but for much of the winter it remains too weak (≤10^{-1} Pa). Thus, wind pumping appears as an episodic driver of ventilation, tied to short bursts of strong wind.

Barometric forcing (right column, Calculation procedure in Appendix A3):
Oscillations in surface pressure are consistently large on the log scale, ranging from ~1 Pa (10^{0} Pa) up to >100 Pa (10^{2} Pa), and in some cases approaching 1000 Pa (10^{3} Pa). These magnitudes exceed the required ΔP envelopes across all lag times by more than an order of magnitude. Importantly, unlike wind, barometric oscillations are persistent rather than intermittent, providing a sustained mechanism for sub-surface ventilation throughout the season.

When viewed together, the log-scaled comparisons show a strong asymmetry: wind pumping provides sporadic pressure pulses that only sometimes reach the required 10^{0}–10^{1} Pa range, while barometric forcing is continuous and consistently exceeds the required ΔP by one to three orders of magnitude (10–1000 Pa vs. 0.01–10 Pa). However, whether this forcing translates into actual equilibration also depends on the diffusion timescales (Figure 2), which remain on the order of 6–12 hours in late winter. This helps explain why pore-space vapor in our Picarro measurements can remain undersaturated relative to equilibrium, even when external forcings appear more than sufficient.

Figure 4 provides a categorical, time-resolved view of ventilation feasibility under average snowpack conditions. Each vertical stripe indicates whether the available forcing (wind, barometric, or both) exceeded the required ΔP in 15, 30, or 60 min windows. Consistent with the magnitude-based comparison in Fig. 3, barometric oscillations dominate: exceedances are flagged almost continuously across the season (red). Wind forcing (green) rarely exceeds the threshold alone, but occasionally coincides with barometric events (purple). Grey intervals indicate times when neither mechanism was sufficient, which occur mainly at short lag windows (15 min). By 30–60 min windows, barometric oscillations alone are nearly always strong enough to ventilate the pore space. This barcode representation therefore provides a complementary, threshold-focused confirmation of the Fig. 3 result: ventilation is physically feasible primarily through barometric pumping, with wind playing only an episodic role.

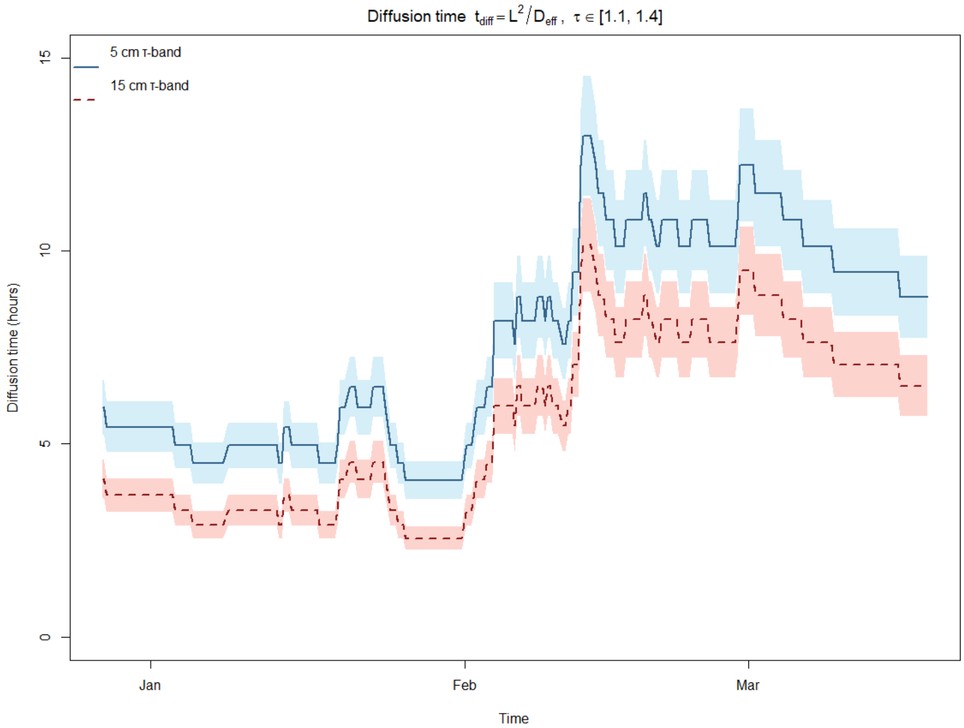

Figure 2 Estimated molecular diffusion timescales for pore-space vapor transport in the snowpack. Diffusion time was calculated as the squared transport distance divided by the effective diffusivity, where the latter accounts for a tortuosity range (τ = 1.1–1.4). Solid blue line = mean diffusion time for 5 cm depth, dashed red line = mean diffusion time for 15 cm depth. Shaded bands represent the range across the tortuosity values. Diffusion times are consistently longer at 5 cm than at 15 cm because of the greater distance to the snow–atmosphere interface. Temporal variability reflects evolving snow depth, with diffusion times spanning from ~3–5 hours in early winter to >10 hours during February–March. When compared to the forcing plots (Fig. 2), these diffusion times indicate that barometric pressure oscillations, which occur at sub-hourly to hourly scales, can easily outpace molecular diffusion and drive ventilation events.

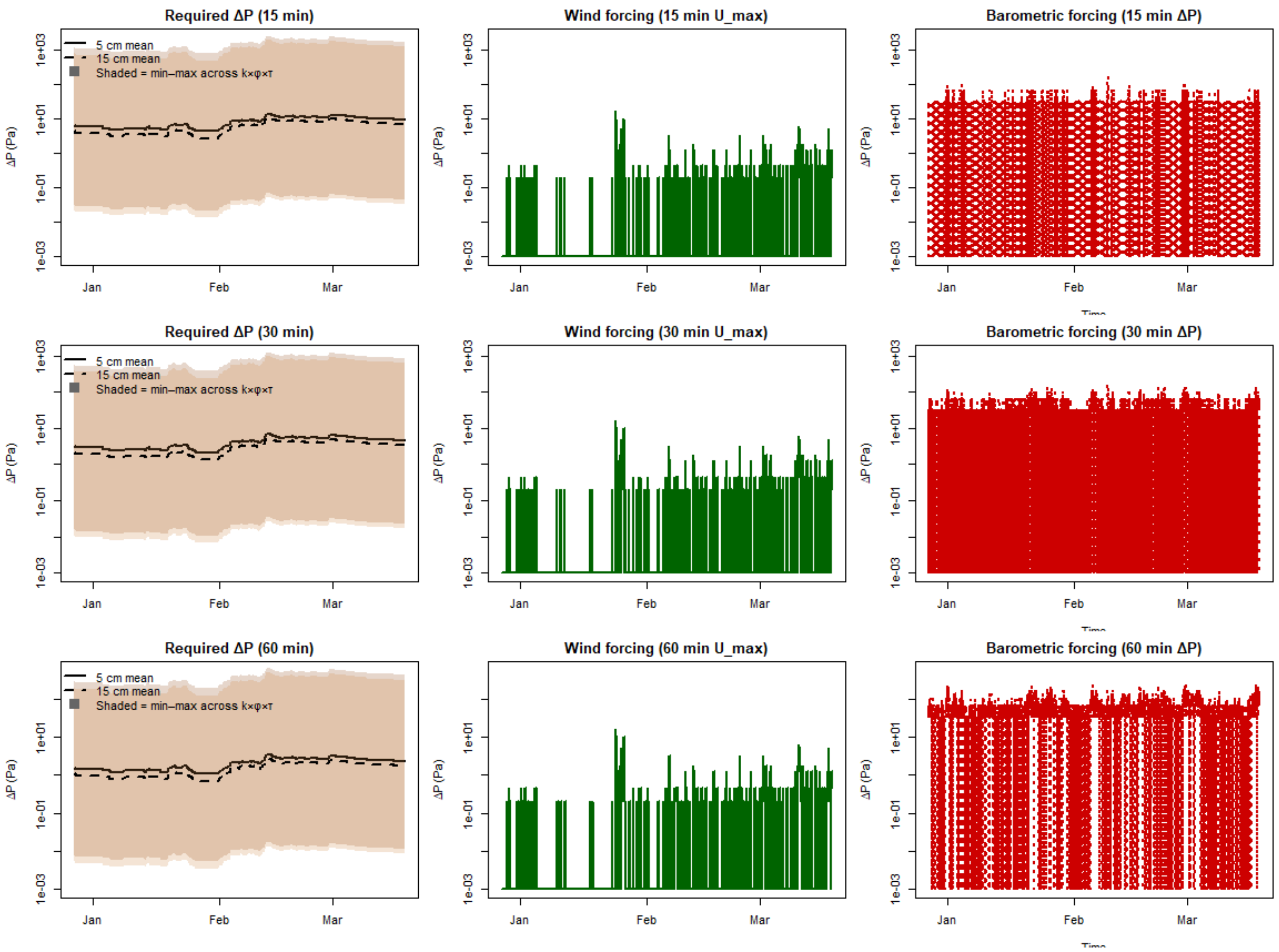

Figure 3 Comparison of required and observed pressure gradients for pore-space ventilation at 5 cm and 15 cm depth. Each row corresponds to a prescribed lag window of ***15 min*** *(top),* ***30 min*** *(middle), and* ***60 min*** *(bottom).* ***Left column (Required ΔP):*** *Pressure difference required to drive air advection across the snowpack depth within the lag window, calculated from Darcy's law using a broad range of snow properties. Shaded envelopes show the min–max range across property combinations. Solid black line = mean at 5 cm depth; dashed black line = mean at 15 cm depth. Shorter lag times correspond to higher required ΔP values.* ***Middle column (Wind forcing):*** *Dynamic pressure forcing estimated from maximum wind speeds in each lag window. Spikes correspond to gust events that drive strong but intermittent pressure loads.* ***Right column (Barometric forcing):*** *Pressure oscillations associated with barometric variability, quantified as the peak-to-trough swing within each lag window from atmospheric pressure measurements. All axes are log-scaled for ΔP. This side-by-side framework enables direct comparison of required versus available pressure forcing, illustrating when wind and barometric variability are sufficient to ventilate the snowpack faster than molecular diffusion (Figure 2).*

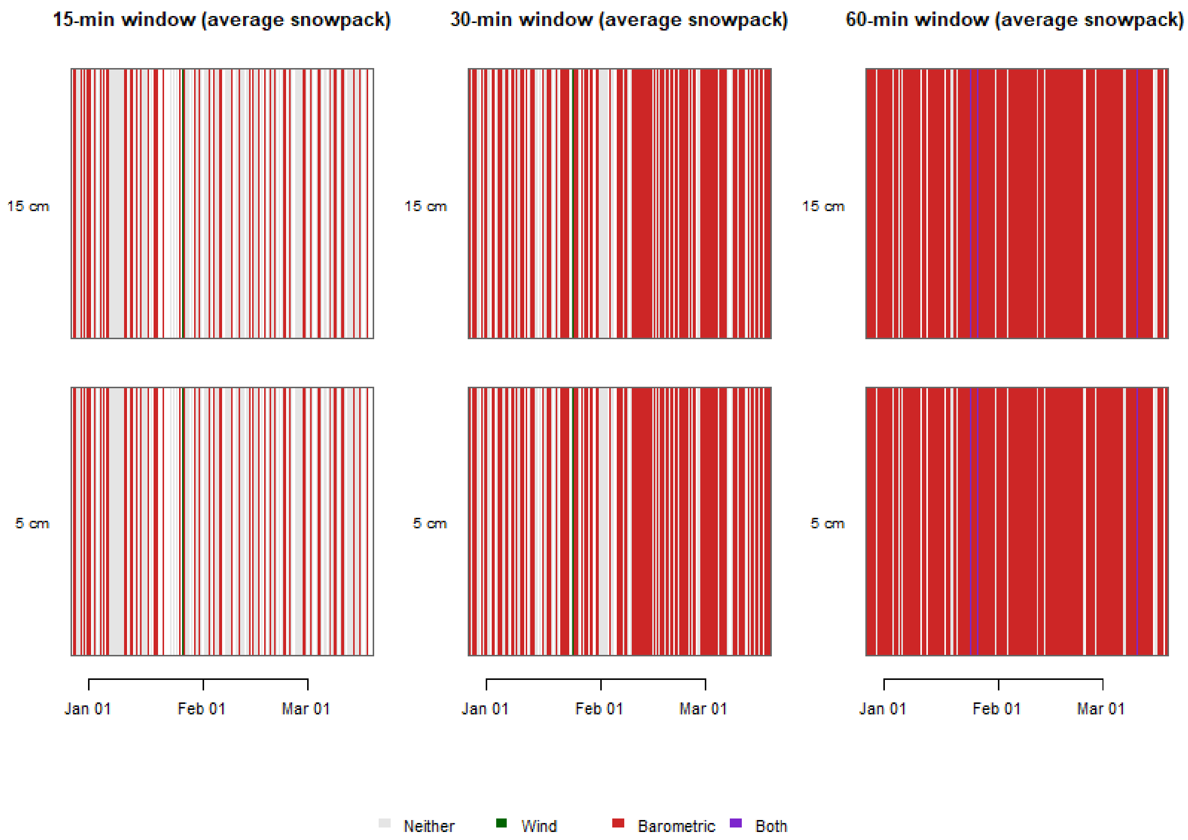

Figure 4 Categorical exceedance of required pressure gradients for ventilation under average snowpack conditions. Panels show 15, 30, and 60 min lag windows (columns) for pore-space intakes at 5 cm and 15 cm depth (rows). Colors indicate which forcing mechanism exceeded the required ΔP: barometric only (red), wind only (green), both (purple), or neither (grey). Results confirm that barometric oscillations alone are sufficient to drive ventilation across most of the record, particularly at longer windows, while wind pumping is only intermittently strong enough to contribute.

Sometimes you are talking about that vapor measurements were taken at 5 or 15 cm depth. This is a bit misleading because when you are talking about the depth some readers will see it as the distance from the surface into the snowpack. I would suggest to skip the 'depth' or call it 'height' to improve the readiness.

We thank the reviewer for pointing this out. In our setup, vapor intakes were positioned at fixed heights above the ground, not as distances below the snow surface. We agree that calling them "depths" is potentially misleading. We have revised the manuscript to use "height within the snowpack" (e.g. "5 cm height" and "15 cm height") throughout and clarified in the Methods that these are measured upward from the ground.

I'm missing important information to get a better understanding of the setup and to interpret the results. How did you check that your system is leak-tight and did you perform a humidity correction of the Picarro?

Leak-tightness: Prior to field deployment, each sampling line was connected to a dry air cylinder, pressurized, and isolated by closing the cylinder valve. Pressure in the sealed line was monitored for 30 minutes while sequentially switching lines via the multiplexer. No pressure decay was observed, confirming that all lines were leak-proof.

We did not apply a humidity correction to the Picarro data; instead, we validated the raw humidity measurements against a co-located RH sensor. This comparison showed very good agreement (R^2 = 0.91, RMSE = 5.3 %RH, mean bias = −2.2 %RH), confirming that no systematic offset was present. Details are provided in our response to the major comment. We will add details on both leak testing and clarified that humidity-isotope correction in the revised Methods.

I'm a bit concern about your comparison of your results between the three different periods (early, mid and late) because the snow depth is not constant and is changing up to 30 cm during the campaign. I would suggest to provide an explanation why you can still compare the different periods (especially about the data of the two intakes within the snowpack) with each other.

We agree that snow depth changed substantially during the campaign. However, the intake heights were fixed at 5 cm and 15 cm above ground, such that they remained within the snowpack throughout the entire measurement period, even as total depth increased. The intakes therefore sampled pore vapor air at consistent vertical positions relative to the ground.

While the overlying snow depth did vary, this primarily altered the boundary conditions above the intakes (e.g. thickness of snow cover, permeability to ambient exchange), rather than the absolute meaning of the intake heights. Thus, comparing the three periods provides insight into how changes in snowpack thickness and atmospheric forcing affected the same pore-space levels. We now clarify this in the revised Methods and Discussion and emphasize that our comparisons are made at fixed heights above ground, not relative to a shifting snow surface.

How do you justify that 15 cm is a mid-snowpack position for a snowpack depth of 90 cm?

We thank the reviewer for pointing this out. The intake heights were fixed relative to the ground (5 cm and 15 cm), and we mistakenly described the 15 cm level as "mid-snowpack." We agree this wording is misleading, particularly during periods when total snow depth exceeded 50–90 cm. In the revised manuscript we now consistently describe the intakes as "5 cm" and "15 cm above ground level within the snowpack." We no longer refer to them as "mid-snowpack," but rather emphasize that they represent lower snowpack pore-space levels, with overlying snow depth varying over time.

I questioning the wind pumping effect on the isotope signal without knowing your spatial density profile of your snowpack. In addition, based on Figure 2 you measured a max. wind speed of 2 m/s and you are intakes are between 0.4m and 0.8m below the snowpack surface. For this condition I would not expect any significant ventilation inside the snow pack (see Colbeck et al., 1989). But without knowing your density profile of your snowpack it is hard to make a conclusion.

We acknowledge that we did not measure a snow density profile, and this limitation is now stated explicitly in the manuscript. Nevertheless, as outlined in our response to the major comment, we carried out a diffusion–ventilation analysis. This analysis shows that barometric pressure oscillations routinely exceeded the thresholds required for sub-hourly exchange supports our interpretation that ventilation events did occur despite modest wind speeds.

Specific Comments:

2) Methods

Line 115: Did you check your system for leaks? And did you do a humidity correction of the Picarro? It seems like that either your setup was not leak-tight or there is an offset in the humidity measurement of your Picarro. See major comments.

Yes, we checked the system for leaks prior to deployment using a pressure-hold test, which confirmed that the sampling lines were leak-tight. We did not apply a humidity correction to the Picarro data; instead, we validated the raw humidity measurements against a co-located RH sensor. This comparison showed very good agreement (R^2 = 0.91, RMSE = 5.3 %RH, mean bias = −2.2 %RH), confirming that no systematic offset was present. Details are provided in our response to the major comment.

Line 115: In Figure 2 you showed the snow depth. I would suggest to quickly mention it here with all the other parameters.

Done

Line 115: Is there a specific reason why you measured the isotopic composition at 5cm, 15cm and 1.5m above ground? I would suggest to provide a reason for it.

The 5 cm inlet was deliberately planned to monitor pore vapor near the basal snow. The 15 cm inlet, however, was unintentionally buried deeper than intended during an early-season snowstorm and was not repositioned, in order to avoid disturbing the snowpack structure. We had already noted this point in the limitations section of the original manuscript. Finally, the 1.5 m inlet was placed in ambient air to characterize atmospheric vapor this height was selected because ~1 m corresponds to the average historical snow depth at the site, ensuring that the inlet remained above the snowpack throughout the season.

Line 135-136: How did you make sure that the sensors did not get frozen during the measurements, especially your humidity sensor?

The ambient RH/temperature sensor at 1.5 m was installed in a radiation shield, which prevented frosting and ensured reliable measurements. For the buried RH probes at 5 and 15 cm, no active heating was applied to avoid disturbing the snowpack structure. As a result, these probes were prone to frost deposition and often reported near-constant values around 100% RH. Hence, the in-snow RH measurements were likely affected by frost. In the original manuscript we stated that the snowpack was saturated based on these measurements; however, we have now removed this claim in the revised version

Line 141-142: How did you make sure that the intakes are not sucking in small ice/water particles?

The final 0.5 m of each intake line was placed horizontally within the snowpack and terminated in a downward-facing stainless-steel frit (1" diameter, 10 µm pore size). This configuration minimized the risk of entraining small ice particles into the sampling lines while preserving the integrity of the surrounding snow. The frit also introduced hydraulic resistance (detailed calculation in response to reviewer 3), confining the sampling footprint to the immediate vicinity of the inlet.

Line 145-147: Could you provide a bit more explanation how you buried the last 0.5m inside the snow. Were the last 0.5m directly horizontally inside the snow? If not, how did you make sure that the temperature gradient inside the snowpack does not have an impact on condensation inside the tube?

Yes, the final ~0.5 m of each intake line was buried directly and horizontally within the snowpack, maintaining thermal continuity with the surrounding snow. This segment was also insulated, which, together with the lack of active heating, minimized the risk of condensation inside the tube.

Line 146: '... and minimizing the risk of condensation': It is hard to understand what you want to say here. I assume the reason why you didn't heat the last 0.5m is because you could have potential *heating up/melting of the snow at the intake. Why is there then a risk of condensation? Could you elaborate a bit more.*

You are correct, the last ~0.5 m of tubing was intentionally left unheated to avoid warming or melting the surrounding snow at the intake. The phrase "minimizing the risk of condensation" referred to the fact that this segment was buried horizontally, insulated, and maintained at the local snow temperature. We have rephrased the sentence in the Methods to read: "...the final 0.5 m of tubing was unheated but insulated and buried horizontally at intake height, ensuring thermal equilibrium with the surrounding snow and preventing condensation inside the line."

Line 148-149: How far was the valve actuator away from the intakes?

The valve actuator was housed at room temperature and located approximately 5.5 m from the inlets.

Line 149: '... the three inactive sampling lines...' How can you have three inactive sampling lines when you have only three sampling lines. Why do you have a fourth one? Is it relevant to have a fourth one? Please provide more information.

The system was designed with four measurement lines in total. The original purpose of the fourth line was to monitor vapor isotopic composition at <5 cm above the snowpack surface. However, as the season progressed, this inlet was repeatedly buried under new snowfall. To minimize complexity in the dataset we decided not to include this line in the present analysis.

Methods

Line 149: '... continuously flushed': Please specific mention it that it continuously flush the line with the vapor of the pore space (I assume this is what you did).

Yes, that is correct. The inactive sampling lines were continuously flushed with vapor from their respective pore-space locations. This ensured that fresh vapor was always present in the lines, reducing residence time and preventing stagnation before switching to active sampling. We have revised the Methods to specify that the continuous flushing was with pore-space vapor.

Line 154: I don't see a reason why you should discharge the last 2 minutes before switching the valve. Did you see any impact on the signal in the last 2 minutes? If yes, why do you think that it has to do something with the valve? Could you elaborate a bit more?

We did not observe any influence of valve switching but excluded the last two minutes to retain a central measurement window.

Line 155-156: I would delete this sentences because it confuses a bit. Actually, you measured one intake twice during one hour.

Our system included four lines, and the valve switched every 15 minutes, so each intake was measured once per hour.

Line 158-161: I'm questioning your explanation about water percolation. Looking at Figure 2 I don't see a reason why you should have water percolation into the snowpack. The ambient temperature was far below zero and also the temperature at 15cm shows value below zero. Could it not be that the Picarro sucked in ice crystals which melted inthe heated tube? How do you prevent that ice particles can enter the intakes?

As noted in the manuscript, we discarded all 15 cm measurements after 7 March 2023 because the Picarro issued a high-water concentration alarm. On that date, hourly averaged temperatures exceeded 0 °C for ~6 hours, even though the daily boxplots in Figure 2 (of the manuscript) smooth over these excursions. This warm spell coincided with the instrument alarm, after which all data from the 15 cm line were excluded. Entry of ice particles was unlikely due to the intake design (downward-facing stainless-steel frit, 10 μm pores, final 0.5 m of tubing buried horizontally and insulated).

Line 170: 'Humidity corrections were applied...': I assume it is not a humidity correction but a humidity-isotope correction.

Yes, thank you for pointing this out. We have corrected the wording to "humidity–isotope correction" in the revised manuscript to avoid confusion.

Line 177: '... minimal drift over time': At what humidity level did you perform your drift measurement? Close to the humidity levels of the intakes inside the snowpack?

Thank you for this question. The drift measurement was performed at ~20,000 ppmv, i.e. at higher humidity levels than those inside the snowpack. This was done to ensure stable instrument operation and ideal conditions for evaluating long-term drift.

Line 181-182: You indicate that 10% of your vapor concentration measurements inside the snow were below 2000 ppmv. I doubt that this is realistic for a snowpack where the lowest temperature was around -4 degrees. Could you check what was the snowpack temperature when you measured vapor concentration below 2000 ppmv.

We checked all cases with vapor concentrations <2000 ppmv. At 5 cm, these occurred when the snowpack temperature was between about −1.7 and −0.2 °C (median −1.5 °C early period ; −0.26 °C late period). At 15 cm, they occurred when the snowpack was colder, between about −4.7 and −0.7 °C (median −4.4 °C early period; −1.05 °C late period). At the same times, the ambient air was much colder (−19 to −14 °C). As noted in our major comment response, this indicates that undersaturation arose from mixing with colder, drier ambient air rather than from measurement artifacts.

Line 195-196: Could you elaborate a bit more why you didn't include sample measuring above 20 cm from ground level? Such measurements would help to get a better idea how the signal changed with depth and why there was a potential disequilibrium at the intakes.

The 5 cm inlet was deliberately planned to monitor pore vapor near the basal snow. The 15 cm inlet, however, was unintentionally buried deeper than intended during an early-season snowstorm and was not repositioned, in order to avoid disturbing the snowpack structure. Finally, the 1.5 m inlet was placed in ambient air to characterize atmospheric vapor; this height was selected because ~1 m corresponds to the average max historical snow depth at the site, ensuring that the inlet remained above the snowpack throughout the season. We had already noted the burial of the 15 cm inlet in the limitations section of the original manuscript, and we now clarify these points in the Methods as well.

Line 202: '... using a Picarro CRDS system.' Could you mention which model e.g. L2120, L2130 or L2140?

Picarro L2130-i

Line 216: I assume that the relative humidity was measured at 1.5 m. Please mention it.

Corrected

Line 231: 'Relative humidity within the snowpack remained saturated ...': I can't find any evidence that your data shows saturated conditions inside the snowpack. See comments above.
We have removed this claim as explained in response to major comment.

3) Results

Figure 2: How did you measure the snow depth and what was the resolution of it?

Snow depth at the site was initially monitored using daily manual readings from a snow stake. These measurements generally agreed within 1–2 cm of the automated observations from Ted Stevens Anchorage International Airport (~7 km away). However, because the manual record was occasionally missed or became inconsistent during periods of heavy snowfall, we ultimately relied on the continuous 6-hourly snow depth data from the airport station. We have clarified this in the revised Methods section.

Figure 3: Could you also add the temperature profile to see whether the concentration (ppmv) is following the temperature profile or not.

We have revised Figure 3 (shown below) to include the temperature profiles at 5 cm, 15 cm, and 1.5 m alongside the corresponding water vapor concentrations and isotope compositions. The new temperature panels allow direct comparison of concentration (ppmv) with co-located snowpack and atmospheric temperatures. At 1.5 m, vapor concentrations broadly covary with temperature, consistent with Clausius–Clapeyron control on ambient air humidity. By contrast, at 5 cm and 15 cm within the snowpack, vapor concentrations show weaker and more variable correspondence with local temperatures, reflecting the additional influence of vapor diffusion, soil vapor input at the base, and ventilation processes. We believe this addition clarifies the relationship between vapor concentration and temperature, and strengthens the interpretation of undersaturation and non-equilibrium dynamics within the snowpack.

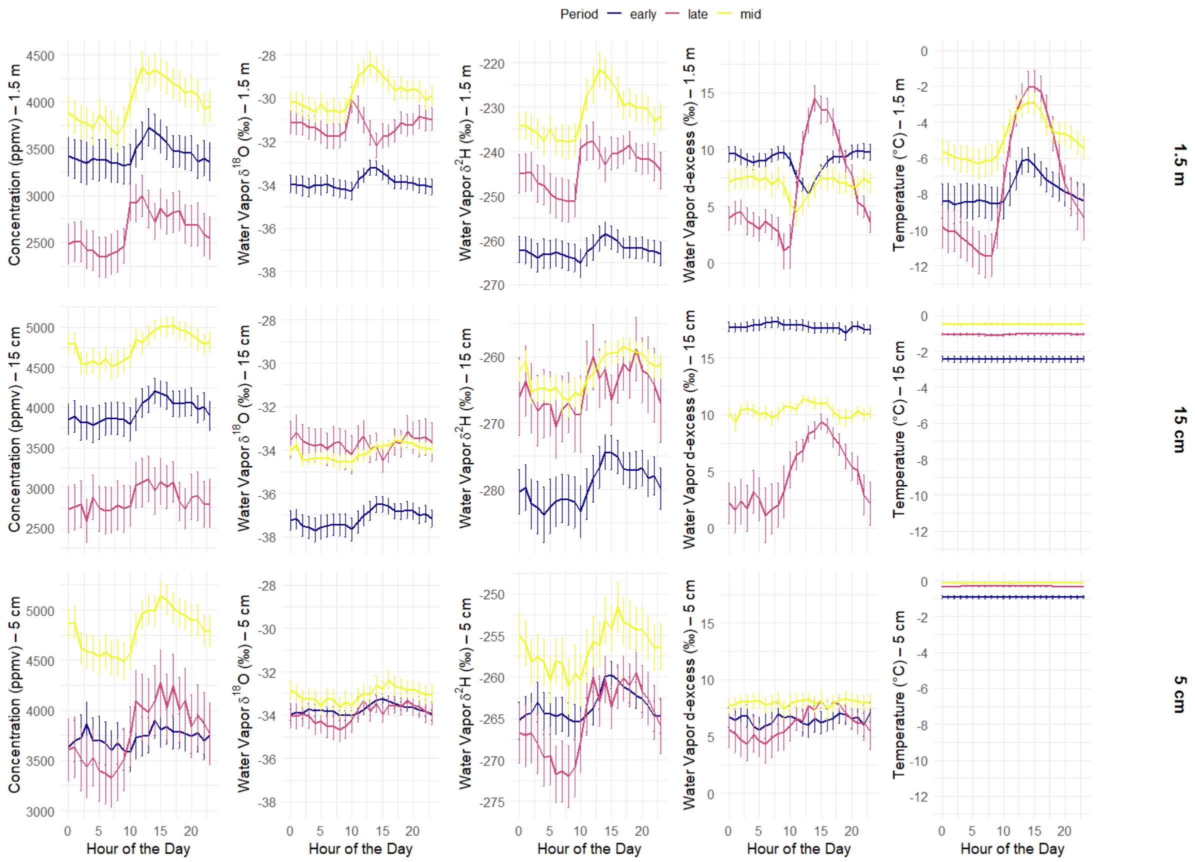

Figure 3: Is it possible to extract a time-shift between the measured atmosphere data and inside the two snowpack locations? If yes, would it be possible to compare this time-shift with the diffusion time ($\Delta t=L^2/D$) from the snowpack surface to the intake locations (maybe include a tortuosity factor for the diffusion length inside the snowpack) to check whether it is consistent.

We extracted the time-shift by cross-correlation between ambient vapor (1.5 m) and the pore-space vapor at 15 cm and 5 cm depth. In all continuous windows, the maximum correlation occurred at zero lag on the hourly series. Because our multiplexed sampling is based on 15-min intervals (later averaged to hourly), this means that the pore-space vapor responded essentially synchronously with the atmosphere, with an upper bound of ≤ 1 h for any lag. We then compared this observational constraint to diffusion timescales that include a tortuosity correction (Figure 2) . For the 15 cm intake, diffusion times are in the range 3–7 h, while for the 5 cm intake they are 5–10+ h. Thus, molecular diffusion is far too slow to explain the observed near-synchronous (< 1 h) coupling between atmosphere and pore-space vapor. Instead, the comparison highlights that ventilation processes (barometric pumping), which operate at sub-hourly scales, are required to transmit the atmospheric signal into the snowpack.

Figure 4: I would suggest to change the colour of the '0-5 cm' and 5-10 cm' snow data points. It is hard to distinguish it.

We have changed the colour in the revised manuscript

Figure S4: How do you explain that you measured a vapor concentration below 1900 ppmv inside the snow pack but your temperature is only around -4 degrees? I'm also surprised that the vapor concentration inside the snowpack is almost the same as the 1.5m measurement.

We examined all cases where in-snow vapor concentrations dropped below 1900 ppmv. At 15 cm depth, these occurred when snowpack temperatures were −4.7 to −3.9 °C (median −4.4 °C). At such temperatures, saturation would correspond to ~4300 ppmv, indicating clear undersaturation relative to local ice. At the same times, the ambient air was much colder (−19 to −15 °C) and contained only 1400–1800 ppmv vapor. The overlap between in-snow and ambient concentrations therefore reflects exchange with colder, drier air. As outlined in our major comment response, ventilation by barometric oscillations and episodic wind pumping can replace pore air on sub-hourly timescales, faster than sublimation can restore vapor to saturation. This mechanism explains why in-snow vapor concentrations could drop well below the ice-saturation value at the measured snow temperature. More generally, however, in-snow vapor concentrations were higher than those in the overlying atmosphere. Across the full record, median vapor concentrations were 4309 ppmv at 5 cm and 4441 ppmv at 15 cm, compared to 3496 ppmv in ambient air. Thus, while short episodes of ambient–snowpack similarity occurred during ventilation events, the broader dataset shows that pore-space vapor was usually enriched relative to the atmosphere.

4) Discussion

Line 459-460: '… at different snowpack heights (5 cm, 15 cm, and 1.5 m)…' -> please rewrite this part because 1.5m does not belong to the snowpack but to the atmosphere.

Thanks, this has been corrected

Line 487-488: '… than in ambient air, Within the …': I assume that the sentence ends after 'ambient air.'

Corrected

Line 527: I questioning this paragraph without knowing your spatial density profile of your snowpack. In addition, based on Figure 2 you measured a max. wind speed of 2 m/s and you are intakes are between 0.4m and 0.8m below the snowpack surface. For this condition I would not expect any significant ventilation inside the snow pack (see Colbeck et al., 1989). But without knowing your density profile of your snowpack it is hard to make a conclusion. I would suggest that you provide more evidence to support your hypothesis. Maybe you could provide an estimation about what wind speed inside the snowpack would be needed to transport the atmospheric vapor into the snowpack. E.g you could try to extract a time-shift between the measured atmosphere data and inside the two snowpack locations and calculate a wind speed needed to transport the signal into the snowpack.

We agree that without a detailed density–depth profile it is impossible to compute a precise wind-driven ventilation rate. For this reason we did not attempt to estimate wind-driven advection in the manuscript. Instead, we adopted a wide range of snowpack permeabilities, porosities and tortuosities from the literature and showed that the pressure difference required to ventilate 0.05 and 0.15 m heights above the ground in 15–60 min windows is small (≈10^{-2} to 10^{1} Pa) compared to the barometric pressure variations measured in our study. Wind pumping occasionally reaches the threshold, but it is barometric oscillations, operating independently of wind speed, that routinely exceed it. Figure 3 illustrates this magnitude comparison, while Figure 4 provides a categorical time-series view: for the "average snowpack" case, barometric forcing alone exceeds the required threshold almost continuously, whereas wind forcing does so only sporadically. Thus, ventilation can occur on sub-hourly time scales even with weak ambient winds because pressure oscillations propagate through the snowpack and drive advective flow

Line 608: '... in the mid-snowpack (around 10-15 cm).': How do you justify that 15 cm is a mid-snowpack position for a snowpack depth of 90 cm?

We thank the reviewer for pointing this out. The intake heights were fixed relative to the ground (5 cm and 15 cm), and we mistakenly described the 15 cm level as "mid-snowpack." We agree this wording is misleading. In the revised manuscript we now consistently describe the intakes as "5 cm" and "15 cm above ground level within the snowpack.

Line 606 and 610: Would it be possible to provide an explanation that first 'In early winter, the snowpack behaved as a closed system...' and afterwards the snowpack is not closed anymore and wind-pumping and '... ventilation became the primary transport mode...'? Looking at your snow depth data on Figure 2 I would expect that your two intakes locations inside the snowpack are even more decoupled from the atmosphere because the snowpack is rising by additional 20-30cm.

In our original submission we described the system as transitioning from "closed" to "open." Based on further analysis of barometric pressure fluctuations, we now recognize that barometric pumping was active throughout the record and consistently ventilated the pore space. To avoid the misleading impression that the snowpack was ever fully closed, we revised the text to frame the seasonal evolution as a shift in the relative dominance of diffusion versus ventilation.

In the early period, strong soil–snow thermal gradients sustained upward diffusion, producing clear isotopic stratification: vapor near 5 cm was relatively enriched in $\delta^{18}O$ (–33.7‰) with low d-excess (6.7‰), whereas vapor at 15 cm was more depleted (–36.3‰) with elevated d-excess (17.5‰). Although barometric pumping was present, its isotopic imprint was muted because ambient vapor (–33.5‰, 8.6‰) was similar to pore vapor near the base, so ventilation did not override the diffusion signal.

After the 24 January warm event, thermal gradients collapsed and diffusion weakened, while isotopic contrast with ambient vapor grew. For example, in the mid period, ambient vapor was enriched (–29.8‰, 6.9‰) relative to pore vapor (5 cm: –33.5‰ / 9.3‰; 15 cm: –34.0‰ / 10.4‰). By the late period, pore vapor values converged toward ambient (5 cm: –33.7‰ / 7.5‰; 15 cm: –32.9‰ / 6.2‰; ambient: –31.9‰ / 6.7‰), vertical stratification diminished, and diurnal cycles emerged. These shifts show that while ventilation was always active, its isotopic imprint became dominant only once ambient vapor diverged from the internal reservoir. Importantly, even with a 20–30 cm increase in snow depth, pore spaces were not decoupled from the atmosphere, as reflected in convergence of $\delta^{18}O$ and d-excess toward ambient values and the emergence of diurnal cycles.

Line 636-637: Could you elaborate this a bit more? What do you mean '... buried well below its intended mid-snowpack position during an early-season snowstorm'? Didn't you want to keep the intake locations constant at 5 cm and 15 cm above ground? Or what was your intended mid-snowpack position? And how do you justify that 15 cm is a mid-snowpack position for a snowpack depth of 90 cm?

We appreciate the reviewer's request for clarification. The 5 cm inlet was deliberately positioned to monitor pore vapor close to the basal snow. The 15 cm inlet was installed above it, but during an early-season snowstorm it was buried more deeply than originally intended and was not repositioned in order to preserve snowpack stratigraphy. We recognize that describing this level as "mid-snowpack" was misleading, particularly once snow depth exceeded 50–90 cm. In the revised manuscript we now consistently describe the intakes as being fixed at "5 cm" and "15 cm above ground level within the snowpack," rather than referring to them as "mid-snowpack." We have clarified these points in the Methods and Limitations sections

5) Conclusion

Line 692: The link is not working. Please correct it.

Thank you for flagging this. The dataset has been uploaded to our repository and is currently under restricted (embargoed) access for peer review. In line with our policy, the archive will be made public upon publication (DOI listed in the Data Availability statement). If the reviewer would like to inspect the data during review, we will be happy to provide temporary private access upon request.

S1) Supplement material

Line 4: '... fluctuations in water vapor com concentrations.' -> remove 'com'

Done

Line 7: '... relative humidity at the four inlets, a HOBO...': I think there is a type. You are talking about four inlets but based on your experimental setup you have only three (5cm, 15cm and 1.5m).

As explained previously, the system was designed with four measurement lines in total. The original purpose of the fourth line was to monitor vapor isotopic composition at <5 cm above the snowpack surface. However, as the season progressed, this inlet was repeatedly buried under new snowfall. To minimize complexity in the dataset and maintain consistency across levels, we decided not to include this line in the present analysis.

Technical comments:

Line 255: '... the snowpack slightly enriched than the ...' Typo -> '... the snowpack was slightly more enriched than the ...'

Corrected

Line 339: 'The 5-10 cm layer shows a steeper slope ...' Typo -> 'The 5-10 cm layer showed a steeper slope ...'

corrected

Line 354: '... vapor was negatively correlated ...' Typo -> '... vapor were negatively correlated ...'

corrected

Line 678: 'Our data set ...' -> 'Our dataset ...'

corrected

Remove redundant commas in citations (e.g., "Bailey et al., (2019)" → "Bailey et al. (2019)")

done

APPENDIX:

Diffusion Timescales Pressure Gradient Requirements and Atmospheric Forcing

1. Diffusion timescales (t_diff)
To provide a baseline for snowpack air exchange in the absence of pressure forcing, we calculated the characteristic diffusion timescale:

$t\_diff = L^2 \div D\_eff$,

where L is the distance from the intake to the snow surface (0.05 m or 0.15 m), Because L increases as the snowpack deepens, diffusion timescales lengthen markedly through the season. D_eff is the effective diffusivity of water vapor through snow. D_eff was calculated as:

$D\_eff = D\_air \div \tau$,

where D_air is the molecular diffusivity of water vapor in air ($2.1 \times 10^{-5}\ m^2\ s^{-1}$) and τ is the tortuosity factor (tested over 1.1–1.4).

2. Required pressure gradients (ΔP_req)
We estimated the pressure difference required to ventilate pore air in the snowpack by combining prescribed lag times with Darcy's law. The lag time is not an observed variable, but a benchmark that we imposed to test how much pressure forcing would be required for ventilation at different timescales. Conceptually, the question is: *If air must be exchanged between the snow surface and a depth of 5 cm or 15 cm within a specified lag time, what pressure difference is needed to achieve that exchange?*

First, the lag time was converted into a pore velocity:

- Pore velocity (v_p) = exchange depth (L) ÷ lag time (s).

This pore velocity represents the effective air movement that would be needed to flush the pore space within the specified time window.

Darcy's law relates this pore velocity to the required pressure difference across the snow depth:

- $\Delta P = (\mu \times \phi \times v\_p \times L) \div k$.

μ is the dynamic viscosity of air (1.7×10^{-5} Pa s), ϕ is the porosity of the snow, v_p is the pore velocity defined above, L is the vertical distance over which air must move (0.05 m for the 5 cm sensor level; 0.15 m for the 15 cm sensor level), k is the permeability of the snow.

We explored a range of realistic seasonal snow properties: Permeability (k): 10^{-11} to 10^{-7} m^2, Porosity (ϕ): 0.55 to 0.80 (Calonne et al., 2012). Tortuosity (τ): 1.1 to 1.4, reflecting the meandering of flow paths through the snow matrix (Lieblappen et al., 2020)

For each lag window (15, 30, and 60 minutes), ΔP_req was calculated across all combinations of k, ϕ, and τ. The resulting shaded bands in the plots show the minimum–maximum envelope of ΔP_req, while the solid (5 cm) and dashed (15 cm) curves represent the geometric mean values.

3. Observed atmospheric forcings

We then compared the calculated ΔP_req against two atmospheric mechanisms capable of generating pressure gradients in snow: wind forcing and barometric forcing. Both forcings were aggregated into 15, 30, and 60 minute sliding windows to directly match the lag times used for ΔP_req.

- Wind forcing (dynamic pressure):
  Dynamic pressure was calculated as
  $\Delta P\_wind = ½ \times \rho \times U^2$,
  where ρ is air density (1.3 kg m^{-3}) and U is the maximum wind speed observed within the lag window. Dynamic pressure represents the potential overpressure available from wind pumping during gusts.

- Barometric forcing (pressure oscillations):
  Barometric pressure forcing was defined as the absolute difference between maximum and minimum atmospheric pressure within each lag window:
  $\Delta P\_baro = |P\_max – P\_min|$.
  This captures oscillatory barometric pumping of the snowpack and was calculated using pressure measurements spanning a 30 m vertical offset.

The observed forcings and the required ΔP were plotted on the same axes to allow a direct visual comparison of magnitudes and timescales.

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