Response to Reviewer #3 for EGU-2025-2724: *Isotopic Stratification and Non-Equilibrium Processes in a Sub-Arctic Snowpack*

We sincerely thank Reviewer 3 for their careful and detailed evaluation of our manuscript. We recognize the importance of critically examining potential artifacts in pore-space vapor measurements, particularly in porous snowpacks where the act of sampling itself can influence the system. The reviewer has raised thoughtful concerns regarding possible pump-induced entrainment of atmospheric air, and we greatly value the opportunity to clarify our experimental design, inlet hydraulics, and the physical basis for our interpretations.

Reviewer 3 highlights an important concern about whether our continuous sampling could disturb the snowpack vapor environment and influence the measured isotopic signals. They argue that the extraction rates might artificially ventilate the snowpack, potentially explaining observed humidity and isotope variability. They note that diurnal humidity variations observed at 5 and 15 cm depths, without corresponding temperature variations, may indicate pump-induced airflow rather than natural processes.

In our response, we provide additional details on the inlet hardware and hydraulics, demonstrating that the frit resistance confines any perturbation to very local scales. We also show that the temporal and vertical structures of our data are inconsistent with steady sampling artifacts. The frits confine any sampling perturbations to millimeter–centimeter scales, as supported by calculated pressure budgets. Consequently, the large-scale replacement effects suggested by the reviewer do not apply to our setup. To clarify this for readers, we will revise the Methods to describe the inlet hardware in detail and include a summary of the supporting hydraulic calculations.

For clarity, we have structured our replies such that the reviewer comment is presented first (in *italics*), followed immediately by our detailed response (shown in blue).

Review 3:

The manuscript argues that difusion and wind ventilation cause non-equilibrium fractionation, which reshapes the water isotopic composition within the snowpack in both the vapor and the snow on hourly to seasonal timescales.

The argument is based on a comprehensive dataset of water vapor isotope observations from both above and within the snowpack, combined with snowpack isotope profiles and direct temperature measurements.

The authors support their conclusions based on the finding that their measurements of the water vapor isotopic composition show that the pore-space vapor is rarely in isotopic equilibrium with the surrounding ice.

Their experimental setup consists of two inlets, located respectively 5 and 15 cm above the ground, which are buried by snow deposited throughout the season. At the beginning of the campaign, the 15 cm inlet is 45 cm below the snow surface, while at the end of the campaign, it is 65 cm below the snow surface.

The target question of the manuscript is crucial for understanding the physical processes that affect the climate signal recorded in the stable isotopic composition stored in the ice crystals that comprise the snowpack. Since the early work of Waddington et al., who hypothesized that wind pumping is important for driving the isotopic composition in the snow, discussions and attempts have been made to quantify the vapor transport within the snowpack through direct measurements.

Unfortunately, it is this reviewer's view that the authors make similar mistakes as previous attempts to measure interstitial water vapor, in that they disregard the influence of their measurements on the medium they are trying to measure, i.e., the interstitial water vapor.

Contrary to the statement on line 640, "However, the small volume of vapor extracted relative to total pore-space vapor produced no systematic artifacts," I will argue below that the volume of vapor extracted in fact is producing artifacts, which prevent the authors from reaching a robust conclusion.

The fundamental problem with their setup is that the authors remove air from the snowpack continuously:

L 149 "The three inactive sampling lines were continuously flushed by a single pump at a total flow rate of 100 ml/min, yielding approximately 33 ml/min through each inactive line"

L152 "The active line connected to the analyzer was sampled at the instrument´s internal flow rate of approximately 40 ml/min.

This means that a constant flow through each inlet line buried in the snow is 33-40 ml/min. As the air for the inlet lines in the snowpack cannot come from the ground, it must come from the atmosphere above the snowpack. This means that a total of 66-80 sccm of air will flow to the combined inlets in the snow. See Figure 1 below as a sketch of the setup. Figure 1: Sketch of setup

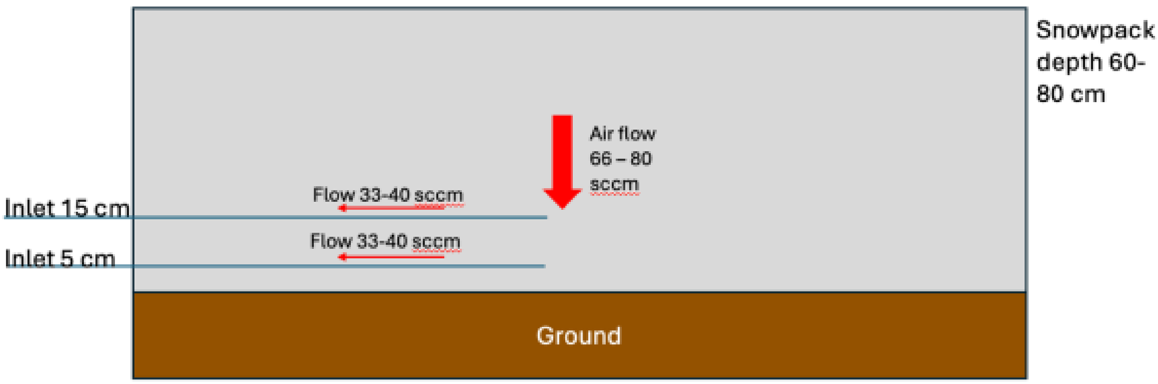

Figure 1: Sketch of setup

The fundamental question that then arises is, where does the air come from? It must be such that the air will follow a path of the smallest integrated resistance. This means that the air cannot come from infinity. On the other side, it also seems unlikely that the air follows a tube flow straight from the surface through a path with a diameter of 6 mm equal to the inlet ID.

Below I therefore consider two situations: Conservative option 1: The air enters the snowpack through an area with a diameter of twice the depth of the inlet (90 cm beginning of season and 130 cm end of season) and travels through a semi-sphere of the snowpack. See figure 2 for a sketch of the setup. Figure 2: Sketch of a conservative thought experiment of how the air travels through the snowpack.

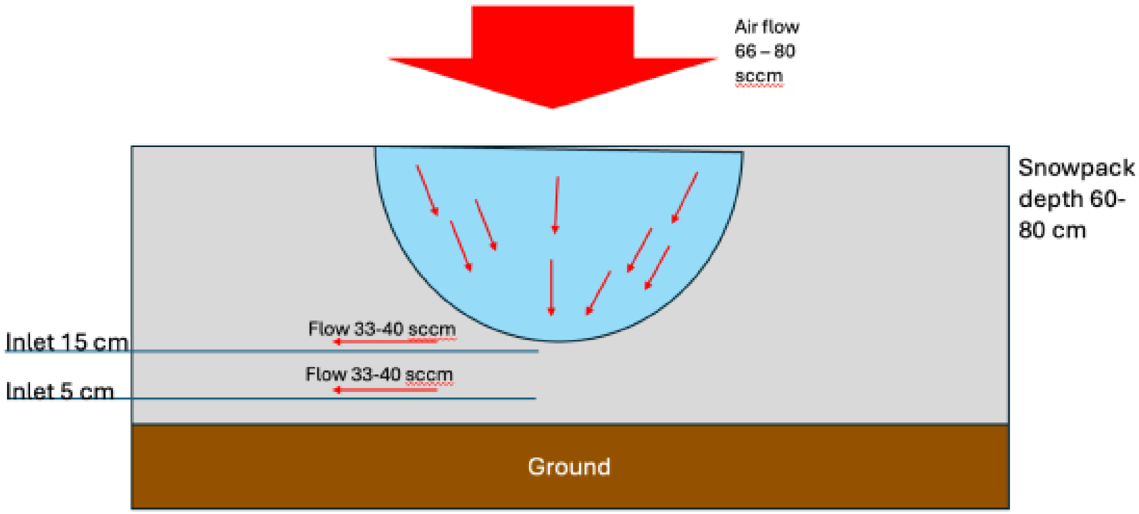

Figure 2: Sketch of a conservative thought experiment of how the air travels through the snowpack.

Making the following assumption that the density of the snow is 500 kg/m3 based on the information in the text that the authors observed compaction during periods of no precipitation and the relatively high temperatures at the field site.

For the calculations of snow depth at 60 cm:

The volume of the semi-sphere is 190e3 cm3 . This means that the volume of air is 95e3 cm3 . With a flow rate of respectively 33 or 40 sccm per inlet, this would mean that all the interstitial air will be replaced every 20 to 24 hours.

Even for this relatively conservative estimate, I will therefore argue that the author's argument on line 640, "However, the small volume of vapor extracted relative to total porespace vapor produced no systematic artifacts," does not hold.

A more realistic flow field through the snowpack would probably be better described by a column flow with a diameter of 40 cm from the top of the snowpack down to the inlet. Figure 3 illustrates perhaps a more realistic flow field through the snowpack. Figure 3: Illustration of a perhaps more realistic flow field through snowpack.

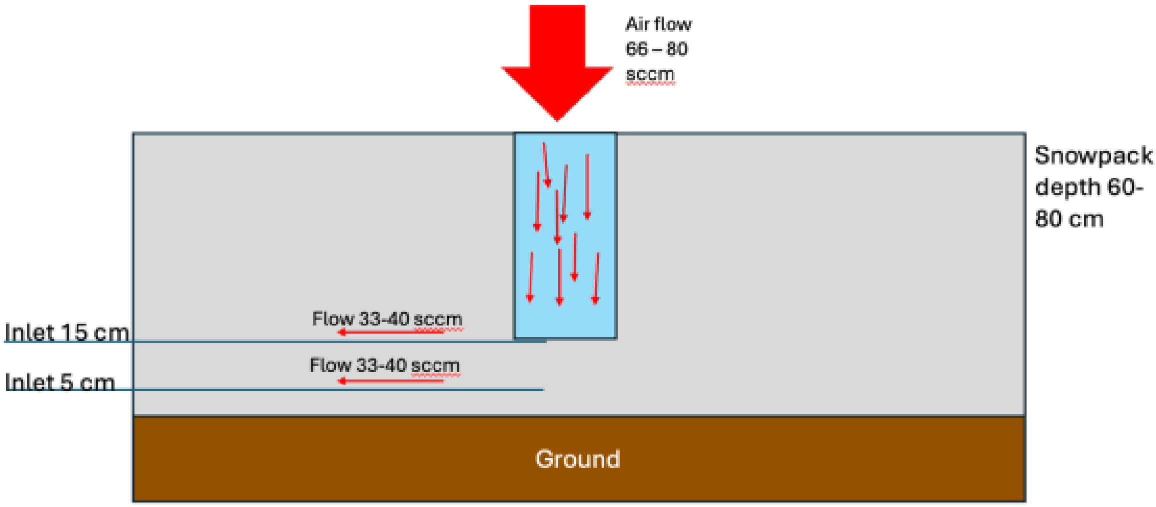

Figure 3: Illustration of a perhaps more realistic flow field through snowpack.

Again, carrying out the calculations for a snow depth of 60 cm.

In this case, the volume of the column is 56e3 cm3 and the total volume of the interstitial air is 28 cm3 .For the given flow rates through the inlet lines, this would mean that the air in the snow column is replaced every 6 to 7 hours.

Based on these calculations, I believe that the effect on the interstitial vapor isotopic composition, which the authors attribute to diffusion and wind ventilation, is a result of the forced transport of atmospheric air through the snowpack.

Further support for my conclusion is provided by the authors in the observed snowpack temperature at the depth of the inlet and the observed diurnal variations in humidity of the interstitial vapor:

Figure S2 shows that no diurnal variation in snowpack temperature is observed at the 5 and 15 cm inlet

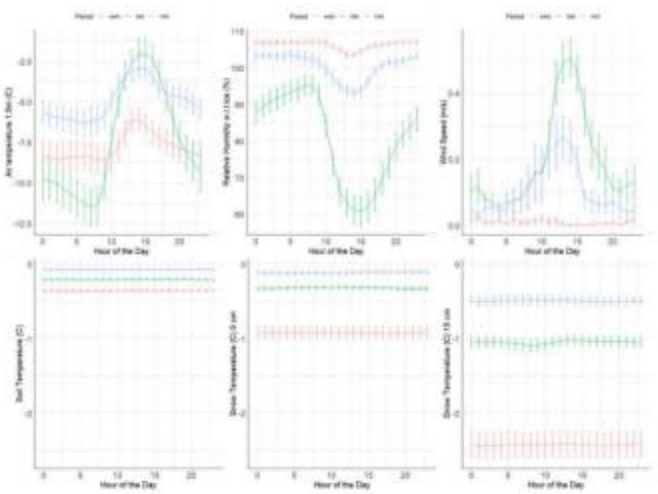

Figure S2 Plots depicting diurnal patterns in ambient air temperature (C), relative humidity w.r.t. ice (%), wind speed (m/s), and soil and snow temperatures (5cm and 15cm) depth, measured over three distinct periods: early, mid, and late.

However, the authors also demonstrate clear diurnal variations in the observed humidity at the inlets, as shown in Figure 3.

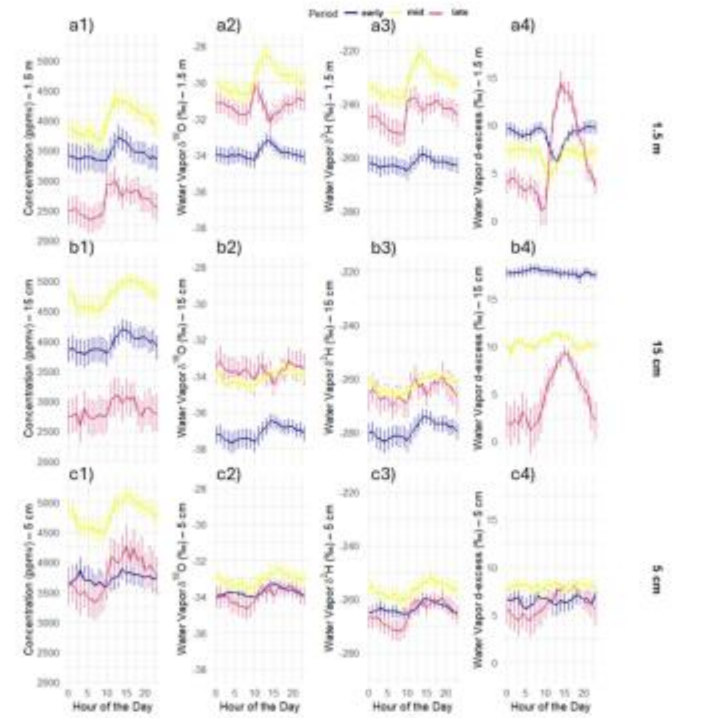

Figure 3 Plots depicting diurnal variations in water vapor concentration (1) and isotopic compositions ($\delta^{18}O$ (2), $\delta^{2}H$ (3), *d*-excess (4)) in ambient air (1.5 m) (a) and at 5cm (c), 15 cm (b) within a snowpack and across three distinct periods: blue-early, yellow-mid and magenta-late.

Following the findings of Neumann et al. 2009 (Sublimation rate and the mass-transfer coefficient for snow sublimation): "Our data (e.g. Fig. 4) suggest that the snow sublimates rapidly, and that for snow samples with thickness 1 cm or greater, pore spaces in snow are typically saturated with vapor, as other investigators have assumed [5]"

This means that the snow at the 5 and 15 cm inlet must have a diurnal variation in temperature in order to create a diurnal variation in humidity. As the temperature at 5 and 15 cm does not show any diurnal temperature variation, this means that the flow of air into the inlets must influence the temperature in the vicinity of the inlets, but not be recorded by the temperature observations. Hence, one might conclude that even the "perhaps more realistic flow field in the snowpack" is in fact still too conservative, and the flow from the surface to the inlet follows an even narrower corridor through the snowpack.

Based on my above argument, I therefore believe that the setup in the manuscript of Dar et al. does not allow the authors to reach the presented conclusions

Response to Reviewer:

All of the reviewer's points converge on a central issue: whether our sampling significantly perturbs the snowpack vapor environment. In the response below, we provide additional details on inlet geometry, quantify pressure drops across the frits versus the snowpack, and show that any perturbation is confined to millimeter–centimeter scales rather than the decimeter–meter scales suggested by the reviewer's thought experiments. In practice, nearly all of the pressure drop occurs across the frit, thus, the snowpack does not experience the column-scale suction envisioned by the reviewer, and the induced flow field is localized to centimeters around the frit.

Our original manuscript did not describe the buried inlet hardware, which is essential to the hydraulics. Each snowpack intake terminated in a downward-facing, sintered stainless-steel frit (2.54 mm face, 10 μm pore size). This geometry (i) truncates the accessible solid angle (no upward-facing draw from the snow surface) and (ii) introduces a large internal resistance.

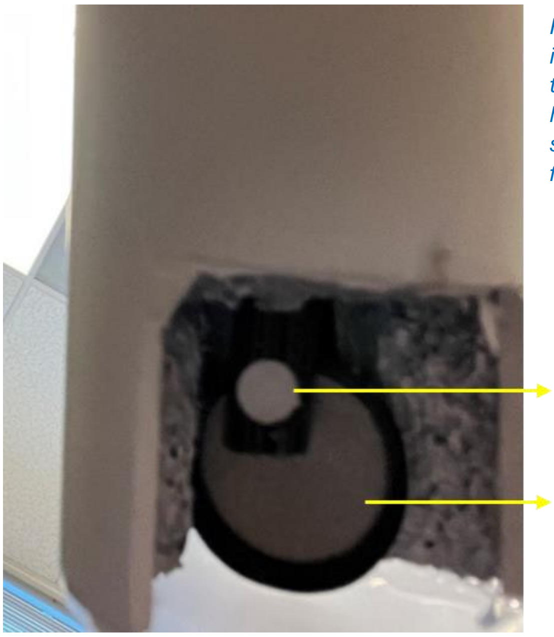

Figure 1 Photograph showing the orientation of the sampling inlets (downward-facing frits at 5 cm and 15 cm above ground) together with the co-located RH/temperature sensor inside its housing. The downward-facing geometry prevents direct line-of-sight entrainment from the snow surface and minimizes artifacts from dynamic pressure fluctuations.

1) Hardware makes broad entrainment impossible.

The reviewer's sketches treat each line's measured flow (≈33–40 mL min^{-1}) as if it were supplied from a large region extending to the snow surface, either a hemisphere with radius equal to inlet depth (≈0.45–0.65 m) or a 0.40 m-diameter, 0.60 m-tall column, so that a large pore volume is "replaced" every ~6–24 h. That construction implicitly requires most of the pump head (the suction applied by the analyzer) to be available across the bulk snowpack.

With a downward-facing frit, almost all the pump head is consumed inside the frit. The measured per-inlet flow is 40 mL min^{-1}; for a 2.54 mm diameter, "10 μm" frit this requires on the order of 10^2–10^3 Pa across the frit (Kozeny–Carman bound) (Appendix A2). By contrast, when we bound the pressure drop available in the snow using a conservative local control volume (lateral supply from the immediate neighborhood under the frit) and take the inlet heights above ground (5 cm and 15 cm) as upper limits for the local path length, the resulting snow pressure drops are sub-Pa to a few Pa (Appendix A3) for realistic seasonal/fresh-snow permeabilities. Under such small residual drops, Darcy scaling confines the radius of the perturbed zone to millimeters–centimeters, not decimeters (Appendix A4).

Because the frit dissipates essentially all the pump head, the snow is not hydraulically driven as a half-meter hemisphere or a 40-cm-wide column. The draw is local (mm–cm scale), and the reviewer's replacement-time arithmetic for large volumes does not diagnose our downward-facing frit configuration.

We will add (i) a concise description of the inlet geometry and (ii) a reference to the calculations below, which document the head budget, the local snow pressure drops, and the resulting perturbed-zone size.

2) The flow regime is slow, laminar, and well within Darcy's law (Appendix A5)
Both inside the frit and in the snow, Reynolds numbers are much less than one. This ensures creeping, linear Darcy flow. There is no possibility of jetting or channel-like flows that might connect the inlet directly to the ambient air.

3) The temporal structure of the data contradicts an artifact.
If sampling artifacts were important, they would produce a slow, quasi-steady drift of pore vapor toward ambient conditions over the 6–24-hour turnover times implied by the reviewer's volumes. Instead, our measurements show sharp, episodic excursions that align with external forcing. We observe persistent differences between 5 cm and 15 cm vapor that evolve through the season in systematic ways (Fig 4 in the manuscript). These vertical gradients scale linearly with measured temperature differences, exactly as expected for gradient-driven diffusion, and cannot be explained by external suction. We perceive transitions are evidence of physical vapor transport processes, not constant biases from sampling.

Response to "no T cycle at 5–15 cm means RH cycles are pump artifacts"

- **Neumann et al. (2009) does not directly apply to our field setting.** Neumann's lab samples (1–5 cm thick) show the air exiting a thin sample is typically saturated, with saturation reached within roughly the first millimeter to centimeter of snow; they also note that undersaturation can occur in large-pore layers or at higher flows. This does not imply that RH at 5–15 cm depth in a field snowpack can only vary if local temperature varies.
- **Why RH can vary at depth without a local temperature cycle.** RH equals e/es(T). Even if temperature at 5–15 cm is flat (so es is steady there), diurnal swings in ambient temperature, ambient RH, and wind change the surface boundary: colder ambient air lowers es at the surface (Clausius–Clapeyron), and wind-driven pressure gradients periodically ventilate the near-surface snow (wind pumping). These forcings create vertical gradients in vapor pressure (e) that drive time-varying diffusive and advective fluxes into the pack. As a result, e(z,t) and therefore RH can oscillate at 5–15 cm without any measurable local temperature cycle and without a pump-forced corridor.
- **New barometric pumping evidence.** Our time-shift analysis demonstrates that snowpack vapor responds to barometric pressure oscillations on sub-hourly to hourly scales (details in response to major comment of Reviewer 2). These timescales are much shorter than molecular diffusion (3–10 h at our depths) and show that pressure-driven advection is active throughout the record. This barometric pumping efficiently propagates humidity and isotopic variability into the snowpack, explaining the observed RH cycles at 5–15 cm without requiring a local temperature cycle.
- **Laboratory evidence under isothermal conditions.** Ebner et al 2017. forced saturated airflow through snow under isothermal and temperature-gradient conditions and observed non-

equilibrium vapor–snow interaction and large $\delta^{18}O$ changes. This demonstrates that humidity and isotope signals propagate in snow without co-located temperature cycles at depth.

The claim that RH cycles at 5–15 cm require a local temperature cycle or a narrow pump corridor is unsupported. Surface-forced ventilation is sufficient to explain the observed RH cycles at depth.

To summarize, the hydraulics of the frit–snow system, supported by our calculations and external literature, show that pump-induced artifacts are limited to the immediate vicinity of the inlets and cannot explain the observed vertical isotope gradients, their temporal variability, or seasonal transitions in isotopic composition. We therefore maintain that the observed signals reflect physical processes of diffusion and ventilation within the snowpack.

APPENDIX:

A1. Constants and measured quantities

- Volumetric flow (instrumental flow): $Q=40$ mL/min$=(40\times10^{-6})/60=6.67\times10{-}7$ m^3/s$=6.67\times10^{-7}$ m^3/s.
- Air viscosity: $\mu=1.7\times10{-}5$ Pa s
- Air density (for Reynolds): rho ≈ 1.3 kg/m^3
- Frit face: diameter 2.54 cm, radius rf=12.7 mm area $Af=\pi rf^2=5.067\times10^{-4}$ m^2
- Superficial velocity through frit: $qf=Q/Af=1.316\times10^{-3}$ m/s

A2. Frit pressure drop

Permeability of the frit: Nominal "10 µm" frit, use pore size d_p = 1.0×10^{-5} m as an engineering proxy. Kozeny–Carman to calculate the frit permeability:
$k\_f = d\_p^2 \times eps^3 / [180 \times (1 - eps)^2]$

We bracket porosity eps = 0.25–0.45 and thickness L_f = 1–3 mm

Darcy's law, the fundamental relation for fluid flow through porous media is used to describe the pressure drop when air passes through the frit of thickness L_f

$\Delta P\_frit = \mu * (L\_f / k\_f) * q\_f$

Results:

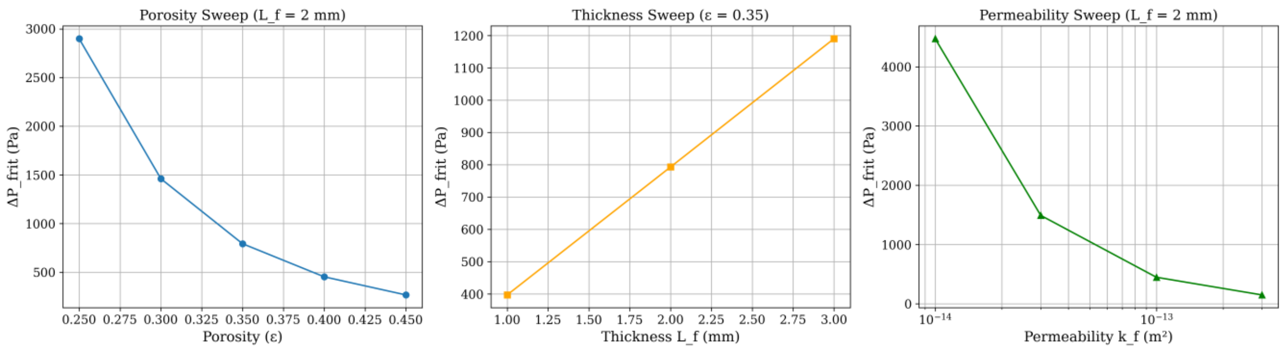

Figure 2 Pressure drop across the frit (ΔP_frit) as a function of (a) porosity at fixed thickness Lf=2 mm, (b) frit thickness at fixed porosity ε=0.35, and (c) permeability at fixed thickness Lf=2 mm.Porosity sweep at L_f = 2 mm:

Hence, ΔP_frit is robustly 10^2 to10^3 Pa at the measured flow.

A3. Snow pressure drop for a local lateral supply:

The frit faces downward; the intake is lateral from a local neighborhood. We model a cylinder of radius r_c and length L_s that supplies the frit. Because the frits are 5 cm and 15 cm above ground, we use $L_s \le 5$ cm (lower inlet) and $L_s \le 15$ cm (upper inlet) as upper bounds. We take two footprints $r_c = 5$ cm and 10 cm. The frit face radius is ~1.27 cm. Choosing rc=5 cm already represents a local neighborhood that extends ~4× the frit radius in all directions, well beyond the hardware footprint and into the surrounding snow. It is a reasonable lower bracket for a local supply region. rc=10 cm is intentionally large: its cross-sectional area is ~62× the frit face area. Taking such a large rc demonstrates conservatism

Snow permeability sweep: $k = 10^{-11}$–10^{-7} m^2 (Calone et al. 2012)

Darcy's law across snow:
$\Delta P\_snow = mu * (L_s / k) * (Q / (pi\ r_c^{\ 2}))$

One worked example:
$k = 1e-10\ m^2$, $L_s = 0.05$ m, $r_c = 0.05$ m.
$Q/(pi\ r_c^{\ 2}) = 6.67e-7 / [pi*(0.05)^2] = 8.49e-5$ m/s.
$mu*(L_s/k) = 1.7e-5 * (0.05 / 1e-10) = 8.5e3$ Pa.
$\Delta P\_snow = 8.5e3 * 8.49e-5 \approx 0.72$ Pa.

Results:

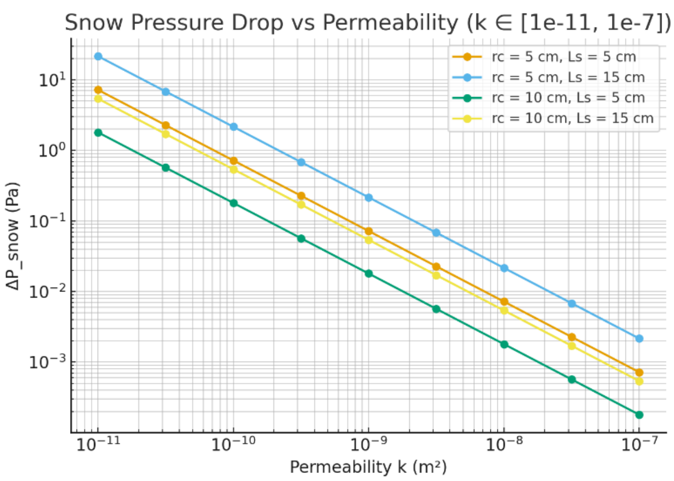

Figure 3 Pressure drop across the snow layer (ΔP_snow) as a function of snow permeability (k) for two cylinder radii (rc = 5 cm and rc = 10 cm) and two snow thicknesses (Ls = 5 cm and Ls = 15 cm). Results are shown on log–log axes

This plot shows that even at the lowest permeabilities (10^{-11} m^2), the snow pressure drop remains far smaller than the frit drop (10^2–10^3 Pa), so the frit overwhelmingly dominates the hydraulic resistance.

A4. Radius of the perturbed zone

When flow is drawn through it, the frit creates a small pressure disturbance in the snow directly beneath. We want to estimate how far sideways that disturbance spreads, the lateral reach, called a.

Radial Darcy inflow (hemispherical assumption)

If we imagine flow lines spreading out like a hemisphere beneath the frit, Darcy's law gives:

$Q = 2\pi k\,(\Delta P_{snow}/\mu)\,a$ (1)

Here Q = flow rate through the frit, k = permeability of the snow, μ = air viscosity, ΔP_{snow} pressure drop in the snow, a = perturbed radius

Control-volume Darcy relation:

We can also think of the snow under the frit as a cylindrical plug of radius r_c and depth L_s. In that case:

$\Delta P_{snow} = \mu\,(L_s /k)\,(Q/\pi r_c^2)$

$k\,\Delta P_{snow/}\mu = L_s\,(Q/\pi r_c^2)$ (2)

Where r_c = frit radius, Ls = penetration depth of the flow beneath the frit

Now substitute (2) into (1):

$Q=2\pi[L_s\,(Q/\pi r_c^2]a$

$a=r_c^2/2L_s$

So the disturbed radius depends only on geometry: frit radius and penetration depth.

Example Calculations:

- r_c =5 cm, L_s =5 cm ; a=2.5cm
- r_c =5 cm, L_s =15 cm ; a=0.83cm
- r_c =10 cm, L_s = 5 cm ; a=10 cm
- r_c =10 cm, L_s =5 cm ; a=3.3 cm

Hence, the perturbed zone radius is only millimeters to a few centimeters, not tens of centimeters.

A5. Flow regime (including porosity and tortuosity ranges)

We evaluate the flow regime in both the frit and the surrounding snowpack using interstitial velocities, effective pore dimensions, and Reynolds numbers**.**

- Frit interstitial velocity: $u_i=q_f/\varepsilon$, where q_f is the superficial velocity through the frit and ε is the frit porosity.
- Snow interstitial velocity: $u_i=u/\phi$, $u=Q/(\pi r_c^2)$, Q is the volumetric flow rate, r_c is the intake radius, and is the snow porosity.
- Effective pore length: $d_{eff}=d_p/\tau$, where d_p is the mean pore diameter and τ is the tortuosity.
- Reynolds number: $R_e=\rho u_i d_{eff}/\mu$, where ρ is the air density and μ is the viscosity.

Frit:

- With pore sizes of about 1×10^{-5} m, porosity between 0.30–0.40, and tortuosity 1.1–1.4, the superficial velocity through the frit is 1.3×10^{-3} m/s (baseline flow)
- Interstitial velocities range from about 3.3 to 4.4×10^{-3} m/s.
- Effective pore sizes fall in the range 7–9 μm.

- The corresponding Reynolds numbers are very low: 1.8–3.1×10^{-3}.

Snow:

- For snow, we allowed pore sizes between 1×10^{-4} and 1×10^{-3} m to represent the variability from dense wind slabs to fresh snow. Porosity was taken between 0.55–0.80, and tortuosity between 1.1–1.4.
- At rc=5r_c = 5rc=5 cm:
  - Superficial velocities are 8.5×10−m/s (baseline)
  - Interstitial velocities span 1.1–1.5×10−4 m/s
  - Effective pore sizes range from 0.07 to 0.9 mm.
  - Reynolds numbers are 5.8×10−4–1.1×10−2
- At rc=10r_c = 10rc=10 cm:
  - Superficial velocities are 2.1×10−5 m/s
  - Interstitial velocities span 2.7–3.9×10−5 m/s.
  - Effective pore sizes range from 0.07 to 0.9 mm.
  - Reynolds numbers are 1.5×10−4–2.7×10−3

Creeping (Darcy/Stokes) flow holds; no inertial or turbulent enhancement is available to drive bulk flushing.

For the conservative high-flow case (Q = 73 mL/min = 40 + 33):

- Frit still dominates the pressure budget. Scaling ∝ Q, ΔPfrit rises to roughly 2×10^2 to 2×10^3 Pa, remaining 1–3 orders larger than any snow drop over local paths.
- Snow pressure drops remain small over local supply lengths.
  For k=10−11–10−7 m^2, r_c = 5–10 cm, Ls=5–15 cm:
  ΔPsnow ~ 3.3×10−^{4} to 4.0×10 Pa .
- Perturbation footprint is unchanged (set by geometry).
  Flow regime remains creeping.
  With ϕ=0.55–0.80, τ=1.1–1.4
  - rc=5cm → Re ≈ 3.2×10^{-3} to 5.9×10^{-3}
  - rc=10 cm → Re ≈ 7.9×10^{-4} to 1.5×10^{-3}
    All Re ≪ 1 → Darcy/Stokes; no inertial/turbulent flushing available.

Even at this conservative, higher draw, the frit's hydraulic resistance confines perturbations to the immediate intake neighborhood, and cannot drive bulk snowpack flushing.

References:

Ebner, P. P., Steen-Larsen, H. C., Stenni, B., Schneebeli, M., & Steinfeld, A. (2017). Experimental observation of transient $\delta^{18}O$ interaction between snow and advective airflow under various temperature-gradient conditions. *The Cryosphere, 11*, 1733–1743. https://doi.org/10.5194/tc-11-1733-2017

Neumann, T. A., Albert, M. R., Engel, C., Courville, Z., & Perron, F. (2009). Sublimation rate and the mass-transfer coefficient for snow sublimation. *International Journal of Heat and Mass Transfer, 52*(1–2), 309–315. https://doi.org/10.1016/j.ijheatmasstransfer.2008.06.003