



Hydrodynamic controls on stable isotopic exchange during meltwater percolation through stratified ice

Yalalt Nyamgerel¹, Hyejung Jung², Chaeyoung Kim², Won Sang Lee³, Jeonghoon Lee^{2*}

¹Chemistry and Chemical Technology of Mongolian Academy of Sciences, Ulaanbaatar 13260, Mongolia

²Department of Science Education, Ewha Womans University, Seoul 03760, Republic of Korea

³Division of Glacier and Earth Sciences, Korea Polar Research Institute, Incheon 21990, Republic of Korea

Correspondence to: Jeonghoon Lee (jeonghoon.d.lee@gmail.com)

Abstract. Stable water isotopes are fundamental tracers for interpreting snowpack dynamics, stratigraphy, and meltwater export in the cryosphere. However, the isotopic signals exported from melting snow and ice are often modified internally before release, as natural snowpacks and glacier ice are vertically isotopically heterogeneous and percolating meltwater undergoes dynamic isotopic exchange with the surrounding solid matrix. Here, we quantified how initial isotopic stratigraphy and meltwater flow regimes jointly control this non-conservative isotope transport. We conducted eight controlled column-melting experiments using two-layer ice columns composed of isotopically depleted and enriched layers arranged in reversed vertical sequences under different melting conditions. Effluent $\delta^{18}\text{O}$ and $\delta^2\text{H}$ were interpreted using a process-based, one-dimensional isotope-exchange model. The experiments show that meltwater isotopic evolution is governed primarily by the vertical order of the isotopically distinct layers and cannot be explained by conservative end-member mixing alone. The model successfully reproduced the observed isotope trajectories using effective exchange parameters, yielding exchange rate constants (k_r) of 0.11–0.54 h^{-1} for oxygen isotopes and 0.11–0.49 h^{-1} for hydrogen isotopes, with no statistically distinguishable difference between the two isotopic systems within individual experiments. Across the experiments, k_r tended to increase with percolation velocity, most clearly in depleted-top configurations, whereas the active exchange fraction (f) decreased under faster-flow conditions within each stratigraphic group. This hydrodynamic decoupling demonstrates that isotopic exchange during meltwater percolation is dictated not only by contact time but also by flow-path organization and the accessibility of ice-water interfaces. Our results highlight that isotopic signatures exported from melting snow and ice must be interpreted as process-modified signals rather than strictly conservative source end-members. Incorporating flow-dependent phase exchange into cryospheric models will improve the interpretation of meltwater export dynamics and the evolution of isotopic stratigraphy in snow- and ice-dominated environments.

1. Introduction

Isotopic heterogeneity in snow and ice arises from temporal variations in precipitation sources, atmospheric conditions, and post-depositional processes, yielding vertically stratified tracer structures in natural frozen porous media (Jasechko, 2019). During meltwater percolation through these heterogeneous layers, multi-phase isotopic exchange between the mobile liquid



phase and the solid matrix dynamically modifies the evolving tracer signals, rendering the transport inherently non-conservative and distinct from simple advective mixing relationships (Lee *et al.*, 2009). This non-conservative behavior introduces substantial predictive uncertainty when using stable isotopes to interpret macro-scale hydrological processes, including the quantification of snowmelt contributions, identification of physical flow pathways, and estimation of catchment-scale hydrological connectivity (McDonnell, 1990; McDonnell *et al.*, 1990; Kim *et al.*, 2017). Specifically, neglecting these internal multi-phase mass transfer processes can severely bias conventional isotope-based hydrograph separations and obscure the hydrodynamic timing and routing of runoff (Taylor *et al.*, 2001; Feng *et al.*, 2002; Lee *et al.*, 2010; Pu *et al.*, 2020). Despite its critical importance, the process-level coupling between initial stratigraphic heterogeneity and flow-regime-dependent exchange kinetics remains insufficiently constrained under non-uniform melting and percolation conditions. Such flow-mediated tracer modification is pervasive across both temperate and polar porous systems, where omitting internal snowpack or ice-matrix processes leads to systemic biases in source partitioning and the mechanistic characterization of fluid flow pathways (Jacobs *et al.*, 1985; Dini and Stenni, 2000; Kaczmarska *et al.*, 2006; Abram *et al.*, 2013; Silvano *et al.*, 2018; Fujita *et al.*, 2021; Porter and Opel, 2020).

Isotopic exchange between liquid water and ice in snowpacks and ice layers has been extensively studied using modeling approaches (Nakawo *et al.*, 1993; Taylor *et al.*, 2001, 2002; Feng *et al.*, 2002; Hashimoto *et al.*, 2005; Nyamgerel *et al.*, 2024), field observations (Taylor *et al.*, 2001; Zhou *et al.*, 2008; Lee *et al.*, 2010; Hashimoto *et al.*, 2005; Pu *et al.*, 2020), and laboratory experiments (Lee *et al.*, 2009; Ham *et al.*, 2019). Most of these studies, however, assume isotopically homogeneous snowpacks or ice layers, under which meltwater typically exhibits gradual isotopic enrichment during melting, known as the melt-out effect (Taylor *et al.*, 2002; Ala-aho *et al.*, 2017). In natural catchments, the isotopic composition of snow varies through time due to changes in precipitation sources, atmospheric conditions, and post-depositional processes (Vystavna *et al.*, 2018; Pu *et al.*, 2019). As a result, isotopic heterogeneity is pervasive in seasonal snowpacks and glacier ice. Such heterogeneity is expected to influence the time-varying isotope signals exported from the cryosphere to streams and subsurface flow paths. However, its influence on meltwater isotopic evolution, and therefore on the interpretation of snowmelt isotope signals in hydrological applications, remains poorly constrained. Only a limited number of studies have explicitly examined how initial isotopic heterogeneity in snow or ice layers affects meltwater isotope signals (Herrmann *et al.*, 1981; Pu *et al.*, 2020; Nyamgerel *et al.*, 2024). Consequently, the combined effects of isotopic stratigraphy and flow-dependent exchange remain a key uncertainty when using meltwater isotopes to infer runoff generation and source partitioning in snow-dominated catchments.

Building on these unresolved effects of isotopic heterogeneity, reported isotopic exchange rate constants for oxygen and hydrogen span wide ranges ($0.01\text{--}0.77\text{ h}^{-1}$ and $0.07\text{--}0.82\text{ h}^{-1}$, respectively; Taylor *et al.*, 2001, 2002; Ham *et al.*, 2019; Pu *et al.*, 2020; Nyamgerel *et al.*, 2024) and are commonly assumed to be similar for the two isotopic systems. Such variability introduces substantial uncertainty in how strongly meltwater isotope signals are modified during percolation, and thus in



isotope-based inference of runoff generation and hydrological connectivity. However, it remains unclear whether these exchange rate constants respond systematically to isotopic heterogeneity and to melting conditions, particularly the prevailing flow regime. Notably, conflicting relationships between isotopic exchange rates and percolation velocity have been reported: modeling studies suggest enhanced exchange at lower velocities (Feng *et al.*, 2002), whereas laboratory studies indicate reduced exchange under similar conditions (Lee *et al.*, 2009; Ham *et al.*, 2019). These inconsistencies suggest that isotopic exchange cannot be explained by flow velocity alone and may instead reflect interactions between flow structure and isotopic heterogeneity. This highlights the need for controlled experimental constraints on isotopic exchange under heterogeneous conditions and varying flow regimes.

From a hydrodynamic perspective, fluid transport through a melting porous ice matrix or snowpack is inherently non-uniform. As the physical structure undergoes rapid thermal degradation, the dynamic evolution of permeability and moisture retention induces severe pore-scale flow heterogeneity, routing fluid through localized channelized networks while leaving a substantial portion of the solid matrix weakly wetted (Colbeck and Anderson, 1982; Juras *et al.*, 2017). Since inter-phase isotopic mass transfer strictly depends on sustained ice and water contact, such non-uniform fluid routing can either suppress overall exchange via advective short-circuiting or locally enhance kinetics where concentrated fluxes continuously refresh the interfacial boundary, ultimately leading to highly non-linear relationships between bulk percolation velocity and effective exchange efficiency (Zhou *et al.*, 2008; Lee *et al.*, 2009; Ham *et al.*, 2019). Furthermore, the microscopic mass exchange operating between relatively immobile pore water and the advecting fluid phase can significantly modulate the transient breakthrough tracer signals (Hashimoto *et al.*, 2005; Taylor *et al.*, 2002). Collectively, these complex multi-scale phenomena necessitate that the macroscopic isotopic exchange rate constant (k_r) and the active solid-phase exchange fraction (f) be treated as effective parameters that mathematically integrate both the initial stratigraphic heterogeneity and the evolving internal flow regimes.

Motivated by these unresolved inconsistencies, this study quantifies multi-phase isotopic exchange between liquid water and ice during the melting of structurally heterogeneous ice layers under diverse hydrodynamic regimes. We conducted controlled laboratory column experiments utilizing vertically stratified ice configurations with highly contrasting isotopic compositions to establish a rigorous benchmark for initial tracer heterogeneity. The emergent effluent meltwater isotope trajectories were interpreted using a physically based, one-dimensional transport framework (Taylor *et al.*, 2001; Feng *et al.*, 2002; Lee *et al.*, 2010; Pu *et al.*, 2020). As a fundamental advance, this work unifies previous contradictory literature regarding flow-velocity dependencies by revealing an intrinsic hydrodynamic decoupling of effective parameters: the isotopic exchange rate constant (k_r) systematically increases with percolation velocity (u^*), whereas the active solid-phase exchange fraction (f) decreases under higher flow intensities. This inverse behavior demonstrates that flow conditions dynamically modulate the effective ice and water contact geometry and mass-transfer efficiency within the melting matrix. By linking process-scale



transport dynamics to macroscopic breakthrough signatures, this study delivers a robust physical foundation for upscale
isotope-based transport modeling and water resource characterization in cold regions.

2. Material and methods

2.1 Melting experiments

Eight controlled melting experiments were conducted in the cryosphere laboratory at Ewha Womans University (Seoul, Republic of Korea) to investigate isotope exchange between meltwater and heterogeneous ice layers during melting. The experimental setup consisted of a vertical Plexiglas (acrylic) column mounted on a perforated base plate and connected to an outlet tube (Fig. 1), following the general design of previous laboratory snow- and ice-melting column studies (Taylor *et al.*, 2002; Ham *et al.*, 2019). Ice cubes of uniform dimensions ($3 \times 3 \times 2.5$ cm) were prepared from two distinct end-members: distilled water (DW) and desalinated deep ocean water (SW, obtained as commercial bottled water). These two water types were specifically selected to maximize the initial isotopic contrast between the stacked stratigraphic layers ($\sim 8.7\text{‰}$ for $\delta^{18}\text{O}$ and $\sim 60\text{‰}$ for $\delta^2\text{H}$). This high-contrast boundary condition ensures an exceptionally high signal-to-noise ratio during percolation, preventing numerical dilution and enabling a robust optimization of the effective transport parameters, k_r (isotopic exchange rate constant) and f (how much ice involved in the isotopic exchange), within the ice matrix. The cubes were then packed into the column according to the configurations summarized in Table 1.

The column was packed to form two vertically stacked layers with contrasting isotopic compositions and equal mass (~ 1 kg per layer), representing the isotopic heterogeneity commonly observed in natural snowpacks and glacier ice. In experiments 1, 3, 5, and 7, the isotopically depleted DW ice layer was placed above the enriched SW layer, whereas the sequence was reversed in experiments 2, 4, 6, and 8. This paired experimental design allowed a systematic evaluation of how initial isotopic stratification and layer order influence meltwater isotope evolution under otherwise comparable melting conditions. To minimize unintended heat inputs, the column and outlet tube were wrapped with thermal insulation, and the cold-room temperature was maintained at -1 °C. Melting was induced using an infrared heat lamp positioned above the ice surface, and melt rates were regulated by adjusting the lamp voltage and the lamp-to-surface distance. Effluent meltwater was collected sequentially at the column outlet, and each fraction was weighed to quantify meltwater production and discharge through time.

Using the measured mass and geometric volume of the packed ice matrix within the column, bulk density was calculated for each experiment and subsequently used to estimate porosity. Meltwater mass was expressed as a fraction of the initial ice mass (F , fraction of melt). Time series of meltwater discharge were used to determine specific discharge (Darcy flux), mean flow rate, cumulative meltwater volume, and the arrival time of the first meltwater at the column outlet. These metrics provided the basis for quantifying percolation velocity (u^*), defined as the pore-water velocity corrected for porosity and effective

saturation, including irreducible water. The derived flow parameters characterize meltwater flow conditions within the ice matrix and provide the hydrological framework for interpreting isotopic exchange during melting.

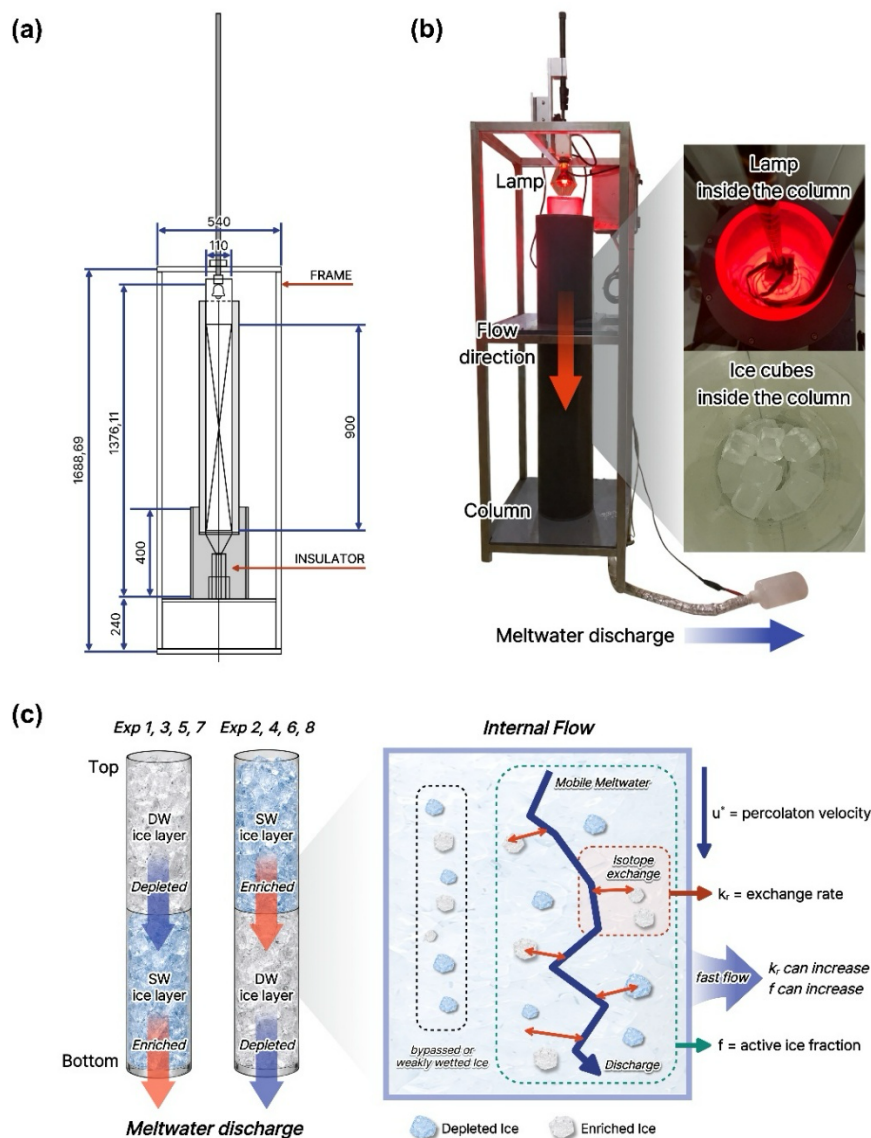


Figure 1. Experimental setup and conceptual model of isotope exchange in two-layer ice-melting experiments. (a) Schematic and (b) photograph of the melting column apparatus. (c) Two-layer isotope configurations used in the experiments and conceptual illustration of internal meltwater flow, preferential routing, and isotope exchange between mobile meltwater and accessible ice surfaces. Experiments 1, 3, 5, and 7 had a depleted DW upper layer and enriched SW lower layer, whereas experiments 2, 4, 6, and 8 had the reverse configuration. u^* , k_r , and f denote percolation velocity, isotope exchange rate constant, and active exchange fraction, respectively.



Oxygen and hydrogen isotope ratios ($\delta^{18}\text{O}$ and δD) of meltwater samples were measured using cavity ring-down spectroscopy (L2140-i, Picarro Inc., USA) at Ewha Womans University (Jung *et al.*, 2026). Isotopic compositions are reported in delta notation (‰) relative to the Vienna Standard Mean Ocean Water (VSMOW) according to

$$\delta = \left(\frac{R_{\text{sample}} - R_{\text{VSMOW}}}{R_{\text{VSMOW}}} \right) \times 1000 \quad (1)$$

where R denotes the $^{18}\text{O}/^{16}\text{O}$ or D/H ratio. Instrument calibration was performed using USGS46 and USGS48 water standards. Analytical precision was better than $\pm 0.1\text{‰}$ for $\delta^{18}\text{O}$ and $\pm 1.0\text{‰}$ for δD .

2.2 Numerical model

The one-dimensional, physically based isotope-exchange model used in this study was originally developed by Taylor *et al.* (2001), further refined by Feng *et al.* (2002), and later modified by Lee *et al.* (2010) to explicitly track the isotopic composition of the solid phase (ice). The model has been widely applied to investigate isotopic exchange between liquid water and ice in laboratory melting experiments and snowpack studies (Taylor *et al.*, 2001, 2002; Lee *et al.*, 2009; Ham *et al.*, 2019; Pu *et al.*, 2020). In this study, the model is used to quantify isotope exchange during controlled melting and percolation through a layered ice matrix representative of snowmelt-driven hydrological systems. The formulation assumes (i) a constant and spatially uniform melting rate, (ii) one-dimensional vertical flow within the column, and (iii) a constant effective ice and water contact area during melting. Under these assumptions, the isotopic evolution is governed by advection of percolating meltwater coupled with isotope exchange between liquid water and ice, while dispersive mixing is neglected. The resulting nondimensional governing equations for the isotopic ratios of liquid water and ice are expressed as follows:

$$\frac{\partial R_{\text{liq}}}{\partial t} = -\frac{\partial R_{\text{liq}}}{\partial z} + \psi\gamma(R_{\text{ice}} - \alpha R_{\text{liq}}) \quad (2)$$

$$\frac{\partial R_{\text{ice}}}{\partial t} = \psi(1 - \gamma)(\alpha R_{\text{liq}} - R_{\text{ice}}) \quad (3)$$

where R_{liq} and R_{ice} denote the D/H or $^{18}\text{O}/^{16}\text{O}$ ratios of liquid water and ice, respectively. The variables z and t represent dimensionless depth and dimensionless melt time. The parameter α is the equilibrium fractionation factor between ice and liquid water at 0°C (1.0031 for oxygen and 1.0195 for hydrogen; O'Neil, 1968). The parameter γ represents the fraction of ice participating in isotopic exchange, and ψ is the dimensionless isotopic exchange rate constant. Following Taylor *et al.* (2002), the isotopic compositions of ice and irreducible pore water are assumed to be identical. The model parameters used in this study are listed in Table 2.

The parameter γ is defined as



(4)

$$\gamma = \frac{bf}{a + bf}$$

where a and b are the respective masses of liquid water and ice per unit volume of snow or ice, and f (0 to 1) denotes the fraction of ice involved in isotopic exchange. The quantities a and b are given by

$$a = \phi(1-S_i)(S+\beta)\rho_{liq} \quad (5)$$

$$b = (1-\phi)\rho_{ice} \quad (6)$$

where ρ_{liq} and ρ_{ice} are the densities of liquid water and ice, respectively; S is water saturation; S_i is the irreducible water content; ϕ is porosity; and $\beta = S_i/(1 - S_i)$. The parameter f reflects physical characteristics of the ice matrix, including grain size, surface roughness, and the accessibility of ice surfaces to percolating meltwater, as well as melt–refreeze processes at the ice and water interface. The dimensionless exchange rate constant ψ is related to the isotopic exchange rate constant k_r by

$$\psi = \frac{k_r Z}{u^*} \quad (7)$$

where k_r (h^{-1}) is the isotopic exchange rate constant, Z (cm) is the initial ice column height, and u^* (cm h^{-1}) is the percolation velocity of meltwater. Physical and hydrological parameters used in the simulations are summarized in Tables 1 and 2. Best-fit values of ψ and f were obtained by minimizing the sum of squared differences between modeled and observed meltwater isotopic compositions.

3. Results

The experimental conditions and resulting melt characteristics are summarized in Table 1. The lowest melt-rate experiments (Experiments 1–2) were conducted using a 50 W infrared lamp positioned 30 cm above the ice surface. Intermediate melting conditions were applied in Experiments 3–4 (50 W, 20 cm) and Experiments 5–6 (75 W, 20 cm), whereas the highest melt-rate experiments (Experiments 7–8) used a 75 W lamp placed 10 cm above the ice surface. Across all experiments, total melt duration ranged from 19.25 h (Experiment 8) to 71.02 h (Experiment 1). Even within experimental pairs conducted under nominally identical lamp power and distance, melt duration varied, with the largest difference observed between Experiments 1 and 2 (13.5 h) and the smallest between Experiments 3 and 4 (0.25 h).

Specific discharge, defined as meltwater equivalent depth per unit time, was calculated for each experiment and is shown in Fig. 2. Experiments 1 and 2, as well as experiments 7 and 8, exhibited similar mean specific discharge under comparable melting conditions, whereas larger variability was observed for experiments 3 and 4 and for experiments 5 and 6.

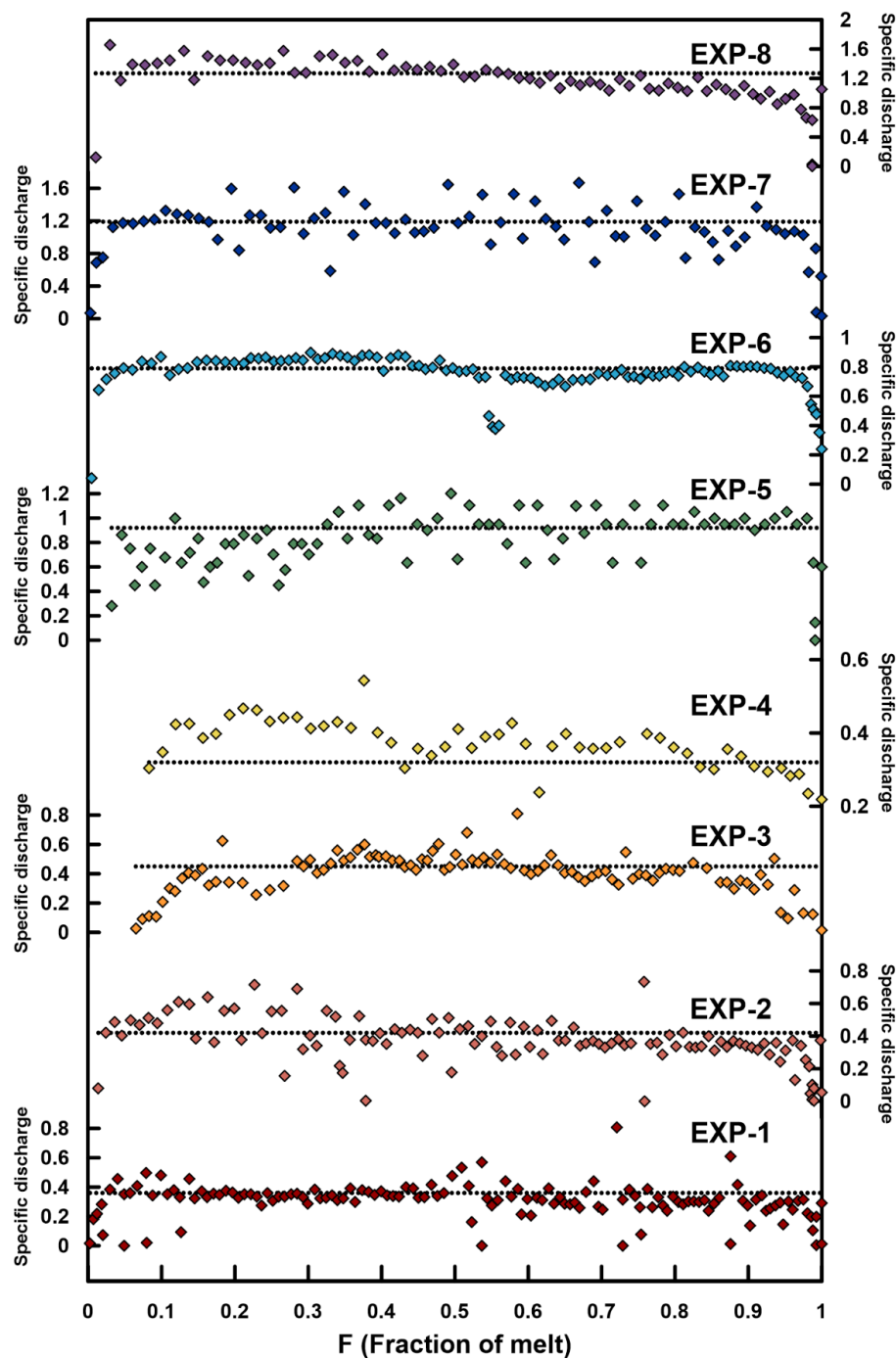


Figure 2. Specific discharge as a function of melt fraction (F) for the eight melting experiments (EXP-1–EXP-8). Each panel shows the discharge evolution during melting, and dotted lines represent the mean specific discharge for each experiment.



Such differences likely reflect variations in internal flow regimes within the ice column, potentially associated with differences in grain-size distribution and the development of unstable or channelized flow pathways (Zhou *et al.*, 2008; Juras *et al.*, 2017). Across all experiments, the mean mass of melted ice was 2.03 ± 0.055 kg, corresponding to column heights of 37.5–40 cm and a mean bulk density of 0.55 ± 0.01 g cm⁻³. Total meltwater recovery exceeded 94.8% in experiments 3–6 and 96.0% in experiments 1, 2, 7, and 8. Minor mass losses (< 5.2%), likely attributable to evaporation or sublimation, fall within the range reported in previous laboratory melting experiments (0.4–13%; Herrmann, 1981; Taylor *et al.*, 2002; Ham *et al.*, 2020). Although meltwater mass was measured using a low-precision electronic scale, experimental conditions were maintained consistently among runs, and the resulting uncertainty in the mass balance is considered negligible, consistent with previous studies (Taylor *et al.*, 2002; Ham *et al.*, 2020).

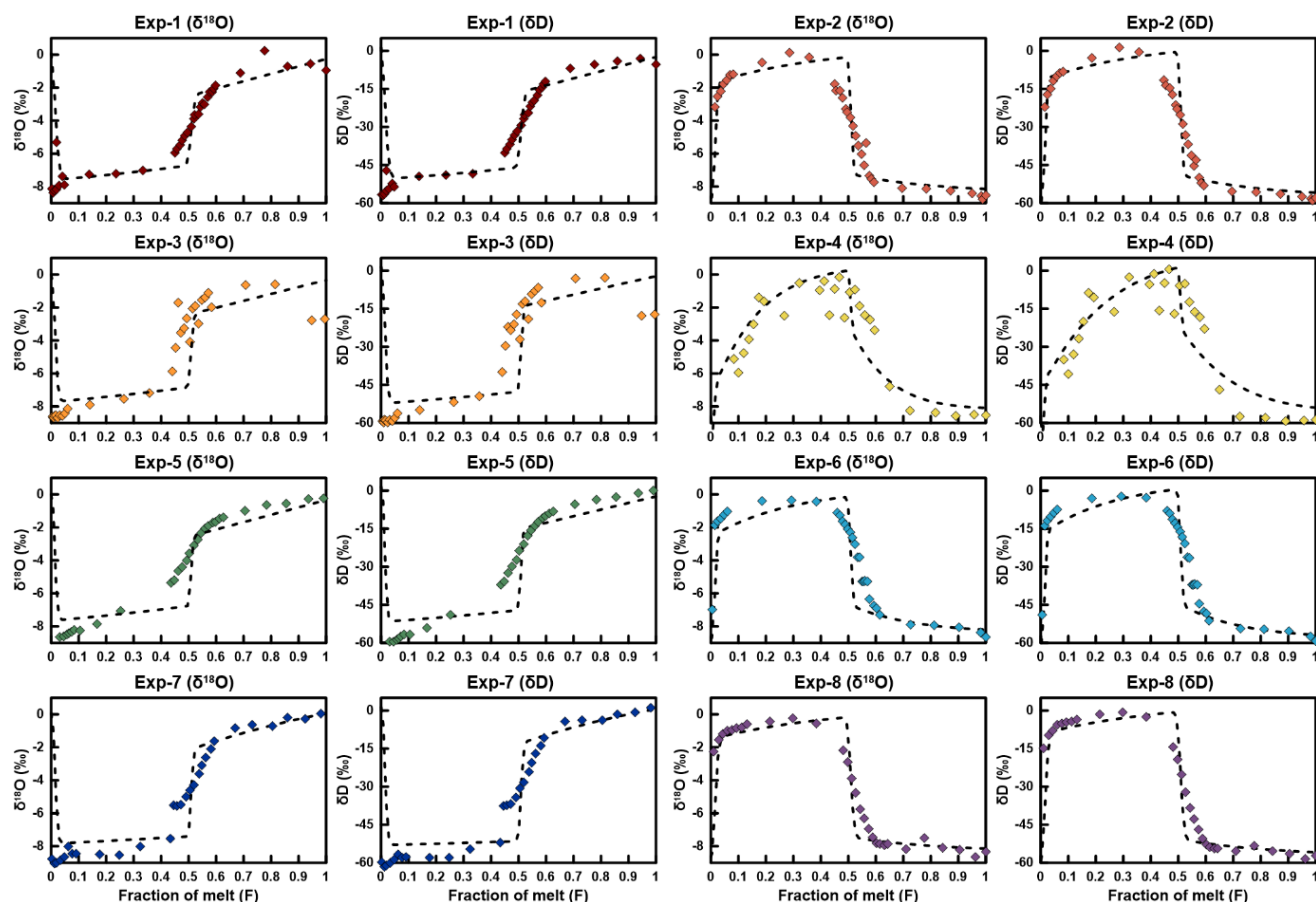


Figure 3. Measured and simulated meltwater isotope compositions ($\delta^{18}\text{O}$ and δD) as a function of melt fraction (F) for the eight melting experiments (Exp-1–Exp-8). Symbols denote measured isotope values of meltwater samples, and dashed lines represent model simulations of isotopic evolution.



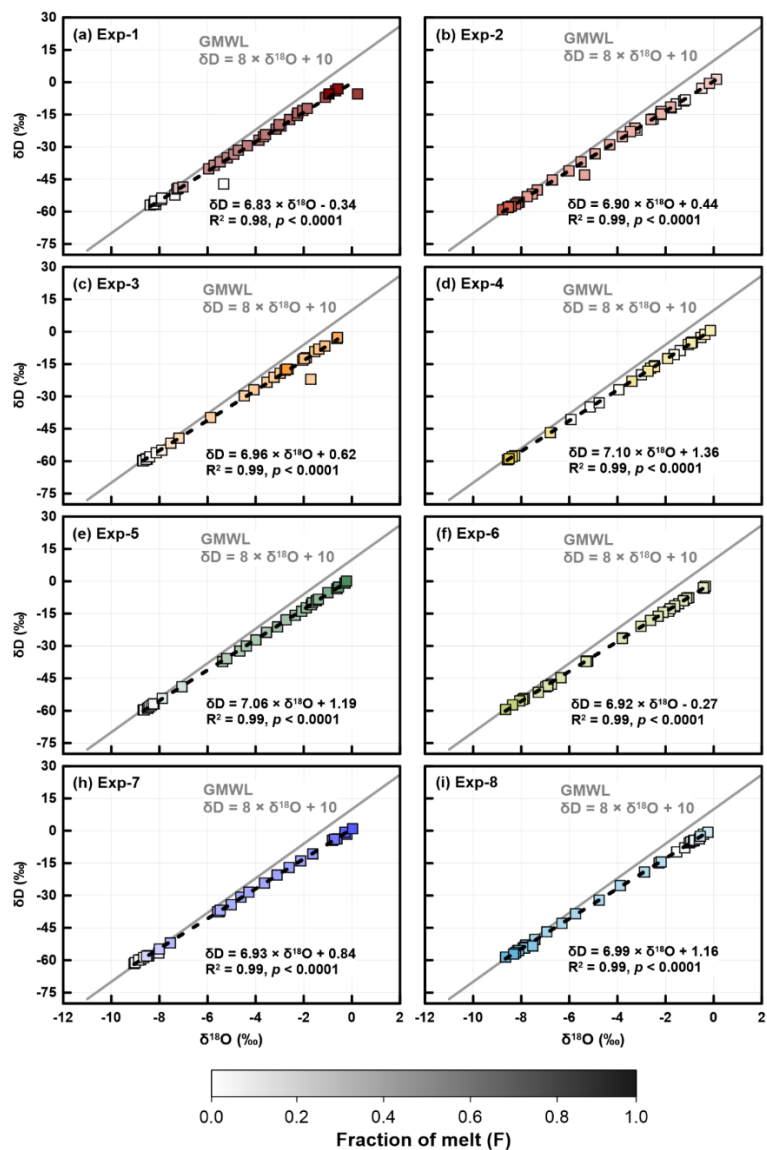
The isotopic evolution of meltwater as a function of the melt fraction (F) is shown in Fig. 3. The isotopic composition of the initial meltwater reflects that of the upper ice layer. In experiments with an isotopically depleted upper layer (experiments 1, 3, 5, and 7), $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values show a slight increase during the early stage of melting ($F < 0.5$). Near the interface between the two ice layers (approximately $F \approx 0.5$), both isotopes exhibit increase, reflecting the transition to meltwater influenced by the underlying enriched layer. During the later stage of melting ($F > 0.5$), $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values increase gradually as meltwater becomes progressively influenced by the lower ice layer. In experiments with an isotopically enriched upper layer and a depleted lower layer (experiments 2, 4, 6, and 8), $\delta^{18}\text{O}$ and $\delta^2\text{H}$ values increase during the early stage of melting ($F < 0.5$), followed by a progressive decrease during the later stage of melting ($F > 0.5$). These contrasting patterns reflect the sequence of isotopically distinct ice layers and are consistent with observations reported in previous experimental and field studies (Herrmann *et al.*, 1968; Nyamgerel *et al.*, 2024). Despite differences in melt rate among experiments, the overall patterns of isotopic evolution remain broadly similar, indicating a consistent influence of isotopic layering on meltwater composition. Deviations from the general trend are most evident in experiments 3 and 4, which exhibit more variable isotopic trajectories. This variability may reflect differences in internal flow regimes within the ice column, potentially allowing portions of isotopically exchanged but relatively immobile water to be bypassed during meltwater percolation (Ham *et al.*, 2019).

The $\delta^{18}\text{O}$ – $\delta^2\text{H}$ relationships of meltwater samples are shown in Fig. 4. For experiments with an isotopically depleted upper layer, $\delta^{18}\text{O}$ – $\delta^2\text{H}$ slopes range from 6.83 to 7.06, whereas experiments with an enriched upper layer exhibit slopes between 6.80 and 7.10. In all experiments, the $\delta^{18}\text{O}$ – $\delta^2\text{H}$ slopes are lower than 8, consistent with previous observations for isotopically heterogeneous snow and ice systems (Lee *et al.*, 2010). The variability in slope among experiments is small (standard deviation = 0.09) and comparable to values reported in earlier laboratory studies (Lee *et al.*, 2010). Variations in d-excess (d-excess = $\delta^2\text{H} - 8 \times \delta^{18}\text{O}$; Craig, 1961) for observed meltwater and corresponding model simulations are shown in Fig. 5. With the exception of experiment 4, observed and modeled d-excess values agree within standard deviations of 2.61% and 3.84%. Temporal variations in d-excess broadly follow changes in $\delta^2\text{H}$ and $\delta^{18}\text{O}$, consistent with previous observations of melting snow and ice (Lee *et al.*, 2010). Overall, the $\delta^{18}\text{O}$ – $\delta^2\text{H}$ relationships observed in this study are consistent with results from both isotopically heterogeneous and homogeneous snow and ice experiments (Lee *et al.*, 2010; Ham *et al.*, 2019), indicating minimal influence of evaporation or sublimation during melting (Lee *et al.*, 2009).

Meltwater isotopic compositions were simulated by simultaneously solving Eqs. (2) and (3) to estimate the parameters f and ψ . In the model, the isotopic compositions of ice and irreducible pore water are assumed to be identical. While this simplified assumption regarding the initial state leads to a minor and transient mismatch during the very early stage of melting ($F < 0.05$) where complex solid and liquid interactions prevail in natural porous systems (Feng *et al.*, 2002), it does not compromise the overall model validity or parameter optimization. Beyond this brief initial phase ($F \geq 0.05$), the modeled isotopic evolution captures the bulk experimental trajectories with high fidelity (Fig. 3), demonstrating that the subsequent



230 extraction of effective transport parameters (k_r and f) remains highly robust and uncoupled from early-stage transient artifacts. Best-fit values of ψ and f for oxygen and hydrogen isotopes are summarized in Table 2. The corresponding isotopic exchange rate constants (k_r) for oxygen range from 0.11 to 0.54 h^{-1} across experiments 1–8, while hydrogen isotope k_r values range from 0.11 to 0.49 h^{-1} . For each experiment, the difference between oxygen and hydrogen k_r values is less than 12.5%, indicating similar isotope exchange behavior for the two isotopes under the investigated melting conditions.



235 **Figure 4.** $\delta^{18}\text{O}$ – $\delta^2\text{H}$ relationships for meltwater samples from the eight melting experiments (Exp-1–Exp-8). The gray line represents the Global Meteoric Water Line (GMWL; $\delta^2\text{H} = 8 \times \delta^{18}\text{O} + 10$). Linear regression equations and R^2 values for each experiment are shown in the panels.



Table 1. Summary of the melting experiments.

	Exp-1	Exp-2	Exp-3	Exp-4	Exp-5	Exp-6	Exp-7	Exp-8
Top layer	DW	SW	DW	SW	DW	SW	DW	SW
Bottom layer	SW	DW	SW	DW	SW	DW	SW	DW
$\delta^{18}\text{O}$ (initial SW), ‰	0.08	0.08	0.002	0.002	0.002	0.002	0.08	0.08
$\delta^{18}\text{O}$ (initial DW), ‰	-8.65	-8.65	-8.68	-8.68	-8.68	-8.68	-8.65	-8.65
$\delta^2\text{H}$ (initial SW), ‰	1.27	1.27	1.54	1.54	1.54	1.54	1.27	1.27
$\delta^2\text{H}$ (initial DW), ‰	-59.11	-59.11	-59.82	-59.82	-59.82	-59.82	-59.11	-59.11
Weight of ice (kg)	2.01	2.005	2.005	2.01	2.14	2.1	2.01	1.99
Ice height (cm)	39	39	38	37.5	40	39.5	38.5	38
Bulk density (g cm^{-3})	0.54	0.54	0.55	0.56	0.56	0.56	0.55	0.55
Watts of lamp	50	50	50	50	75	75	75	75
Distance between ice and lamp (cm)	30	30	20	20	20	20	10	10
Total mass retrieved, percent	98.81	96.2	95.94*	94.80*	102.6*	97.84*	99.52	99.59
Duration of the experiment, hr	71.02	57.52	54.27	54.52	29.62	30.82	20.17	19.25
Time to first meltwater sample, hr	7.50	5.50	3.52	4.52	2.65	2.38	1.00	1.75
Specific discharge (weighted mean), cm hr^{-1}	0.36	0.42	0.45	0.32	0.92	0.79	1.19	1.27

*Measured by low-precision electronic scale.



Table 2. Model parameters used and obtained from the melting experiments.

Parameters	Exp-1	Exp-2	Exp-3	Exp-4	Exp-5	Exp-6	Exp-7	Exp-8	Source
Bulk density, g/cm ³	0.54	0.54	0.55	0.56	0.56	0.56	0.55	0.55	Measured
Ice height, Z, cm	39	39	38	37.5	40	39.5	38.5	38	Measured
Specific discharge (weighted mean value), cm h ⁻¹	0.36	0.42	0.45	0.32	0.92	0.79	1.19	1.27	Measured
Porosity, ϕ , %	0.42	0.42	0.41	0.4	0.4	0.4	0.41	0.41	Calculated
Irreducible water content, Si	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	Jordan, 1991
Water saturation, S	0.122	0.074	0.077	0.042	0.057	0.08	0.069	0.124	Calculated
Percolation velocity, u^* , cm h ⁻¹	5.48	9.02	9.70	10.08	24.51	17.15	27.60	19.64	Calculated
Intrinsic permeability, k, m ²	2.2 × 10 ⁻¹⁰	2.2 × 10 ⁻¹⁰	2.2 × 10 ⁻¹⁰	2.2 × 10 ⁻¹⁰	2.2 × 10 ⁻¹⁰	2.2 × 10 ⁻¹⁰	2.2 × 10 ⁻¹⁰	2.2 × 10 ⁻¹⁰	Colbeck and Anderson, 1982
Hydraulic conductivity, K, cm h ⁻¹	3.12 × 10 ⁻³	3.12 × 10 ⁻³	3.12 × 10 ⁻³	3.12 × 10 ⁻³	3.12 × 10 ⁻³	3.12 × 10 ⁻³	3.12 × 10 ⁻³	3.12 × 10 ⁻³	Morris and Johnson, 1967
α ($\delta^{18}\text{O}$ and δD)	1.0031, 1.0195	1.0031, 1.0195	1.0031, 1.0195	1.0031, 1.0195	1.0031, 1.0195	1.0031, 1.0195	1.0031, 1.0195	1.0031, 1.0195	O'Neil, 1968
f ($\delta^{18}\text{O}$ and δD)	1.00, 1.00	0.10, 0.10	1.00, 1.00	0.15, 0.20	1.00, 1.00	0.10, 0.10	0.40, 0.35	0.10, 0.10	Optimized
γ ($\delta^{18}\text{O}$ and δD)	0.85, 0.85	0.44, 0.44	0.88, 0.88	0.62, 0.51	0.90, 0.90	0.43, 0.43	0.77, 0.85	0.35,0. 35	Calculated
Mass of liquid (a)	0.07	0.05	0.05	0.03	0.04	0.05	0.04	0.06	Calculated
Mass of ice (b)	0.36	0.36	0.35	0.34	0.34	0.34	0.35	0.35	Calculated
ψ ($\delta^{18}\text{O}$ and δD)	0.80, 0.78	0.48, 0.50	0.72, 0.64	2.02, 1.82	0.76, 0.68	0.68, 0.74	0.66, 0.60	0.48, 0.48	Optimized
k_r ($\delta^{18}\text{O}$ and δD)	0.11, 0.11	0.11, 0.12	0.18, 0.16	0.54, 0.49	0.47, 0.42	0.30, 0.32	0.47, 0.43	0.25, 0.25	This work

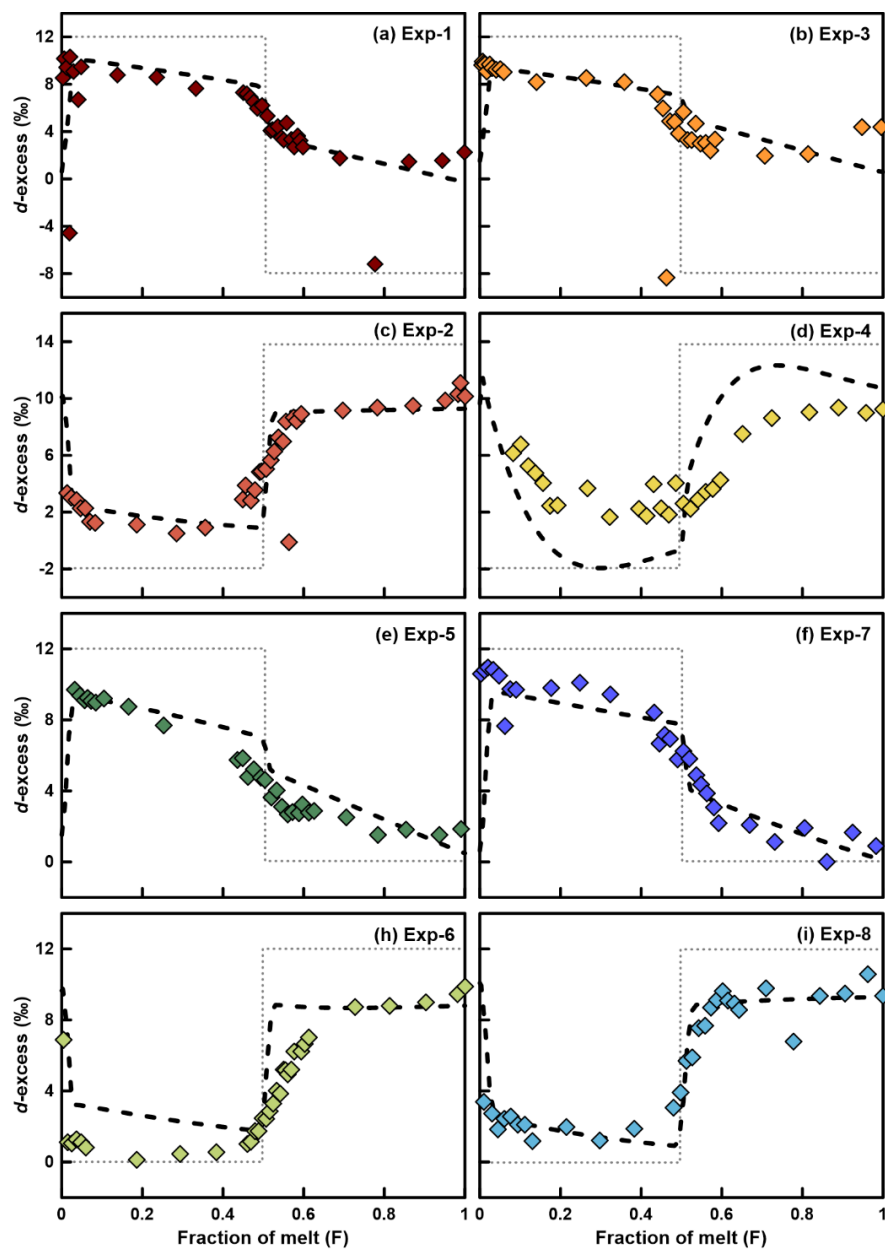


Figure 5. Observed and modeled d-excess evolution during melting of two-layer ice columns. Observed d-excess values are shown as colored diamonds, and black dashed lines represent model simulations. Gray dotted step lines indicate the conservative two-layer reference signal expected from the initial isotopic compositions of the upper and lower ice layers. Panels show individual experiments arranged by isotopic configuration: depleted-top experiments in the left column and enriched-top experiments in the right column. The transition near $F \approx 0.5$ corresponds to the interface between the two isotopically distinct ice layers.



3. Discussion

To assess whether the estimated k_r and f values differ between oxygen and hydrogen isotopes, 95% confidence regions in the k_r – f parameter space were calculated for each experiment (Fig. 6). For all experiments, the confidence regions and
250 corresponding best-fit values for oxygen and hydrogen isotopes overlap, indicating no statistically distinguishable difference between the two isotopic systems. The size and shape of the confidence regions vary among experiments, reflecting differences in melting and flow conditions that affect the sensitivity of the fitted parameters. This result indicates that although k_r and f values for oxygen and hydrogen isotopes are comparable within a given experiment, their estimated values vary depending on the imposed melting conditions.

255 4.1 Isotopic exchange rate constant (k_r) relation to flow conditions

The isotopic exchange rate constants (k_r) estimated in this study ranged from 0.11 to 0.54 h^{−1} for oxygen isotopes and from 0.11 to 0.49 h^{−1} for hydrogen isotopes. These values are comparable to those reported for homogeneous ice layers (0.21–0.77 h^{−1} for oxygen and 0.21–0.82 h^{−1} for hydrogen; Ham *et al.*, 2019). In contrast, narrower ranges of k_r have been reported for homogeneous snowpacks (0.07–0.19 h^{−1} for oxygen and 0.08–0.20 h^{−1} for hydrogen; Lee *et al.*, 2009). The broader variability
260 in k_r observed in the present study and in Ham *et al.* (2019) suggests that isotopic exchange during melting may be more sensitive to meltwater flow conditions in ice layers than in snowpacks. Such sensitivity may be associated with differences in grain-size distribution and internal flow regimes within the melting ice matrix.

To summarize the hydrological controls on oxygen-isotope exchange parameters, Pearson correlation matrices were calculated for all experiments and for each stratigraphic configuration (Figs. 7a–c). Across all experiments, $k_{r,180}$ was
265 positively correlated with percolation velocity (u^*) and negatively correlated with effective water saturation (S), whereas f_{180} showed only weak correlations with the bulk hydrological variables (Fig. 7a). When the experiments were separated by stratigraphic configuration, the depleted-top experiments showed a strong positive association between $k_{r,180}$ and u^* and a negative association between u^* and S (Fig. 7b), whereas the enriched-top experiments showed a positive u^* – S association and stronger covariation between f_{180} and $k_{r,180}$ (Fig. 7c). These contrasting correlation structures indicate that the response
270 of isotope-exchange parameters to hydrological conditions depends on the initial isotopic layering of the ice column.

The relationship between $k_{r,180}$ and percolation velocity u^* for the present experiments is shown in Fig. 7d, together with previously reported values from homogeneous snowpacks, homogeneous ice layers, and heterogeneous or natural snowpacks (Lee *et al.*, 2009; Ham *et al.*, 2019; Pu *et al.*, 2020). Previous studies have reported variable exchange-rate responses to meltwater flow conditions. Conceptually, lower isotopic exchange efficiency is often expected at higher melt rates and
275 percolation velocities because of reduced contact time between liquid water and ice (Feng *et al.*, 2002). However, the



experimental results presented here show a contrasting tendency, with $k_{r,180}$ generally increasing with u^* , most clearly in the depleted-top configuration (Fig. 7d).

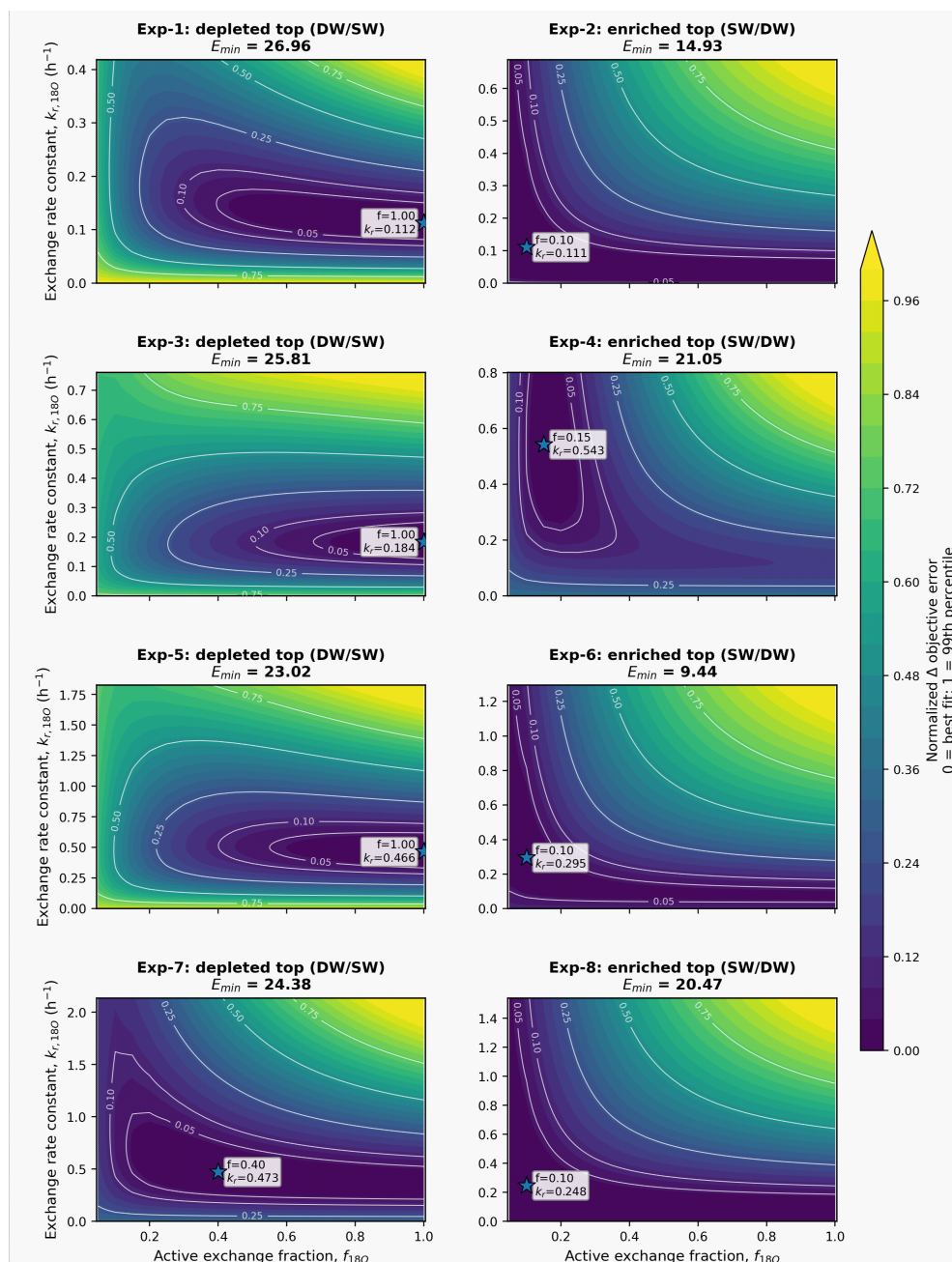


Figure 6. Ninety-five percent confidence regions in the k_r - f parameter space for the eight melting experiments (Exp-1–Exp-8). Contours represent parameter uncertainty for oxygen and hydrogen isotope fits, and symbols denote the corresponding best-fit values.



In contrast, the enriched-top configuration shows a weaker dependence of $k_{r,180}$ on u^* , largely due to the relatively high $k_{r,180}$ value observed in Experiment 4. These results suggest that isotopic exchange during meltwater percolation is strongly influenced by internal flow conditions within the melting snow or ice matrix. The corresponding scatter plots further show that f_{180} does not respond to hydrological conditions in the same way as $k_{r,180}$. Instead, f_{180} tends to decrease with increasing percolation velocity, particularly when the experiments are grouped by stratigraphic configuration (Fig. 7e). The relationship between f_{180} and effective water saturation is also configuration dependent (Fig. 7f). In the depleted-top experiments, f_{180} remains relatively high over a narrow range of S , except for Experiment 7, whereas the enriched-top experiments show consistently low f_{180} values. The u^* – S relationship further differs between the two configurations, with a negative trend in the depleted-top experiments but a positive trend in the enriched-top experiments (Fig. 7g). These contrasting relationships indicate that bulk wetness and percolation velocity alone cannot fully explain the effective exchange behavior.

Together, these results support a hydrodynamic decoupling between the exchange rate constant and the active exchange fraction. Faster or more organized flow may enhance the apparent exchange rate along active flow paths, while simultaneously limiting the fraction of the ice matrix that remains hydraulically connected to mobile meltwater. Thus, isotopic exchange during meltwater percolation is controlled not only by contact time, but also by flow-path organization and the accessibility of ice–water interfaces within the melting matrix. In natural snowpacks, meltwater flow pathways and percolation velocities can vary substantially during snowmelt events. Consequently, the degree of isotopic exchange between liquid water and snow or ice may evolve dynamically as meltwater moves through layered snowpacks, potentially modifying the isotopic composition of meltwater entering catchment drainage systems. For example, Pu *et al.* (2020) reported relatively large k_r values (0.39 and 0.35 h^{−1}) for natural snowpacks at lower percolation velocities (1.642 and 2.445 cm h^{−1}) than those observed in the present experiments. Differences in the magnitude of k_r and its apparent dependence on u^* among studies likely reflect contrasts in internal flow regimes, particularly those associated with grain-size distribution and the development of preferential flow pathways. In the column experiments presented here, the use of ice cubes may promote flow structures that differ from those occurring in natural snowpacks. Such structural differences may influence meltwater routing and contact between liquid water and ice surfaces, contributing to the observed variability in $k_{r,180}$ and f_{180} .

4.2 Fraction of ice involved in the exchange (f) relation to flow conditions

Across all experiments, the active exchange fraction for oxygen isotopes ($k_{r,180}$) shows no single relationship with either percolation velocity (u^*) or effective water saturation (S) when the full dataset is considered (Figs. 7a, e, f). However, when the experiments are separated according to the isotopic configuration of the ice layers, configuration-dependent trends become more apparent. In the depleted-top experiments, (f_{180}) tends to decrease with increasing (u^*), although Experiment 7 deviates from the high f_{180} behavior observed in Experiments 1, 3, and 5 (Fig. 7e). In the enriched-top experiments, f_{180} remains consistently low over the investigated range of (u^*), indicating that only a limited fraction of the ice matrix actively



participates in isotope exchange under this stratigraphic configuration (Fig. 7e). The relationship between f_{180} and effective water saturation also differs between the two stratigraphic configurations (Fig. 7f). In the depleted-top experiments, f_{180} remains relatively high over a narrow range of S , except for Experiment 7, whereas the enriched-top experiments show low f_{180} values across the observed saturation range. The contrasting $u^* - S$ relationships further indicate that the hydrological response of the ice columns depends on the initial isotope stratigraphy: percolation velocity decreases with increasing S in the depleted-top experiments, whereas u^* increases with S in the enriched-top experiments (Fig. 7g). These contrasting behaviors suggest that bulk wetness alone cannot explain the fraction of ice involved in isotope exchange.

The previous experimental studies shown in Fig. 7 also indicate that the relationship between f and wetness varies with porous-medium structure. Ham *et al.* (2019) reported decreasing f values with increasing wetness for homogeneous ice layers, whereas Lee *et al.* (2009) reported increasing f values with wetness for homogeneous snowpacks. The discrepancy between these studies likely reflects structural differences in porous media geometry and the resulting internal flow organization. Fine-grained snowpacks may promote more uniform capillary wetting and expand the effective ice–water contact area under wetter conditions, whereas coarse ice matrices, including the ice cubes used in this study and the coarse ice aggregates of Ham *et al.* (2019), may promote preferential or channelized flow pathways as water saturation increases. Under such conditions, percolating meltwater may be rapidly routed through limited high-permeability flow paths rather than uniformly penetrating the ice matrix. This localized flow routing can bypass weakly wetted or hydraulically disconnected ice, thereby reducing the bulk active solid-phase fraction participating in isotope exchange. Thus, the observed variability in f_{180} reflects not only the amount of liquid water present in the column, but also the spatial organization of flow paths and the accessibility of ice–water interfaces. This interpretation is consistent with the hydrodynamic decoupling observed between $k_{r,180}$ and f_{180} . While $k_{r,180}$ can increase with percolation velocity along active flow paths, f_{180} may decrease if a smaller proportion of the ice matrix remains hydraulically connected to mobile meltwater. Nyamangerel *et al.* (2024) explored isotopic evolution under a wide range of exchange efficiencies (ψ), corresponding to different combinations of k_r and f , using numerical simulations. Compared to those model results, the experimental observations presented here suggest that changes in f are strongly conditioned by internal flow structure and initial isotopic layering, rather than by bulk hydrological variables alone. Overall, the broad range of f_{180} values observed in this study highlights the sensitivity of the active exchange fraction to melting conditions, porous-medium structure, and initial isotope stratigraphy. In natural snowpacks, similar variability in flow pathways, wetness, and snow structure may influence the proportion of snow or ice participating in isotope exchange during meltwater percolation. Such variability may contribute to the evolution of meltwater isotope signals before water reaches soils and streams, with implications for the interpretation of isotope-based analyses of snowmelt contributions in catchment hydrology.

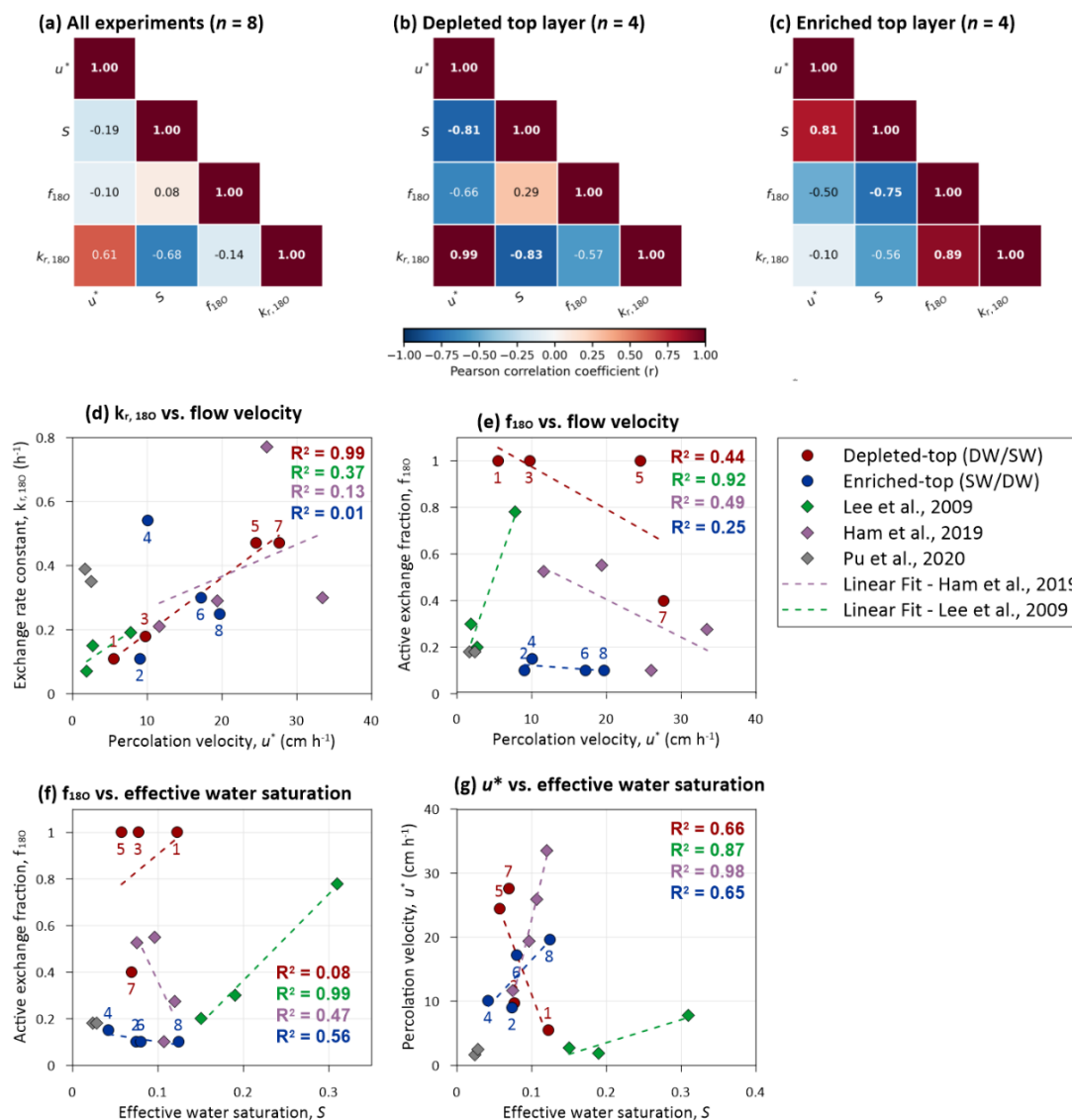


Figure 7. Relationships among oxygen-isotope exchange parameters and hydrological variables during meltwater percolation. Pearson correlation matrices are shown for (a) all experiments, (b) depleted-top configurations, and (c) enriched-top configurations. Panels (d–g) show relationships between the active exchange fraction (f_{180}) and percolation velocity (u^*), f_{180} and effective water saturation (S), the oxygen-isotope exchange rate constant ($k_{r,180}$) and u^* , and u^* and S , respectively. Red and blue circles indicate depleted-top (DW/SW) and enriched-top (SW/DW) experiments from this study, respectively. Diamond symbols denote previously reported values from Lee *et al.* (2009), Ham *et al.* (2019), and Pu *et al.* (2020). Numbers indicate experiment IDs, and dashed lines represent linear regressions for the corresponding datasets. Correlation matrices are based only on the present experiments.



4.3 Limitations and potential implications

The results of this study demonstrate that isotopic exchange during meltwater percolation is highly sensitive to flow conditions in structurally heterogeneous porous media, such as snowpacks and coarse ice layers. The observed increase in isotopic exchange with percolation velocity cannot be explained solely by greater advective flux under the assumption of uniform matrix flow. Rather, it suggests that changes in the internal flow regime, particularly the development of preferential flow pathways, modify the interaction between mobile meltwater and the surrounding ice matrix (Taylor *et al.*, 2001; Zhou *et al.*, 2008). Such flow organization can influence the effective ice–water contact area, residence time, and fraction of the solid phase actively participating in isotopic exchange (Ham *et al.*, 2019). Therefore, isotopic exchange behavior should be interpreted as being controlled not only by bulk percolation velocity but also by the spatial distribution and connectivity of flow pathways within the melting matrix. This flow-mediated modification has important implications for the interpretation of meltwater isotope signals. Isotope compositions exported from snowpacks may not simply reflect source-water composition or conservative mixing among end members. Instead, they can be progressively modified during percolation through exchange with the ice matrix, resulting in flow-integrated signatures that incorporate both source composition and internal transport history. This interpretation is consistent with previous observations of isotope evolution in snowmelt systems (Taylor *et al.*, 2002; Pu *et al.*, 2020) and provides a mechanistic explanation for discrepancies often observed between measured stream isotope compositions and those predicted using conventional mixing approaches.

Several limitations should be considered when extrapolating these experimental and modeling results to natural snowpacks. The use of ice cubes provides a controlled representation of a melting porous medium, but it differs from natural snow in grain structure, pore geometry, specific surface area, capillary retention, and the development of preferential flow pathways. These structural differences may affect residence time distributions, effective ice–water contact, and the fraction of ice involved in exchange. In addition, the model does not explicitly represent processes such as sublimation, refreezing, lateral flow, or spatially heterogeneous energy inputs (Ala-aho *et al.*, 2017). Under natural conditions, freeze–thaw cycles, rain-on-snow events, stratigraphic layering, and variable radiative or turbulent energy fluxes may further influence isotopic evolution during melt (Rücker *et al.*, 2019). Despite these simplifications, the combined experimental and modeling results provide useful process-level constraints on isotope modification during meltwater percolation. The findings indicate that deviations from conservative isotope mixing should not necessarily be interpreted as noise or analytical uncertainty, but may instead represent signatures of flow-mediated exchange between mobile water and the melting matrix. Accounting for such exchange processes is therefore important for improving isotope-based interpretations of runoff generation, storage–release dynamics, and hydrological connectivity in snow-dominated catchments (Kirchner, 2016).



380 5. Conclusions

This study combined eight controlled melting experiments using vertically layered ice with a process-based one-dimensional isotope-exchange model to evaluate how isotopic stratigraphy and internal flow conditions shape meltwater isotope evolution. The results show that meltwater trajectories are strongly controlled by the vertical arrangement of isotopically distinct layers and can be reproduced using effective exchange parameters. Best-fit k_r values ranged from 0.11 to 0.54 h⁻¹ and were
385 comparable between $\delta^{18}\text{O}$ and $\delta^2\text{H}$ within individual experiments. The estimated k_r generally increased with percolation velocity, particularly in experiments with a depleted upper layer, whereas f did not exhibit a single relationship with percolation velocity or effective water saturation across the full dataset. Instead, f varied with both flow conditions and layer configuration and tended to decrease under faster-flow conditions within each stratigraphic group. These patterns indicate that effective
390 isotope exchange is controlled by the interaction between isotopic layering and internal flow structure, rather than by bulk flow metrics alone. Although the experiments simplify natural snowpacks and the model does not represent processes such as refreezing, sublimation, or lateral flow, the combined results show that meltwater isotope signals can be modified during percolation before entering soils, groundwater, or streams. Stable isotopes during snowmelt should therefore be interpreted as process-modified tracers rather than strictly conservative end members. Accounting for such flow-dependent isotope modification should improve isotope-based analyses of snowmelt runoff generation and hydrological connectivity in snow-
395 dominated catchments.

Code and data availability

Any additional information required to reproduce the results is available from the corresponding author upon reasonable request.

Author contributions

400 YN: Conceptualization, Data analysis, Writing – original draft, Review and editing. HJ: Conceptualization, Review and editing. CK: Conceptualization, Review and editing, WL: Conceptualization, Review and editing, JL: Conceptualization, , Data analysis, Review and editing.

Competing interests

The authors declare that they have no conflict of interest.



405 Financial support

This work was supported by a National Research Foundation of Korea grant funded by the Korean government (2022R1A2C3007047). This work was partially supported by Korea Institute of Marine Science & Technology Promotion (KIMST) funded by the Ministry of Oceans and Fisheries (RS-2023-00256677; PM23020). Additional support was provided by the Korea Environment Industry & Technology Institute (KEITI) through Aquatic Ecosystem Conservation Research Program, 410 funded by the Korea Ministry of Environment (MOE) (RS-2024-00332851).

References

- Abram, N. J., Mulvaney, R., Wolff, E. W., Triest, J., Kipfstuhl, S., Trusel, L. D., Vimeux, F., Fleet, L., and Arrowsmith, C.: Acceleration of snow melt in an Antarctic Peninsula ice core during the twentieth century, *Nat. Geosci.*, 6, 404–411, <https://doi.org/10.1038/ngeo1787>, 2013.
- 415 Ala-aho, P., Tetzlaff, D., McNamara, J. P., Laudon, H., Kormos, P., and Soulsby, C.: Modeling the isotopic evolution of snowpack and snowmelt: testing a spatially distributed parsimonious approach, *Water Resour. Res.*, 53, 5813–5830, <https://doi.org/10.1002/2017WR020650>, 2017.
- Colbeck, S. C. and Anderson, E. A.: The permeability of a melting snow cover, *Water Resour. Res.*, 18, 904–908, <https://doi.org/10.1029/WR018i004p00904>, 1982.
- 420 Craig, H.: Isotopic variations in meteoric waters, *Science*, 133, 1702–1703, <https://doi.org/10.1126/science.133.3465.1702>, 1961.
- Dini, M. and Stenni, B.: Oxygen isotope characterization of Terra Nova Bay seawater, in: *Ross Sea Ecology*, edited by: Faranda, F. M., Guglielmo, L., and Ianora, A., Springer, Berlin, Heidelberg, Germany, 27–37, https://doi.org/10.1007/978-3-642-59607-0_3, 2000.
- 425 Feng, X., Taylor, S., Renshaw, C. E., and Kirchner, J. W.: Isotopic evolution of snowmelt 1. A physically based one-dimensional model, *Water Resour. Res.*, 38, 35–1–35–8, <https://doi.org/10.1029/2001WR000814>, 2002.
- Fujita, K., Matoba, S., Iizuka, Y., Takeuchi, N., Tsushima, A., Kurosaki, Y., and Aoki, T.: Physically based summer temperature reconstruction from melt layers in ice cores, *Earth Space Sci.*, 8, e2020EA001590, <https://doi.org/10.1029/2020EA001590>, 2021.
- 430 Ham, J. Y., Hur, S. D., Lee, W. S., Han, Y., Jung, H., and Lee, J.: Isotopic variations of meltwater from ice by isotopic exchange between liquid water and ice, *J. Glaciol.*, 65, 1035–1043, <https://doi.org/10.1017/jog.2019.75>, 2019.
- Hashimoto, S., Zhou, S., Nakawo, M., Shimizu, M., and Ishikawa, N.: Temporal isotope changes in wet snow layers in association with mass exchange between snow particles and liquid water in between the particles, *Ann. Glaciol.*, 40, 128–132, <https://doi.org/10.3189/172756405781813492>, 2005.
- 435 Herrmann, A., Lehrer, M., and Stichler, W.: Isotope input into runoff systems from melting snow covers, *Nord. Hydrol.*, 12, 309–318, <https://doi.org/10.2166/nh.1981.0025>, 1981.



- Jacobs, S. S., Fairbanks, R. G., and Horibe, Y. G.: Origin and evolution of water masses near the Antarctic continental margin: evidence from $\text{H}_2^{18}\text{O}/\text{H}_2^{16}\text{O}$ ratios in seawater, in: *Oceanology of the Antarctic Continental Shelf*, Antarctic Research Series, Vol. 43, edited by: Jacobs, S. S., American Geophysical Union, Washington, DC, USA, 59–85, <https://doi.org/10.1029/AR043p0059>, 1985.
- Jasechko, S.: Global isotope hydrogeology–review, *Rev. Geophys.*, 57, 835–965, <https://doi.org/10.1029/2018RG000627>, 2019.
- Jordan, R. E.: A one-dimensional temperature model for a snow cover: technical documentation for SNTHERM.89, Spec. Rep. 91-16, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, NH, USA, 49 pp., 1991.
- 445 Jung, H., Nyamgerel, Y., Ko, K. S., Koh, D. C., Kee, W. S., and Lee, J.: Redistribution of anthropogenic nitrate via artificial snowmaking to mountain aquifers: isotopic evidence and biogeochemical pathways, *Water Res.*, 297, 125669, <https://doi.org/10.1016/j.watres.2026.125669>, 2026.
- Juras, R., Würzer, S., Pavlásek, J., Vitvar, T., and Jonas, T.: Rainwater propagation through snowpack during rain-on-snow sprinkling experiments under different snow conditions, *Hydrol. Earth Syst. Sci.*, 21, 4973–4987, [https://doi.org/10.5194/hess-](https://doi.org/10.5194/hess-21-4973-2017)
450 [21-4973-2017](https://doi.org/10.5194/hess-21-4973-2017), 2017.
- Kaczmarska, M., Isaksson, E., Karlöf, L., Brandt, O., Winther, J.-G., van de Wal, R. S. W., van den Broeke, M., and Johnsen, S. J.: Ice core melt features in relation to Antarctic coastal climate, *Antarct. Sci.*, 18, 271–278, <https://doi.org/10.1017/S0954102006000319>, 2006.
- Kirchner, J. W.: Aggregation in environmental systems – Part 1: seasonal tracer cycles quantify young water fractions, but not mean transit times, in spatially heterogeneous catchments, *Hydrol. Earth Syst. Sci.*, 20, 279–297, [https://doi.org/10.5194/hess-](https://doi.org/10.5194/hess-20-279-2016)
455 [20-279-2016](https://doi.org/10.5194/hess-20-279-2016), 2016.
- Lee, J., Feng, X., Posmentier, E. S., Faiia, A. M., and Taylor, S.: Stable isotopic exchange rate constant between snow and liquid water, *Chem. Geol.*, 260, 57–62, <https://doi.org/10.1016/j.chemgeo.2008.11.023>, 2009.
- Lee, J., Feng, X., Faiia, A. M., Posmentier, E. S., Kirchner, J. W., Osterhuber, R., and Taylor, S.: Isotopic evolution of a
460 seasonal snowcover and its melt by isotopic exchange between liquid water and ice, *Chem. Geol.*, 270, 126–134, <https://doi.org/10.1016/j.chemgeo.2009.11.011>, 2010.
- Ma, Q., Jin, H. J., Bense, V. F., Luo, D. L., Marchenko, S. S., Harris, S. A., and Lan, Y.-C.: Impacts of degrading permafrost on streamflow in the source area of Yellow River on the Qinghai–Tibet Plateau, China, *Adv. Clim. Change Res.*, 10, 225–239, <https://doi.org/10.1016/j.accres.2020.02.001>, 2019.
- 465 McDonnell, J. J.: A rationale for old water discharge through macropores in a steep, humid catchment, *Water Resour. Res.*, 26, 2821–2832, <https://doi.org/10.1029/WR026i011p02821>, 1990.
- McDonnell, J. J., Bonell, M., Stewart, M. K., and Pearce, A. J.: Deuterium variations in storm rainfall: implications for stream hydrograph separation, *Water Resour. Res.*, 26, 455–458, <https://doi.org/10.1029/WR026i003p00455>, 1990.



- Morris, D. A. and Johnson, A. I.: Summary of hydrologic and physical properties of rock and soil materials, as analyzed by
470 the hydrologic laboratory of the U.S. Geological Survey, 1948–1960, U.S. Geological Survey Water-Supply Paper 1839-D,
<https://doi.org/10.3133/wsp1839D>, 1967.
- Nakawo, M., Chiba, S., Satake, H., and Kinouchi, S.: Isotopic fractionation during grain coarsening of wet snow, *Ann. Glaciol.*,
18, 129–134, <https://doi.org/10.3189/S0260305500011381>, 1993.
- Nyamgerel, Y., Han, Y., and Lee, J.: Isotopic evolution of snowmelt and its hydrometeorological importance in snow-covered
475 regions, *Catena*, 234, 107543, <https://doi.org/10.1016/j.catena.2023.107543>, 2024.
- O'Neil, J. R.: Hydrogen and oxygen isotope fractionation between ice and water, *J. Phys. Chem.*, 72, 3683–3684,
<https://doi.org/10.1021/j100856a060>, 1968.
- Porter, T. J. and Opel, T.: Recent advances in paleoclimatological studies of Arctic wedge- and pore-ice stable-water isotope
records, *Permafrost Periglac. Process.*, 31, 429–441, <https://doi.org/10.1002/ppp.2052>, 2020.
- 480 Pu, T., Wang, K., Kong, Y., Shi, X., Kang, S., Huang, Y., He, Y., Wang, S., Lee, J., and Cuntz, M.: Observing and modeling
the isotopic evolution of snow meltwater on the southeastern Tibetan Plateau, *Water Resour. Res.*, 56, e2019WR026423,
<https://doi.org/10.1029/2019WR026423>, 2020.
- Rücker, A., Boss, S., Kirchner, J. W., and von Freyberg, J.: Monitoring snowpack outflow volumes and their isotopic
composition to better understand streamflow generation during rain-on-snow events, *Hydrol. Earth Syst. Sci.*, 23, 2983–3005,
485 <https://doi.org/10.5194/hess-23-2983-2019>, 2019.
- Silvano, A., Rintoul, S. R., Peña-Molino, B., Hobbs, W. R., van Wijk, E., Aoki, S., Tamura, T., and Williams, G. D.: Freshening
by glacial meltwater enhances melting of ice shelves and reduces formation of Antarctic Bottom Water, *Sci. Adv.*, 4, eaap9467,
<https://doi.org/10.1126/sciadv.aap9467>, 2018.
- Taylor, S., Feng, X., Kirchner, J. W., Osterhuber, R., Klaue, B., and Renshaw, C. E.: Isotopic evolution of a seasonal snowpack
490 and its melt, *Water Resour. Res.*, 37, 759–769, <https://doi.org/10.1029/2000WR900341>, 2001.
- Taylor, S., Feng, X., Renshaw, C. E., and Kirchner, J. W.: Isotopic evolution of snowmelt 2. Verification and parameterization
of a one-dimensional model using laboratory experiments, *Water Resour. Res.*, 38, 36-1–36-8,
<https://doi.org/10.1029/2001WR000815>, 2002.
- Vystavna, Y., Holko, L., Hejzlar, J., Perşoiu, A., Graham, N. D., Juras, R., Huneau, F., and Gibson, J.: Isotopic response of
495 run-off to forest disturbance in small mountain catchments, *Hydrol. Process.*, 32, 3650–3661,
<https://doi.org/10.1002/hyp.13280>, 2018.
- Walther, M., Dashtseren, A., Kamp, U., Temujin, K., Meixner, F. X., Pan, C. G., and Gansukh, Y.: Glaciers, permafrost and
lake levels at the Tsengel Khairkhan Massif, Mongolian Altai, during the late Pleistocene and Holocene, *Geosciences*, 7, 73,
<https://doi.org/10.3390/geosciences7030073>, 2017.
- 500 Zhou, S., Nakawo, M., Hashimoto, S., and Sakai, A.: Preferential exchange rate effect of isotopic fractionation in a melting
snowpack, *Hydrol. Process.*, 22, 3734–3740, <https://doi.org/10.1002/hyp.6977>, 2008.