RESPONSE TO EDITOR COMMENTS

TO MANUSCRIPT tc-2017-16-RC1

Title: Experimental observation of transient δ18O interaction between snow and advective airflow under various temperature gradient conditions

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We thank the Editor for his constructive comments and suggestions. All line numbers correspond to the annotated manuscript.

Comment The authors have responded well to both referees comments, and have made extensive revisions to their manuscript. I have identified only a couple of places where I think the manuscript needs attention. These should be easy to resolve before final publication.

Comment #1: There needs to be an explanation in the text for the identical density and porosity between experiment 1 and experiment 2. Even if the two specimens come from the same bulk sample, it would be surprising if they had the exact same density-- was the density measured on the bulk sample but not on the experimental specimens? In any case, if the density can only be determined to 5%, far too many significant precisions are included in table 1.

Revision: All snow samples were taken from the same snow block but the estimated porosity and density in Table 1 are the exact measured snow sample in each experiment by micro-CT. We reduced the number of decimals in Table 1 to a more realistic precision. We added a text in the methods part and in the caption of table 1.

> "All snow samples were taken from the same snow block with an average density of ≈ 210 kg m^{-3}. The estimated density given in Table 1 was the density of the snow sample in each experiment measured by µCT.".

> "Table 1: Morphological properties and flow characteristics of the experimental runs: µCT measured snow density (ρ), porosity (ε), specific surface area per unit mass (SSA), mean pore space diameter (d_{mean}), …"

Comment #2: The wording of the revision in response to R1's comment 18 is a bit confusing: I would recommend writing: "The mean pore size distribution(d_mean) was estimated using the opening-size-distribution operation. This operation can be imagined..."

Revision: Text changed in the revised manuscript.

Comment #3: The revision in response to R1's comment 23 is not clear. I think there are some words missing from the second sentence, and the authors need to be clear whether the memory effect is known to have been important, or whether it is one possible effect that might have produced the observer result.

Revision: We changed this part and added a reference that the memory effect is known but not relevant for the results.

> "In the first approximately 30 min, the isotopic composition of the measured outflow air δ18Oa increased from a low δ18O to a starting value of around -29‰ in each experiment. This was due to memory effect and one possible effect might be condensed water left in the tubes from a prior experiment which had no further impact on the experiments (Penna et al., 2012).".

Reference added:

> Penna, D., Stenni, B., Šanda, M., Wrede, S., Bogaard, T. A., Michelini, M., et al. (2012). Technical Note: Evaluation of between-sample memory effects in the analysis of δ2H and δ18O of water samples measured by laser spectroscopes. Hydrology and Earth System Sciences, 16(10), 3925–3933. http://doi.org/10.5194/hess-16-3925-2012.

Comment #4: At line 196 of the annotated manuscript, there's a sentence that begins "In wind pumping theory..." I'd recommend rewriting this sentence in the active voice to make clear who used the wind-pumping theory, and then make clear whether your calculation of Re also uses the same wind-pumping theory.

Revision: Text changed in the revised manuscript.

> "We performed the experiments with airflow velocities in the snow sample at $u_D \approx 30$ mm s^{-1}, which is a factor of three higher than calculated by Neumann (2003) for a natural snow pack. But looking at the Reynolds number, describing the flow regime inside the pores, our experiments (Re ≈ 0.7) were in the feasible flow regime (laminar flow) of a natural snow pack (Re ≈ 0.65)."

Minor revisions were made throughout the revised manuscript.

We thank the Editor for his insight, suggestions and recommendations.

The authors

Experimental observation of transient $\delta^{18}O$ interaction between snow and advective airflow under various temperature gradient conditions

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Abstract

Stable water isotopes ($\delta^{18}O$) obtained from snow and ice samples of polar regions are used to reconstruct past climate variability, but heat and mass transport processes can affect the isotopic composition. Here we present an experimental study on the effect of airflow on the snow isotopic composition through a snow pack in controlled laboratory conditions. The influence of isothermal and controlled temperature gradient conditions on the $\delta^{18}O$ content in the snow and interstitial water vapor is elucidated. The observed disequilibrium between snow and vapor isotopes led to the exchange of isotopes between snow and vapor under non-equilibrium processes, significantly changing the $\delta^{18}O$ content of the snow. The type of metamorphism of the snow had a significant influence on this process. These findings are pertinent to the interpretation of the records of stable isotopes of water from ice cores. These laboratory measurements

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suggest that a highly resolved climate history is relevant for the interpretation of the snow isotopic composition in the field.

Keywords: snow, isotope, isothermal, metamorphism, advection, tomography, post-depositional process

1. Introduction

Water stable isotopes in polar snow and ice have been used for several decades as proxies for global and local temperatures (e.g. Dansgaard, 1964; Lorius et al., 1979; Grootes et al., 1994; Petit et al., 1999; Johnsen et al., 2001; EPICA Members, 2004). However, the processes that influence the isotopic composition of precipitation in high-latitude are complex, making direct inference of paleo temperatures from the isotopic record difficult (Cuffey et al., 1994; Jouzel et al., 1997, 2003; Hendricks et al., 2000). Several factors affect the vapor and snow isotopic composition, which give rise to ice core isotopic composition, starting from the process of evaporation in the source region, transportation of the air mass to the top of the ice sheet, and post-depositional processes (Craig and Gordon, 1964; Merlivat and Jouzel, 1979; Johnsen et al. 2001; Ciais and Jouzel, 1994; Jouzel and Merlivat, 1984; Jouzel et al., 2003; Helsen et al., 2005, 2006, 2007; Cuffey and Steig, 1998; Krinner and Werner, 2003). Mechanical processes such as mixing, seasonal scouring, or spatial redistribution of snow can alter seasonal and annual records (Fisher et al., 1983; Hoshina et al., 2014). Post-depositional processes associated with wind scouring and snow redistribution are known to introduce a "post-depositional noise" in the surface snow. Comparisons of isotopic records obtained from closely located shallow ice cores have allowed for estimation of a signal-to-noise ratio

and a common climate signal (Fisher and Koerner, 1988, 1994; White et al., 1997; Steen-Larsen et al., 2011; Sjolte et al., 2011; Masson-Delmotte et al., 2015). After deposition, interstitial diffusion in the firn and ice affects the water-isotopic signal but back-diffusion or deconvolution techniques have been used to establish the original isotope signal (Johnsen, 1977; Johnsen et al., 2000).

Snow is a bi-continuous material consisting of fully connected ice crystals and pore space (air) (Löwe et al., 2011). Because of the proximity to the melting point, the high vapor pressure causes a continuous recrystallization of the snow microstructure known as snow metamorphism, even under moderate temperature gradients (Pinzer et al., 2012). The whole ice matrix is continuously recrystallizing by sublimation and deposition, with vapor diffusion as the dominant transport process. Pinzer et al. (2012) showed that a typical half-life of the ice matrix is a few days. The intensity of the recrystallization is dictated by the temperature gradient and this can occur under mid-latitude or polar conditions. Temperature, and geometrical factors (porosity and specific surface area) also play a significant role (Pinzer and Schneebeli, 2009; Pinzer et al., 2012).

The interpretation of ice core data and the comparison with atmospheric model results implicitly rely on the assumption that the snowfall precipitation signal is preserved in the snow-ice matrix (Werner et al., 2011). Classically, ice-core stable-isotope records are interpreted as reflecting precipitation-weighted signals, and compared to observations and atmospheric model results for precipitation, ignoring snow-vapor exchanges between surface snow and atmospheric water vapor (e.g. Persson et al., 2011). However, recent studies carried out on top of the Greenland and Antarctic ice sheets combining continuous atmospheric water vapor isotope observations with daily snow surface sampling document a clear day-to-day variation of isotopic

composition of surface snow between precipitation events as well as diurnal change in the snow isotopes (Steen-Larsen et al., 2014a; Ritter et al., 2016; Casado et al., 2016). This effect was interpreted as being caused by the uptake of the synoptic-driven atmospheric water-vapor isotope signal by individual snow crystals undergoing snow metamorphism (Steen-Larsen et al., 2014a) and the diurnal variation in moisture flux (Ritter et al., 2016). However, the impact of this process on the isotope-temperature reconstruction is not yet sufficiently understood, but crucial to constrain. This process, compared to interstitial diffusion (Johnsen, 1977; Johnsen et al., 2000), will alter the isotope mean value. The field observations challenge the previous assumption that sublimation occurred molecular layer-by-layer with no resulting isotopic fractionation (Dansgaard, 1964; Friedman et al., 1991; Town et al., 2008; Neumann and Waddington, 2004). It is assumed that the solid undergoing sublimation would not be unduly enriched in the heavier isotope species due to the preferential loss of lighter isotopic species to the vapor (Dansgaard, 1964; Friedman et al., 1991). Because self-diffusion in the ice is about three orders of magnitude slower than molecular diffusion in the vapor, the amount of isotopic separation in snow is assumed to be negligible.

Snow has a high permeability (Calonne et al., 2012; Zermatten et al., 2014), which facilitates diffusion of gases and, under appropriate conditions, airflow (Gjessing, 1977; Colbeck, 1989; Sturm and Johnson, 1991; Waddington et al., 1996). In a typical Antarctic and Greenland snow profile, strong interactions between the atmosphere and snow occurs, especially in the first 2 m (Neumann and Waddington, 2004; Town et al., 2008), called the convective zone. In the convective zone, air can move relatively freely and therefore exchange between snow and the atmospheric air occurs. Air flowing into the snow reaches saturation vapor pressure nearly instantly through sublimation (Neumann et al., 2008; Ebner et al., 2015a). Models of the influence of the so-called

98 'wind pumping'-effect (Fisher et al., 1983; Neumann and Waddington, 2004), in which
99 the interstitial water vapor is replaced by atmospheric air pushed through the upper
100 meters of the snow pack by small-scale high and low pressure areas caused by irregular
101 grooves or ridges formed on the snow surface (dunes and sastrugi), have assumed that
102 the snow grains would equilibrate with the interstitial water vapor on timescales
103 governed by ice self-diffusion. However, no experimental data are available to support
104 this assumption. With this in mind the experimental study presented here is specifically
105 developed to investigate the effect of ventilation inside the snow pack on the isotopic
106 composition. Only conditions deeper than 1 cm inside a snowpack are considered.
107 Previous work showed that (1) under isothermal conditions, the Kelvin effect leads to a
108 saturation of the pore space in the snow but does not affect the structural change (Ebner
109 et al., 2015a); (2) applying a negative temperature gradient along the flow direction
110 leads to a change in the microstructure due to deposition of water molecules on the ice
111 matrix (Ebner et al., 2015b); and (3) a positive temperature gradient along the flow had
112 a negligible total mass change of the ice but a strong reposition effect of water
113 molecules on the ice grains (Ebner et al., 2016). Here, we continuously measured the
114 isotopic composition of an airflow containing water vapor through a snow sample under
115 both isothermal and temperature gradient conditions. Micro computed-tomography
116 (μCT) was applied to obtain the 3D microstructure and morphological properties of
117 snow.

118 **2. Experimental setup**

119 Isothermal and temperature gradient experiments with fully saturated airflow and
120 defined isotopic composition were performed in a cold laboratory at around $T_{lab} \approx$ -15
121 °C with small fluctuations of ± 0.8 °C (Ebner et al., 2014). Snow produced from de-
122 ionized tap water in a cold laboratory (water temperature: 30 ºC; air temperature: -20

ºC) was used for the snow sample preparation (Schleef et al., 2014). The snow was sieved with a mesh size of 1.4 mm into a box, and isothermally sintered for 27 days at -5 ºC to increase the strength, in order to prevent destruction of the snow sample due to the airflow, and to evaluate the effect of metamorphism of snow. The morphological properties of the snow are listed in Table 1. The sample holder (diameter 53 mm, height 30 mm, 0.066 liter) was filled by a cylinder cut out from the sintered snow. To prevent air flow between snow sample and the sample holder walls, the undisturbed snow disk was filled in at a higher temperature (about -5 °C) and sintering was allowed for about 1 h before cooling down and start of the experiment. The setup of Ebner et al. (2014) was modified by additionally inserting a water vapor isotope analyzer (Model: L1102-I Picarro, Inc., Santa Clara, CA, USA) to measure the isotopic ratio $\delta^{18}O$ of the water vapor contained in the airflow at the inlet and outlet of the sample holder. The experimental setup consisted of three main components (humidifier, sample holder, and the Picarro analyzer) connected with insulated copper tubing and Swagelok fitting (Fig. 1). The tubes to the Picarro analyzer were heated to prevent deposition of water vapor and thereby fractionation. The temperature was monitored with thermistors inside the humidifier and at the inlet and outlet of the snow sample. A dry air pressure tank controlled by a mass flow controller (EL-Flow, Bronkhorst) generated the airflow. A humidifier, consisting of a tube (diameter 60 mm, height 150 mm, 0.424 liter volume) filled with crushed ice particles (snow from Antarctica with low $\delta^{18}O$ composition), was used to saturate the dry air entering the humidifier with water vapor at an almost constant isotopic composition. The air temperature in the humidifier and at the inlet of the snow sample was maintained at the same value (accuracy ± 0.2 K) to limit the influence of variability in absolute vapor pressure and isotopic composition. We measured the $\delta^{18}O$ of the water vapor produced by the humidifier before and after each

148 experimental run ($\delta^{18}O_{hum}$). The outlet flow ($\delta^{18}O_a$) of the sample holder was
149 continuously measured during the experiment to analyze the temporal evolution of the
150 isotopic signal. All data from the Picarro analyzer were corrected to the humidity
151 reference level using the established instrument humidity-isotope response (Steen-
152 Larsen et al. 2013; 2014b). In addition, VSMOW-SLAP correction and drift correction
153 were performed. We followed the calibration protocol and used the calibration system
154 described in detail by Steen-Larsen et al. (2013; 2014b).

155 The sample holder described by Ebner et al. (2014) was used to analyze the snow by
156 µCT. Tomography measurements were performed with a modified µ-CT80 (Scanco
157 Medical). The equipment incorporated a microfocus X-ray source, operated at 70 kV
158 acceleration voltage with a nominal resolution of 18 µm. The samples were scanned
159 with 1000 projections per 180º in high-resolution setting, with typical adjustable
160 integration time of 200 ms per projection. The field of view of the scan area was 36.9
161 mm of the total 53 mm diameter, and subsamples with a dimension of 7.2 × 7.2 × 7.2
162 mm^3 were extracted for further processing. The reconstructed µCT images were filtered
163 using a 3 × 3 × 3 median filter followed by a Gaussian filter (σ = 1.4, support = 3). The
164 Otsu method (Otsu, 1979) was used to automatically perform clustering-based image
165 thresholding to segment the grey-level images into ice and void phase. Morphological
166 properties in the two-phase system were determined based on the exact geometry
167 obtained by the µCT. Tetrahedrons corresponding to the enclosed volume of the
168 triangulated ice matrix surface were applied on the segmented data to determine
169 porosity (ε) and specific surface area (SSA). ~~Opening size distribution operation was~~
170 ~~applied in the segmented µCT data to extract the mean pore size (d_{mean}).~~ The mean pore
171 size distribution was estimated using the opening-size-distribution operation. This

operation can be ~~The opening size distribution can be~~ imagined as virtual sieving with different mesh size (Haussener et al., 2012).

Three experiments with saturated advective airflow through the snow sample were performed to record the following parameters and analyze their effects: (1) isothermal conditions to analyze the influence of curvature effects (Kaempfer al et., 2007); (2) positive temperature gradient applied to the snow sample where cold air entering the sample is heated while flowing through the sample in order to analyze the influence of sublimation; (3) negative temperature gradient applied to the snow sample where warm air entering the sample is cooled while flowing across the sample, to analyze the influence of net deposition. During the temperature gradient experiments, a temperature difference of 1.4 ºC and 1.8 ºC was imposed resulting in a gradient of +47 K m^{-1} and -60 K m^{-1}, respectively. The runs were performed at atmospheric pressure and with a volume flow rate of 3.0 liter min^{-1} corresponding to an average flow speed in the pores of $u_D \approx 30$ mm s^{-1}. We performed the experiments with airflow velocities in the snow sample at $u_D \approx 30$ mm s^{-1}, which is a factor of three higher than calculated by Neumann (2003) for a natural snow pack. But looking at the Reynolds number, describing the flow regime inside the pores, our experiments (Re ≈ 0.7) were in the feasible flow regime (laminar flow) of a natural snow pack (Re ≈ 0.65). ~~In wind pumping theory, an airflow velocity of $u_D \approx 10$ mm s^{-1} (corresponding Reynolds number Re ≈ 0.65) was estimated inside the surface snow layers ($d_{mean} \approx 1$ mm) for a high wind speed above the snow surface (≈ 10 m s^{-1}) (Neumann, 2003). We performed experiments with airflow velocities inside the snow sample of around 30 mm s^{-1} (corresponding Reynolds number Re = 0.7), which was a factor three higher than in natural conditions. But looking at the Reynolds number our experiments were in the feasible flow regime (laminar flow) of a natural snow pack.~~ In experiment (2) the outlet temperature and in experiment (3) the

inlet and also the humidifier temperature were actively controlled using thermo-electric elements. Variations in temperature of up to ± 0.8 ºC were due to temperature fluctuations inside the cold laboratory, leading to slightly variable temperature gradients and mean temperature in experiment (2) and (3). Table 1 presents a summary of the experimental conditions and the morphological properties of the snow samples. All snow samples were taken from the same snow block with an average density of ≈ 210 kg m^{-3}. The density given in Table 1 was the density of the snow sample in each experiment measured by µCT. At the end of each experiment, the snow sample was cut into five layers of 6 mm height and the isotopic composition of each layer was analyzed to examine the spatial $\delta^{18}O$ gradient in the isotopic composition of the snow sample.

A slight increase with a maximum of 0.7 ‰ of $\delta^{18}O$ in the water vapor produced by the humidifier was observed in experiment (1), with lower increases during experiments (2) and (3) (Table 2). This change of ~0.7‰ is not significant compared to the difference between the isotopic composition of the water vapor and the snow sample in the sample holder of ~53‰ and the temporal change of the water vapor isotopes on the back side of the snow sample.

In the first approximately 30 min, the isotopic composition of the measured outflow air $\delta^{18}O_a$ increased from a low $\delta^{18}O$ to a starting value of around -29‰ in each experiment. This was due to memory effect and one possible effect might be condensed water left in the tubes from a prior experiment which had no further impact on the experiments (Penna et al., 2012). ~~This was due to memory effect possible condensed water left in the tubes from a prior experiment.~~

3. Results

3.1 Isothermal condition

The experiment (1) was performed for 24 h at a mean temperature of T_{mean} = -15.5 ºC. $\delta^{18}O_a$ decreased exponentially in the outlet flow observed throughout the experimental run as shown in Fig. 2. Initially, the $\delta^{18}O_a$ content in the flow was -27.7 ‰ and exponentially decreased to -47.6 ‰ after 24 h. The small fluctuations in the $\delta^{18}O_a$ signal at $t \approx 7$ h, 17 h and 23 h were due to small temperature changes in the cold laboratory.

We observed a strong interaction between the airflow and the snow as manifest by the isotopic composition of the snow. The $\delta^{18}O_s$ signal in the snow decreased by 4.75 – 7.78 ‰ and an isotopic gradient in the snow was observed after the experimental run, shown in Fig. 3. Initially, the snow had a homogeneous isotopic composition of $\delta^{18}O_s$ = -10.97 ‰ but post-experiment sampling showed a decrease in the snow $\delta^{18}O$ at the inlet side to -17.75 ‰ and at the outlet side to -15.72 ‰. The spatial $\delta^{18}O_s$ gradient of the snow had an approximate slope of 0.68 ‰ mm^{-1} at the end of the experimental run. Table 2 shows the $\delta^{18}O$ value in snow at the beginning (t = 0) and end (t = 24 h) of the experiment.

3.2 Air warming by a positive temperature gradient along the airflow

The experiment (2) was performed over a period of 24 h with an average temperature gradient of approximatively +47 K m^{-1} (warmer temperatures at the outlet of the snow) and an average mean temperature of -14.7 ºC. As in the isothermal experiment (1), we observed a relaxing exponential decrease of $\delta^{18}O_a$ in the outlet flow throughout the measurement period as shown in Fig. 2, but the decrease was slower compared to the isothermal run. Initially, the $\delta^{18}O_a$ content in the flow coming through the snow disk was -29.8 ‰ and exponentially decreased to -41.9 ‰ after 24 h. The small fluctuations in the $\delta^{18}O_a$ signal at $t \approx 2.7$ h, and 12.7 h were due to small temperature changes in the cold laboratory.

The $\delta^{18}O_s$ signal in the snow decreased 4.66 – 7.66 ‰ and a gradient in the isotopic composition of the snow was observed after the experimental run, shown in Fig. 3. Initially, the snow had a homogeneous isotopic composition of $\delta^{18}O_s$ = -11.94 ‰, but post-experiment sampling showed a decrease at the inlet side to -19.6 ‰ and at the outlet side to -16.6 ‰. The spatial $\delta^{18}O_s$ gradient of the snow had an approximate slope of 1.0 ‰ mm^{-1} at the end of the experimental run. Table 2 shows the $\delta^{18}O_s$ value in snow at the beginning (t = 0) and end (t = 24 h) of the experiment.

3.3 Air cooling by a negative temperature gradient along the air flow

The experiment (3) was performed for 84 h instead of 24 h to better estimate the trend in $\delta^{18}O_a$ in the outlet flow. An average temperature gradient of approximately -60 K m^{-1} (colder temperatures at the outlet of the snow) and an average mean temperature of -13.2 ºC were observed during the experiment. As in the previous experiments, a relaxing exponential decrease of $\delta^{18}O_a$ in the outlet flow was observed throughout the experimental run as shown in Fig. 2, but the decrease was slower compared to the isothermal run and temperature gradient opposed to the airflow. Initially, the $\delta^{18}O_a$ content in the flow was -29.8 ‰ and exponentially decreased to -37.7 ‰ after 84 h. The small fluctuations in the $\delta^{18}O_a$ signal at $t \approx$ 7.3 h, 21.3 h, 31.3 h, 45.3 h, 55.3 h, 69.3 h, and 79.3 h were due to small temperature changes in the cold laboratory.

The $\delta^{18}O_s$ signal in the snow decreased 4.46 – 15.09 ‰ and a gradient in the isotopic composition of the snow was observed after the experimental run, shown in Fig. 3. Initially, the snow had an isotopic composition of $\delta^{18}O_s$ = -10.44 ‰ but post-experiment sampling showed a decrease at the inlet side to -25.53 ‰ and at the outlet side to -15.00 ‰. The spatial $\delta^{18}O_s$ gradient of the snow had an approximate slope of 3.5 ‰ mm^{-1} at the end of the experimental run. Table 2 shows the $\delta^{18}O_s$ value in snow at the beginning (t = 0) and end (t = 84 h) of the experiment.

4. Discussion

All experiments showed a strong exchange in $\delta^{18}O$ between the snow and water-vapor saturated air resulting in a significant change of the value of the stable isotopes in the snow. The advective conditions in the experiments were comparable with surface snow layers in Antarctica and Greenland, but at higher temperature, especially compared to interior Antarctica.

The results also showed strong interactions in $\delta^{18}O$ between snow and air depending on the different temperature gradient conditions. The experiments indicate that temperature variation and airflow above and through the snow structures (Sturm and Johnson, 1991; Colbeck, 1989; Albert and Hardy, 1995) seem to be dominant processes affecting water stable isotopes of surface snow. The results also support the statement that an interplay between theoretically expected layer-by-layer sublimation and deposition at the ice-matrix surface and the isotopic content evolution of snow cover due to mass exchange between the snow cover and the atmosphere occurs (Sokratov and Golubev, 2009). The specific surface area of snow exposed to mass exchange (Horita et al., 2008) and by the depth of the snow layer exposed to the mass exchange with the atmosphere (He and Smith, 1999) plays an important role. Our results support the interpretation that changes in surface snow isotopic composition are expected to be significant if large day-to-day surface changes in water vapor occur in between precipitation events, wind pumping is efficient and snow metamorphism is enhanced by temperature gradients in the upper first centimeters of the snow (Steen-Larsen et al., 2014a).

We expect that our findings will lead to improvement of the interpretation of the water stable isotope records from ice cores. Classically, ice core stable isotope records are interpreted as paleo-temperature reflecting precipitation-weighted signals. When

296 comparing observations and atmospheric model results for precipitation with ice core
297 records, such vapor-snow exchanges are normally ignored (e.g. Persson et al., 2011;
298 Fujita and Abe, 2006). However, vapor-snow exchange enhanced by recrystallization
299 rate seems to be an important factor for the high variation in the snow surface $\delta^{18}O$
300 signal as supported by our experiments. It was hypothesized that the changes in the
301 snow-surface $\delta^{18}O$ reported by Steen-Larsen et al. (2014a) are caused by changes in
302 large-scale wind and moisture advection of the atmospheric water vapor signal and
303 snow metamorphism. The strong interaction between atmosphere and near-surface snow
304 can modify the ice core water stable isotope records.

305 The rate-limiting step for isotopic exchange in the snow is isotopic equilibration
306 between the pore-space vapor and surrounding ice grains. The relaxing exponential
307 decrease of $\delta^{18}O$ in the outflow of our experiments predicted that full isotopic
308 equilibrium between snow and atmospheric vapor will not be reached at any depth
309 (Waddington et al., 2002; Neumann and Waddington, 2004) but changes towards
310 equilibrium with the atmospheric state occurs (Steen-Larsen et al., 2013, 2014a).

311 As snow accumulates, the upper 2 m are advected through the ventilated zone
312 (Neumann and Waddington, 2004; Town et al., 2008). In areas with high accumulation
313 rate (e.g. South Greenland), snow is advected for a short time through the ventilated
314 zone. The snow exposed a relatively short time to vapor snow exchange would result in
315 higher spatial variability compared to long-time exposure. However, the effects of snow
316 ventilation on isotopic composition may become more important as the accumulation
317 rate of the snow decreases (< 50 mm a^{-1}), such that snow remains in the near-surface
318 ventilated zone for many years (Waddington et al., 2002; Hoshina et al., 2014; Hoshina
319 et al., 2016). As the snow remains longer in the near-surface ventilated zone, a larger
320 $\delta^{18}O$ exchange between snow and atmospheric vapor will occur. Consequently, the

isotopic content of layers at sites with high and low accumulation rates can evolve differently, even if the initial snow composition had been equal, and the sites had been subjected to the same histories of air-mass vapor.

Despite a relatively small change in the difference between the isotopic composition of the incoming vapor and the snow, large differences in the isotopic composition of the water vapor at the outlet flow exist for the three different experimental setups. Based on the difference in the outlet water vapor isotopic composition, we hypothesized that different processes are at play for the different experiments. It is obvious that there is a fast isotopic exchange with the surface of the ice crystals, and a much slower timescale on which the interior of the ice crystals is altered. Due to the low diffusivity of $H_2{}^{16}O$ and $H_2{}^{18}O$ in ice ($D_{H_2{}^{18}O} \approx D_{H_2{}^{16}O} = \sim 10^{-15}$ m^2 s^{-1} (Ramseier, 1967; Johnsen et al., 2000), we assumed that the interior of the ice crystals is not altered on the timescale of the experiment. This explained why the net isotopic change of the bulk sample is relatively small compared to the changes in the outlet water vapor isotopes. The effective 'ice-diffusion depth' of the isotopic exchange during the experiments is given as $L_D = \sqrt{D \cdot t}$, where D is the diffusion coefficient of $H_2{}^{16}O$ and $H_2{}^{18}O$ in ice, respectively, and t the experimental time. The calculated 'ice-diffusion depth' L_D, is ~ 9.3 μm for experiments (1) and (2), and ~17.4 μm for experiment (3), respectively, indicating an expected a minimal change of the interior of the ice crystal. However, snow has a large specific surface area and therefore a high exchange area. This has an effect on the $\delta^{18}O$ snow concentration. The fraction of the total volume V_{tot} of ice that is close enough to the ice surface to be affected by diffusion in time t is then $\rho_{ice} \cdot SSA \cdot L_D$, where SSA is the specific surface area (area per unit mass), and L_D is the diffusion depth, defined above, for time t. For $t \approx 24$ hours, a large fraction (24 to 43 %) of the total volume V_{tot} of the ice matrix can be accessed through diffusion. It is quite hard to see the total $\delta^{18}O$ snow

346 difference between experiments (1) and (2) after the experiment compared to the $\delta^{18}O$
347 of the vapor in the air at the outlet. There is a small, but notable, difference in the total
348 $\delta^{18}O$ of the snow between experiment (1) and (2). Due to the higher recrystallization
349 rate of experiment (2) the spatial $\delta^{18}O_s$ gradient of the snow (1.0 ‰ mm^{-1}) is higher than
350 for experiment (1) (0.68 ‰ mm^{-1}). Increasing the experimental time, the $\delta^{18}O$ change in
351 the snow increases (experiment (3)). In general, the calculated 'ice-diffusion depth' is
352 realistic under isothermal conditions where diffusion processes are the main factors
353 (Kaempfer and Schneebeli, 2007; Ebner et al., 2015). Applying a temperature gradient,
354 the impact of diffusion is suppressed due to the high recrystallization rate by
355 sublimation and deposition. Due to the low half-life of the ice matrix of a few days, the
356 growth rates are typically on the order of 100 μm per day (Pinzer et al., 2012).
357 Therefore, this redistribution of ice caused by temperature gradient counteracts the
358 diffusion into the solid ice.

359 By comparing similarities and differences between the outcomes of the three
360 experimental setups we will now discuss the physical processes influencing the
361 interaction and exchange processes within the snowpack between the snow and the
362 advected vapor. We first notice that the final snow isotopic profile of experiment (1)
363 (isothermal) and (2) (positive temperature gradient along the direction of the flow) are
364 comparable to each other. Despite this similarity, the evolution in the outlet water vapor
365 of experiment (1) showed a significantly stronger depletion compared to experiment (2).
366 For experiment (3) (negative temperature gradient along the direction of the flow) we
367 observed the smallest change in outlet water vapor isotopes but the largest snow-pack
368 isotope gradient after the experiment. However, this change was caused by 84 hours
369 flow instead of 24 hours.

Curvature effects, temperature gradients and therefore the recrystallization rate influence the mass transfer of $H_2{}^{16}O$/ $H_2{}^{18}O$ molecules. The higher the recrystallization rate of the snow the slower the adaption of the outlet air concentration to the inlet air concentration (see in experiment (2) and (3)). Under isothermal conditions (experiment (1)) the only effect influencing the recrystallization rate is the curvature effect (Kaempfer and Schneebeli, 2007). However, based on the experimental observations (Kaempfer and Schneebeli, 2007) this effect decreases with decreasing temperature and increasing experimental time. Applying an additional temperature gradient on a snow sample causes complex interplays between local sublimation and deposition on surfaces and the interaction of water molecules in the air with the ice matrix due to changing saturation conditions of the airflow. Therefore, the recrystallization rate increases and causes the change in the $\delta^{18}O$ of the air. For experiment (2) there is a complex interplay between sublimation and deposition of water molecules into the interstitial flow (Ebner et al., 2015c) while for experiment (3) there is deposition of molecules carried by the interstitial flow onto the snow crystals (Ebner et al., 2015b). Furthermore, in the beginning of each experiment there is a tendency to sublimate from edges of the individual snow crystals due to the higher curvature. As the edges were sublimated and deposition occurred in the concavities, the individual snow crystals became more rounded, slowing down the transfer of water molecules into the interstitial airflow. We noticed for all three experiments that within the uncertainty of the isotopic composition of the snow, the initial isotopic composition of the vapor was the same and in isotopic equilibrium with the snow. The difference between experiment (1) and (2) lies in the fact that due to the temperature gradient in experiment (2) there is an increased transfer of water vapor with the isotopic composition of the snow into the airflow. Hence the depleted air from the humidifier advected through the snow disk is mixed with a

relatively larger vapor flux from the snow crystals. Additionally, we also expected less deposition into the concavities in experiment (2) compared to experiment (1). However, it is interesting to note that the final isotopic profile of the snow disk is similar in experiment (1) and experiment (2). We interpreted this as being a result of two processes acting in opposite direction: although relatively isotope-depleted vapor from the humidifier was deposited on the ice matrix there was also a higher amount of sublimation of relatively isotope-enriched vapor from the snow disk in experiment (2). Experiment (3) separates itself from the other two experiments in the way that as the water vapor from the humidifier is advected through the snow disk there is a continuous deposition of very depleted air due the negative temperature gradient. As for the case of experiment (1) and (2) there was also in experiment (3) a constant sublimation of the convexities into the vapor stream. We notice that despite the fact that experiment (3) ran for 84 hours the snow at the outlet side of the snow-disk did not become more isotopically depleted compared to experiment (1) and (2). However, the snow on the inlet side became significantly more isotopically depleted. This observation, together with the fact that the vapor of the outlet of the snow-disk is less depleted compared to experiment (1) and (2), leads us to hypothesize that there is a relatively larger deposition of isotopically depleted vapor from the humidifier as the vapor is advected through the snow disk. This means that a relatively larger component of the isotopic composition of the vapor is originating by sublimation from the convexities of the snow disk and less from the isotopically depleted vapor from the humidifier.

Our results and conclusions indicate that there is a need for additional validation. Specifically, it would be crucial to know the mass balance of the snow disk more precisely, which could be done by reconstructing the entire snow disk following the change in density and morphological properties over the entire height. Ideally, the entire

sample would be tomographically measured with a resolution of 4 x 4 x 4 mm^3, each cube corresponding to the representative volume. Insights would also be achieved with experiments using snow of the same isotopic composition, but different SSA, as more precise calculation of the different observed exchange rates would be allowed. Additionally, different and colder background temperatures should be tested to better understand inland Antarctic environment and the effect of the quasi-liquid layer, which is necessary for the development of a numerical model. Isotopically different combinations of vapor and snow should be performed. In the present manuscript, vapor with low $\delta^{18}O$ isotopic composition was transported through snow with relative high $\delta^{18}O$ isotopic composition. It would be interesting to reverse the combination and perform experiments with different combinations to provide more insights on mass and isotope exchanges between vapor and snow. Experiments with longer running time help to understand the change in the ice matrix better under low accumulation conditions.

4. Summary and conclusion

Laboratory experimental runs were performed where a transient $\delta^{18}O$ interaction between snow and air was observed. The airflow altered the isotopic composition of the snowpack and supports an improved climatic interpretation of ice core stable water isotope records. The water vapor saturated airflow with an isotopic difference of up to 55‰ changed within 24 h and 84 h the original $\delta^{18}O$ isotope signal in the snow by up to 7.64 ‰ and 15.06 ‰. The disequilibrium between snow and air isotopes led to the observed exchange of isotopes, the rate depending on the temperature gradient conditions. Concluding, increasing the recrystallization rate in the ice matrix causes the temporal change of the $\delta^{18}O$ concentration at the outflow to decrease (experiment (2) and (3)). Decreasing the recrystallization rate causes the temporal curve of the outlet

444 concentration to become steeper reaching the $\delta^{18}O$ inlet concentration of the air faster
445 (experiment (1)).

446 Additionally, the complex interplay of simultaneous diffusion, sublimation and
447 deposition due to the geometrical complexity of snow has a strong effect on the $\delta^{18}O$
448 signal in the snow and cannot be neglected. A temporal signal can be superimposed on
449 the precipitation signal, (a) if the snow remains near the surface for a long time, i.e. in a
450 low-accumulation area, and (b) is exposed to a history of air masses carrying vapor with
451 a significantly different isotopic signature than the precipitated snow.

452 These are novel measurements and will therefore be important as the basis for
453 further research and experiments. Our results represent direct experimental observation
454 of the interaction between the water isotopic composition of the snow, the water vapor
455 in the air and recrystallization due to temperature gradients. Our results demonstrate that
456 recrystallization and bulk mass exchange must be incorporated into future models of
457 snow and firn evolution. Further studies are required on the influence of temperature
458 and airflow as well as snow microstructure on the mass transfer phenomena for
459 validating the implementation of stable water isotopes in snow models.

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462 **Acknowledgements**

463 The Swiss National Science Foundation granted financial support under project Nr.
464 200020-146540. H.C. Steen-Larsen was supported by the AXA Research Fund. The
465 authors thank K. Fujita, E. D. Waddington and an anonymous reviewer for the
466 suggestions and critical review. M. Jaggi, S. Grimm, A. Schlumpf, and S. Berben gave
467 technical support. The data for this paper are available by contacting the corresponding
468 author.

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711 **Table 1:** Morphological properties and flow characteristics of the experimental runs:
712 μCT measured snow density (ρ), porosity (ε), specific surface area per unit mass (SSA),
713 mean pore space diameter (d_{mean}), superficial velocity in snow (u_D), corresponding
714 Reynolds number ($Re = d_{mean} \cdot u_D/\nu_{air}$), average inlet temperature of the humidifier and
715 at the inlet ($T_{in,mean}$), average outlet temperature at the outlet ($T_{out,mean}$), and average
716 temperature gradient (∇T_{ave}). Experiment (1) corresponds to the isothermal conditions;
717 Experiment (2) to air warming; and Experiment (3) to air cooling in the snow sample.
718

	ρ kg m^{-3}	ε –	SSA m^2 kg^{-1}	d_{mean} mm	u_D m s^{-1}	Re –	$T_{in,mean}$ °C	$T_{out,mean}$ °C	∇T_{ave} K m^{-1}
Experiment (1)	202	0.78	28	0.39	0.03	0.76	-15.5	-15.5	–
Experiment (2)	202	0.78	30	0.36	0.03	0.70	-15.4	-14.0	+47
Experiment (3)	220	0.76	27	0.37	0.031	0.74	-12.3	-14.1	-60

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720 **Table 2:** $\delta^{18}O$ in the vapor in the humidifier ($\delta^{18}O_{hum}$) and of the snow in the sample
721 holder ($\delta^{18}O_s$) at the beginning ($t = 0$) and end (t = end) of each experiment and the final
722 $\delta^{18}O$ content of the snow in the sample holder at the inlet ($z = 0$ mm) and outlet ($z = 30$
723 mm). Experiment (1) corresponds to the isothermal conditions; Experiment (2) to air
724 warming; and Experiment (3) to air cooling in the snow sample.
725

	$\delta^{18}O_{hum}$ ‰		$\delta^{18}O_{s,\ t=0}$ ‰	$\delta^{18}O_{s,\ t=end}$ ‰	
	$t = 0$	t = end		$z = 0$ mm	$z = 30$ mm
Experiment (1)	-68.2	-67.5	-10.97	-17.75	-15.72
Experiment (2)	-66.3	-66.1	-11.94	-19.60	-16.60
Experiment (3)	-62.8	-62.2	-10.44	-25.53	-15.00

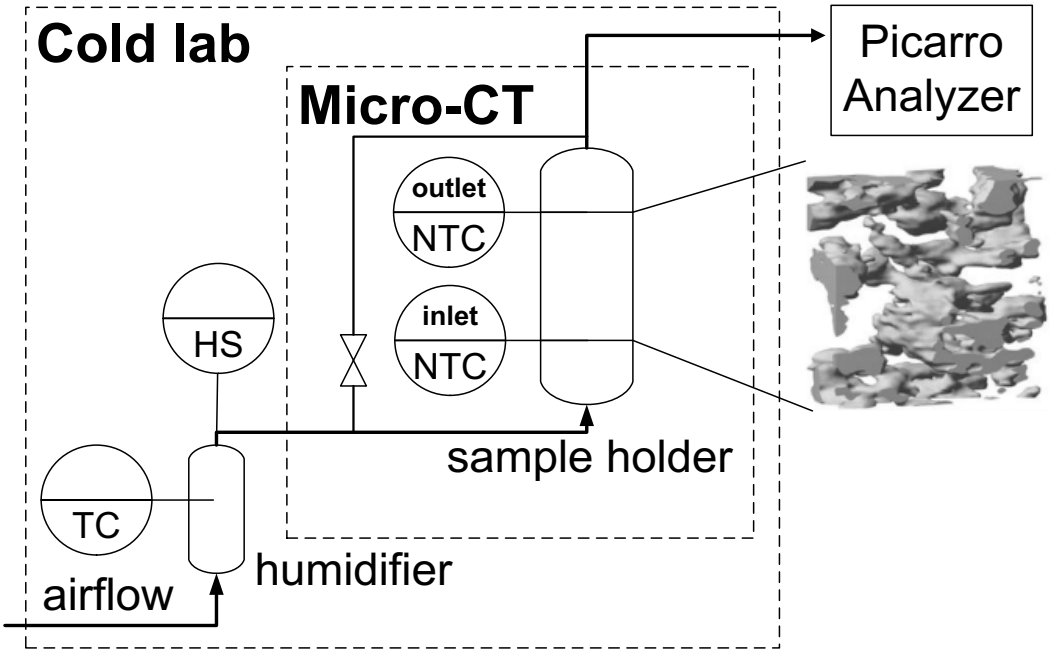
726

Figure captions

Fig. 1. Schematic of the experimental setup. A thermocouple (TC) and a humidity sensor (HS) inside the humidifier measured the the mean temperature and humidity of the airflow. Two thermistors (NTC) close to the snow surface measured the inlet and outlet temperature of the airflow (Ebner et al., 2014). The Picarro Analyzer measured the isotopic composition $\delta^{18}O$ of the outlet flow. Inset: 3D structure of 110 × 42 × 110 voxels (2 × 0.75 × 2 mm^3) obtained by the μCT.

Fig. 2. Temporal isotopic composition of $\delta^{18}O$ of the outflow for each of the experimental runs. The spikes in the $\delta^{18}O$ were due to small temperature changes in the cold laboratory (Ebner et al., 2014). Exp. (1) corresponds to the isothermal conditions; Exp. (2) to air warming; and Exp. (3) to air cooling in the snow sample. The higher the recrystallization rate of the snow the slower the adaption of $\delta^{18}O$ of the outlet air to the inlet air. The illustration in the lower right corner shows the relation between $\delta^{18}O$ of the initial snow, inlet, and outlet of the air.

Fig. 3. Spatial isotopic composition of $\delta^{18}O$ of the snow sample at the beginning (t = 0) and at the end (t = end) for each experiment. The air entered at z = 0 mm and exited at z = 30 mm. Exp. (1) corresponds to the isothermal conditions; Exp. (2) to air warming; and Exp. (3) to air cooling in the snow sample.


Cold lab
Micro-CT
Picarro
Analyzer
outlet
NTC
inlet
NTC
HS
sample holder
TC
humidifier
airflow

748

749 Fig. 1

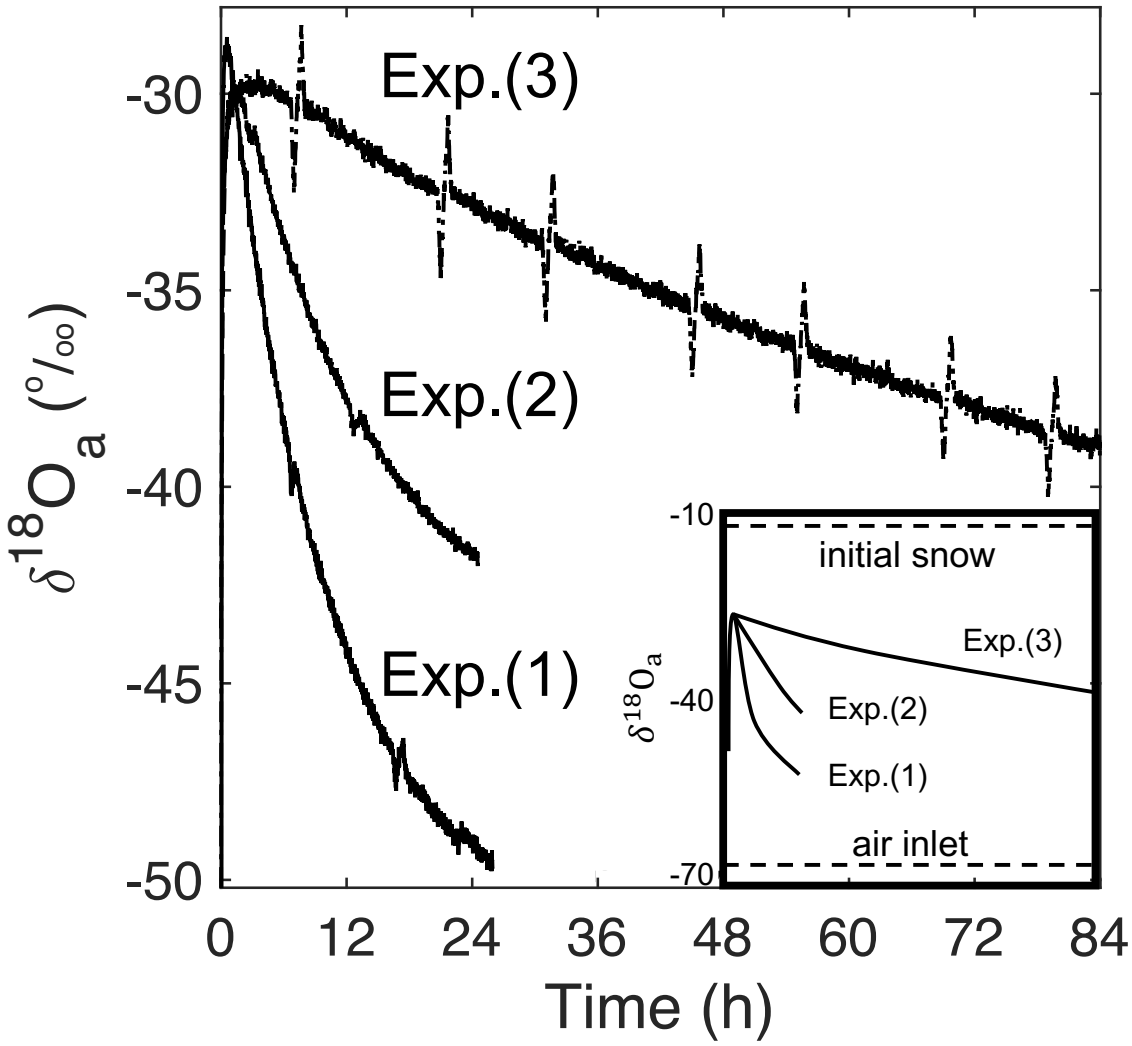
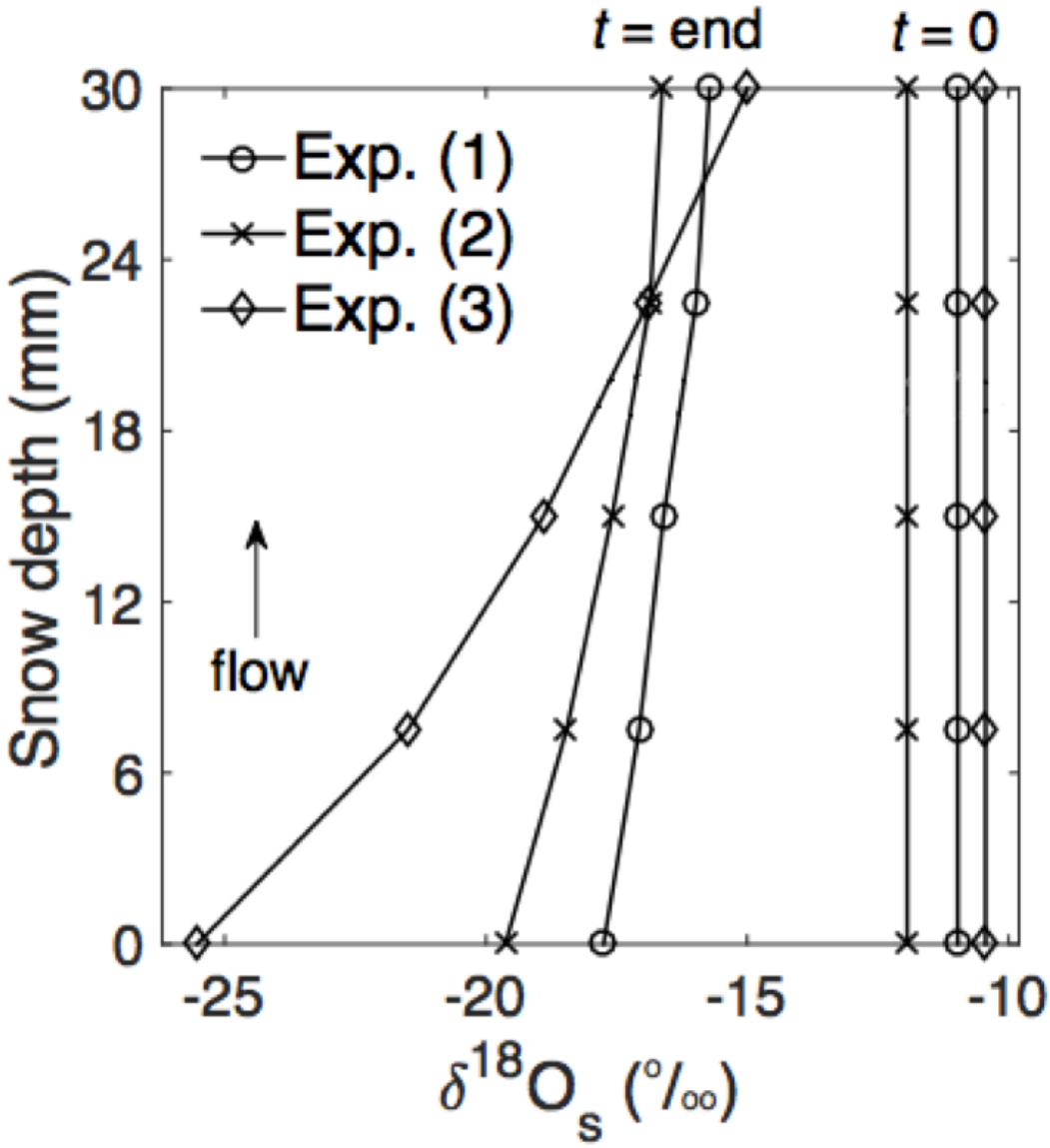

Exp.(3)
Exp.(2)
Exp.(1)
-30
-35
-40
-45
-50
0
12
24
36
48
60
72
84
Time (h)
$\delta^{18}O_a$ (‰)
-10
-40
-70
initial snow
Exp.(3)
Exp.(2)
Exp.(1)
air inlet
$\delta^{18}O_a$

Fig. 2


t = end
t = 0
30
24
18
12
6
0
Snow depth (mm)
Exp. (1)
Exp. (2)
Exp. (3)
flow
-25
-20
-15
-10
δ18Os (°/oo)

753

754 Fig. 3