RESPONSE TO REFEREES' COMMENTS
TO MANUSCRIPT TC-2015-18

Title: Tomography-based monitoring of isothermal snow metamorphism under advective conditions

Authors: P. P. Ebner, M. Schneebeli, and A. Steinfeld

We thank Frédéric Flin for his constructive comments. We agreed with all of his comments, and answered them. The line numbers correspond to those of the revised manuscript.

REVIEWER: Frédéric Flin

The authors have significantly improved the scientific consistency of the manuscript. I recommend publication after the following comments have been taken into account.

Specific comments:

Comment #1: line 11-13: *The effect of diffusion and advection across the snow pores on the snow microstructure were analysed in controlled laboratory experiments and further elaborated on natural snowpacks.*

I suggest removing "and further elaborated on natural snowpacks.", as it does not seem realistic to extrapolate the results obtained on 4 samples (2 snow types) under very specific conditions to all natural snowpacks.

Revision: Text changed in the revised manuscript:

> Line 11-13: "The effect of diffusion and advection across the snow pores on the snow microstructure were analysed in controlled laboratory experiments and possible effects on natural snowpacks discussed."

Comment #2: line 13-15: *The 3D digital geometry obtained by tomographic scans was used in direct pore-level numerical simulations to determine the effective transport properties.*

Actually, only permeability has been computed (no Dupuit-Forchheimer coefficient, no vapor diffusivity, no thermal conductivity…). Replacing "transport properties" by "permeability" would be more informative and accurate.

Revision: Text changed in the revised manuscript:

> Line 13-15: "The 3D digital geometry obtained by tomographic scans was used in direct pore-level numerical simulations to determine the effective permeability."

<u>**Comment #3:**</u> line 17-19: *Isothermal snow metamorphism is driven by evaporation-deposition caused by the Kelvin effect and is the limiting factor independently of the transport regime in the pores.*

This is just a suggestion, but the most appropriate terminology would probably be "sublimation-deposition". Please consider using it more systematically throughout the paper.

Revision: Text changed in the revised manuscript:

> Line 17-19: "Isothermal snow metamorphism is driven by sublimation-deposition caused by the Kelvin effect and is the limiting factor independently of the transport regime in the pores."

<u>**Comment #4:**</u> line 81-82: *Two different snow types with high specific surface area were considered to evaluate the structural change in the earlier stage of isothermal metamorphism of new snow.*

This sentence is unclear. Do you just refer to sa1 and sa2 series or to all series? The sentence is ambiguous because sa1 and sa2 have probably the same snow type while sa3 and sa4 have quite moderate SSAs and cannot be considered as new snow samples. Please clarify these points in the text.

Revision: Text added in the revised manuscript:

> Line 83: "Partly decomposed snow (DFdc) was used for low flow rate ('sa1' and 'sa2') whereas large rounded snow (RGlr) snow was used for higher flow rate ('sa3' and 'sa4') to prevent destruction of the fragile snow structure (Fierz et al., 2009)."

Reference added

Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K. and Sokratov, S.A.: The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology N°83, IACS Contribution N°1, UNESCO-IHP, Paris, 2009.

<u>Comment #5:</u> line 79-87: More generally, please use these lines to clearly define all the experiments sa1, sa2, sa3 and sa4 (and their corresponding snow types according to the international Classification).

Response: See comment #4.

<u>Comment #6:</u> line 99-108: *Assuming an isothermal snowpack, Pe > 1 is unlikely in nature because of: 1) low density snow, which has always a very low strength, will be destroyed due to the high airflow velocity; 2) Pe > 1 would be possible for depth hoar, but this snow type is typically found at depth and rarely exposed to high windspeed (Colbeck, 1997); 3) Pe depends on the temperature due to changing diffusivity. Seasonal temperature fluctuations of -60 ºC to - 30 º C are typical for surface snow layer in Antarctic regions, and lead to Pe variations of up to 25%. Theoretically, Pe ≈ 1.2 could be realistic at -60 ºC for 'sa4'. However, simulations by Neumann (2003) showed a rapid decrease of the airflow velocity inside the snow layer (≤ 0.01 m s-1) for a high wind speed (≈ 10 m s-1) above the snow surface (pore size ≈ 1 mm). This leads to a maximum Pe ≈ 0.8.*

I agree with these explanations, but they are still not perfectly convincing and need to be moderated by the following facts:

- the upper part of an "isothermal snowpack" is generally constituted of moderate density snow (RG, typically), which may have, at the same time, relatively high strength and high pore size -and would consequently allow much higher Pe numbers (see my comment 1024/14-15 and the related table of my previous report on this paper).

- depth hoar structures can also appear close to the surface (Alley et al, 1990; Gallet et al, 2013; Adams and Walters, 2014…).

- depth hoar structures that formed under TG can then undergo isothermal conditions: the snowpack would then be isothermal, while its inherent structure (and Pe) would be much closer to that of depth hoar.

- The pore diameter dp, which is used in Pe estimations, is often estimated qualitatively and can easily change the Pe number by a factor 2 (again, see comment 1024/14-15 of my previous report). Consequently, distinguishing values of Pe between 0.8 and 1.2 may seem quite useless in this context. By the way, the authors still do not give clear information in the paper about the method they used to compute dp (see also comment of line 398).

I agree that generally Pe < 1 , but there can be some occurrences for which Pe would be higher in natural snowpacks. As the authors have just investigated the case were Pe < 1, I think it is easier to state it explicitly (e.g., in the title, abstract and conclusions of the paper) rather than trying to demonstrate Pe > 1 is impossible.

Response: We agree that the upper part of on "isothermal snowpack" is generally constituted of moderate density snow (RG, typically) but still the calculation (see Comment #14) are based on the assumption that the fragile snow structure will not be destroyed. Therefore, the velocity is much lower. As mentioned in the previous reply, for the appearance of depth hoar structures close to the surface one has to consider that the formation of such subsurface depth hoar occurred under light winds conditions. According to the reported Beaufort number (in Alley et al., 1990), this will be a maximum wind speed of ≈ 2-3 m s^{-1} (see also Gallet et al., 2014) above the surface. In addition, the depth hoar developed in the slopes of older dunes, leading to an additional decrease of the actual wind speed (≈ 1 m s^{-1}) above the depth hoar layer (see Alley et al., 1990). The simulation by Neumann (2003) in his PhD thesis showed a rapid decrease of the airflow velocity inside such a snow layer (≤ 0.01 m s^{-1}) for a high wind speed (≈ 10 m s^{-1}) above the snow surface (pore size ≈1 mm). For the depth hoar case, an airflow velocity inside the snow layer of ≤ 0.002 m s^{-1} would be realistic. To reach a Peclet number > 1 under this condition, the mean pore size must be at least 10 mm, which would be a very extreme case for depth hoar formed close to the surface. Additionally, Adams and Walters (2014) showed that the top layer of such depth hoar consists of long slender needle crystals connected in a cross-hatch pattern which has a low strength. And as the referee already pointed out, the estimation of the pore diameter plays an important role. We calculated the pore diameter based on opening size distribution with spherical structuring elements on the micro-CT scans (see Comment #16).

Revision: Text changed in the revised paper to include the depth hoar close to the surface problem:

> Line 99-108: "Assuming an isothermal snowpack, *Pe* > 1 is unlikely in nature because of: 1) low density snow, which has always a very low strength, will be destroyed due to the high airflow velocity; 2) *Pe* depends on the temperature due to changing diffusivity. Seasonal temperature fluctuations of -60 ºC to -30 º C are typical for surface snow layer in Antarctic regions, and lead to *Pe* variations of up to 25%. Theoretically, *Pe* ≈ 1.2 could be realistic at -60 ºC for a superficial velocity of ≈ 0.06 m s^{-1} (experiment 'sa4'). However, simulations by Neumann (2003) showed a rapid decrease of the airflow velocity inside the snow layer (≤ 0.01 m s^{-1}) for a high wind speed (≈ 10 m s^{-1}) above the snow surface (pore size ≈ 1 mm). This leads to a maximum *Pe* ≈ 0.8. 3) *Pe* > 1 would be possible for depth hoar, but this snow type is typically found at depth and rarely exposed to high windspeed (Colbeck, 1997). Depth hoar founded close to the surface (Alley et al., 1990; Gallet et al., 2014) were formed under light winds conditions. According to the reported Beaufort number (in Alley et al., 1990), this will be a maximum wind speed of ≈ 2-3 m s^{-1} (see also Gallet et al., 2014) above the surface. In addition, the depth hoar developed in the slopes of older dunes, leading to an additional decrease of the actual wind speed (≈ 1 m s^{-1}) above the depth hoar layer. Based on the simulations of Neumann (2003) an airflow velocity inside the deph hoar of ≤ 0.002 m s^{-1} would be realistic. To reach a Peclet number > 1 under this condition, the mean pore size must be at least 10 mm, which would be a very

extreme case for depth hoar formed close to the surface. Additionally, Adams and Walters (2014) showed that the top layer of such depth hoar consists of long slender needle crystals connected in a cross-hatch pattern which has a low strength and will be destroyed by such a strong flow."

References added:

Adams, E. E. and Walters, D. J: Fine structure layering in radiation recrystallized snow, International Snow Science Workshop, Proceedings, Banff, 2014.

Alley, R. B., Saltzman, E. S., Cuffey, K. M., and Fitzpatrick, J. J.: Summertime formation of Depth Hoar in central Greenland, Geophysical Research Letters, 17, 2393-2396, 1990.

Gallet, J.-C., Domine, F., Savarino, J., Dumont, M., and Brun. E.: The growth of sublimation crystals and surface hoar on the Antarctic plateau, The Cryosphere, 8, 1205-1215, 2014.

Comment #7: line 106: sa4 has not been defined previously.

Revision: Text changed in the revised manuscript:

Line 106: "Theoretically, *Pe* ≈ 1.2 could be realistic at -60 ºC for a superficial velocity of ≈ 0.06 m s^{-1} (experiment 'sa4')."

Comment #8: line 165-168: *The mass sublimated preferentially at locations of the ice grain with low radii due to Kelvin-effect and was relocated on the grain leading to a smoothing of the ice grain.*

1) The sentence does not seem perfectly clear to me. Here is a suggestion: "Due to Kelvin effect, the mass sublimated preferentially from convexities of the ice matrix to be relocated on its concavities".
2) Actually, this observation is not really obvious from fig 6, which is quite deceiving and cumulates 2 problems:

- 1st, it exhibits a voxel-size horizontal layering, which is typically obtained when image processing algorithms (median and Gaussian filters, threshold…) are only applied in 2D on horizontal cross-sections without considering the vertical direction. I suggest really using a 3D threshold method to improve the quality and reliability of the images. If necessary, some indications and references can be found in e.g., Hagenmuller et al, 2013 (p. 862-863).

- 2nd, the evolutions shown are not really typical from isothermal metamorphism since deposition often seems to occur on convexities rather than on concavities (see e.g. fig 6b as compared to fig 2. of Brzoska et al, 2008, and figs of Calonne et al, 2013). Please check once the vertical cross sections have been re-processed.

Response: For the μ-CT80 (Scanco Medical) it would not make sense to use a 3D threshold method. The device scans the sample stack by stack having a slightly difference in the intensity for each stack. The use of a 3D threshold method will lead to a loss of information, therefore we decided to segment each 2D section separately using the Otsu method.

We checked once the vertical cross sections have been re-processed and compared to Calonne et al., (2013) our results showed the same evolution. We saw sublimation at locations of the ice grain with low radii and relocation on the grain leading a smoothing of the ice grain. Additionally, the simulated results of the vapour-pressure map (Brzoska et al., 2008) supports our observation.

Revision: Text changed in the revised manuscript:

> Line 167-168: "Our observed results were supported by the vapour-pressure map simulated by Brzoska et al. (2008) and the applied airflow velocity did not affect the relocation process."

Reference added

> Brzoska, J.-B., Flin, F., and Barckicke, J.: Explicit iterative computation of diffusive vapour field in the 3-D snow matrix: preliminary results for low flux metamorphism, Annals of Glaciology, 48, 13-18, 2008.

Comment #9: line 210-213: *Experiment 'sa1' and 'sa2' had a higher value of n, indicating a strong coarsening process due to sintering and that surface processes were rate limiting (Legagneux et al., 2004; Legagneux and Domine, 2005).*

This sentence is unclear and seems inconsistent with the previous sentence. Do these experiments have higher value than 2 or than 3? Higher value than sa3 and sa4?

Response: We deleted this sentence in the revised manuscript because the statement is already repeated in the following sentence.

Revision: Text changed in the revised manuscript:

> Line 213-214: "Experiment 'sa1' and 'sa2', and 'sa3' and 'sa4' had similar fitting parameters and a low value of *n*, suggesting that surface effects were rate limiting (Legagneux et al., 2004; Legagneux and Domine, 2005)."

<u>Comment #10:</u> line 225-227: *The effect of decreasing SSA on the permeability was not elucidated in our experiments. A SSA decrease of at least 5% in the experiments could not be reproduced in the permeability.*

Based on the fact that, at constant density, permeability is very well known to increase with decreasing SSA (see e.g. Shimizu, 1970; Courville et al, 2010; Calonne et al, 2012; Calonne et al, 2014), these 2 sentences seem strange. From a presentation point of view, I suggest slightly reformulating this subsection by:

-1) describing the results that have been obtained by the authors (with reference to fig. 11)

-2) commenting the relationships with density, by referring briefly to the results of the literature.

-3) commenting the relationship with SSA, by referring briefly to the results of the literature. It has no need to be long, but some basic references should be present.

Response: It is correct that the relationship between SSA and permeability is well known but there are still uncertainty in the calculations or observations, e.g.: (1) the simulation of Courville et al. (2010) still showed an error of 25% between measured and simulated permeability, (2) further, the simulations of Calonne et al. (2012) had also a standard error in the order of 10 % in the permeability measurements; (3) we observed only a slightly decrease in SSA of 5% compared to the results of Calonne et al. (2014) where changes up to 10% were measured; (4) additionally, a slight increase of permeability for constant SSA was observed in the results of Calonne et al. (2014). We suggest not referring briefly to the results of the literature because we only observed a change of 5% in SSA and our variation in permeability is still in the uncertainty of the permeability calculations (Zermatten et al., 2014).

<u>Comment #11:</u> line 229-230: *The effect of increasing airflow velocity had no influence on the flow characteristics.*

Maybe replace by "This means that the effect of increasing airflow velocity had no influence on the flow characteristics."

Revision: Text changed in the revised manuscript:

> Line 229-230: "This means that the effect of increasing airflow velocity had no influence on the flow characteristics (Fig. 11)."

<u>Comment #12:</u> line 238-239: *This difference could therefore be due to an error during the measurement.*

I am still not convinced by this point and suspect other reasons than errors in experimental setup or tomographic acquisitions (see my previous report).

Response: The impact of the borders of the image file, choice of boundary conditions, or REV cannot be the problems because we extracted the image at the same position of the micro-CT scans and the boundary conditions and REV are the same for each permeability measurements. Meshing could be a further reason, however we re-meshed the file with various element size and we still got the same results.

Revision: Text changed in revised manuscript:

> Line 238-239: "This difference could therefore be due to an error during the measurements or during the meshing procedure."

<u>Comment #13:</u> line 243-244: *The two main transport processes, diffusion and advection, were analysed inside the pore space.*

Actually, the processes themselves were not analyzed. Maybe replace by: The effects of the main transport processes, diffusion and advection, were analyzed inside the pore space.

Revision: Text changed in revised manuscript:

> Line 243-244: "The effects of the main transport processes, diffusion and advection, were analysed inside the pore space."

<u>Comment #14:</u> line 245-246: *Pe > 0.85 were not possible due to the destruction of the snow structure.*

I am still not convinced, as some typical snow types would probably allow higher Pe numbers without damage. Have the authors really tried "old" RG, DH or MF samples in their experiments? See table below:

Maximal velocities and Pe numbers using eq. 2 of Ebner et al, (2014) for images s2 and s4, as well as for other data available from Calonne et al, (2012) (http://www.the-cryosphere.net/6/939/2012/tc-6-939-2012-supplement.pdf):

type	name	density	vol. frac. (x)	K	A	V	SSA	dg	dp	u_max	Pe_max
								6/(SSA*917)	dg*(1-x)/x	eq 2	
	sa2	186,1	0,202944384	3,15E-09	0,00175845	5,27535E-05	43,7	1,50E-04	5,88E-04	**6,48E-02**	**1,87268512**
	sa4	264,93	0,288909487	2,20E-09	0,0015688	4,70639E-05	28	2,34E-04	5,75E-04	**9,18E-02**	**2,59251523**
PP	Fr	120,49	0,131395856	3,69E-09	0,0019163	5,7489E-05	55,3	1,18E-04	7,82E-04	**3,18E-02**	**1,22313609**
PP	I01	102,9	0,11221374	3,33E-09	0,00195862	5,87586E-05	55,79	1,17E-04	9,28E-04	**2,10E-02**	**0,95501965**
RG	I23	256	0,27917121	2,47E-09	0,00159028	4,77084E-05	17,24	3,80E-04	9,80E-04	**9,62E-02**	**4,63054836**
RG	NH0	431,36	0,47040349	4,30E-10	0,00116839	3,50516E-05	17,34	3,77E-04	4,25E-04	**4,76E-02**	**0,99221318**
DH	Grad3	369	0,402399128	1,06E-09	0,00131842	3,95525E-05	21,84	3,00E-04	4,45E-04	**8,58E-02**	**1,87452598**
DH	7A-G	311,23	0,339400218	4,84E-09	0,0014574	4,37221E-05	13,42	4,88E-04	9,49E-04	**2,79E-01**	**12,9871354**
MF	H03	498,11	0,543195202	1,73E-09	0,0010078	3,02339E-05	5,25	1,25E-03	1,05E-03	**2,55E-01**	**13,1323776**
MF	H05-G	471	0,513631407	4,87E-09	0,00107302	3,21906E-05	3,78	1,73E-03	1,64E-03	**6,42E-01**	**51,692107**

D	l	mu	g	r
2,04E-05	0,03	1,80E-05	9,81	0,0265

All quantities are given in SI units.

NB: for dp, an estimation using SSA was used in the table above. While this estimation is very rough, it is consistent with the fact that:
-dg is much smaller than dp for recent snow
-dg is nearly equal to dp for MF snow samples grown in saturated water.
-dp values for sa2 and sa4 are about the same order of magnitude (2 times higher, actually) that those given by the authors

Response: Correct, there are snow types where a higher Peclet number is feasible but there are several concern: (1) the calculations are based on the assumption that the fragile snow structure will not be destroyed, therefore the actual maximum velocity will be lower; (2) simulations of Neumann (2003) and Colbeck (1997) estimated a maximum Pe ≈ 0.8 for a superficial velocity of 0.01 m s^{-1} for surface snow layers and deeper snow layers are exposed to much lower airflow velocities. Using this estimated velocity the actual Peclet number for RG, DH, and MF will be much lower; and (3) therefore, we tried to make the experiments consistent with natural surface snow layers for the estimated Peclet number of Neumann (2003) and Colbeck (1997) (see manuscript line 97-98).

Revision: Text changed in the revised manuscript:

> Line 245-246: "*Pe* > 0.85 for natural surface conditions were not possible due to the destruction of the snow structure and is not frequent in natural snowpacks due to the low airflow velocities in snow (Neumann, 2003, Colbeck, 1997)."

<u>Comment #15:</u> line 246: *and is not realistic in natural snowpacks.*

➔ and is not frequent in natural snowpacks

Revision: Text changed in the revised manuscript:

> Line 246: "and is not frequent in natural snowpacks."

<u>Comment #16:</u> line 398: Table 1: the method used to compute dp (initial pore diameter) is still not explained in this version of the manuscript: was dp estimated according to Dullien (1992)? If so, please specify the formula in the text. Depending on the estimation used, the pore diameter may be 2 times higher than the presently given values (see comment 1024/14-15 of my previous report): this would then result in an increase of all the computed Pe numbers by a factor 2.

Response: No, we used opening size distribution on the micro-CT scans to estimate the mean pore size.

Revision: Text added in the revised paper:

> Line 124: "The opening size distribution with spherical structuring elements on the micro-CT scans was used to estimate the mean pore size (d_p) (Haussener et al., 2012)."

Reference added:

> Haussener, S., Gergely, M., Schneebeli, M., and Steinfeld, A.: Determination of the macroscopic optical properties of snow based on exact morphology and direct pore-level heat transfer modeling, Journal of Geophysical Research, 117, 1–20, 2012.

<u>Comment #17:</u> line 425-427: *The accurateness of the isothermal conditions between the top and base of the sample throughout the experiment is less than 0.2 ºC.*

It is to be noticed that such a temperature difference between the top and bottom induces a temperature gradient of about 6.7 K/m for the used samples (3 cm high snow samples), which can be considered as already far from perfect isothermal conditions.

Response: Correct, the maximal error that can be determined with the accuracy of one thermistor is ± 0.2 K (Ebner et al., 2014). However, our measured 0.2 ºC do not necessarily imply a temperature gradient, as this difference could be caused by the measurement error. In general, that is an interesting comment but as soon as there are curvature effects the isothermal condition is not valid anymore only there is an ice water mixture.

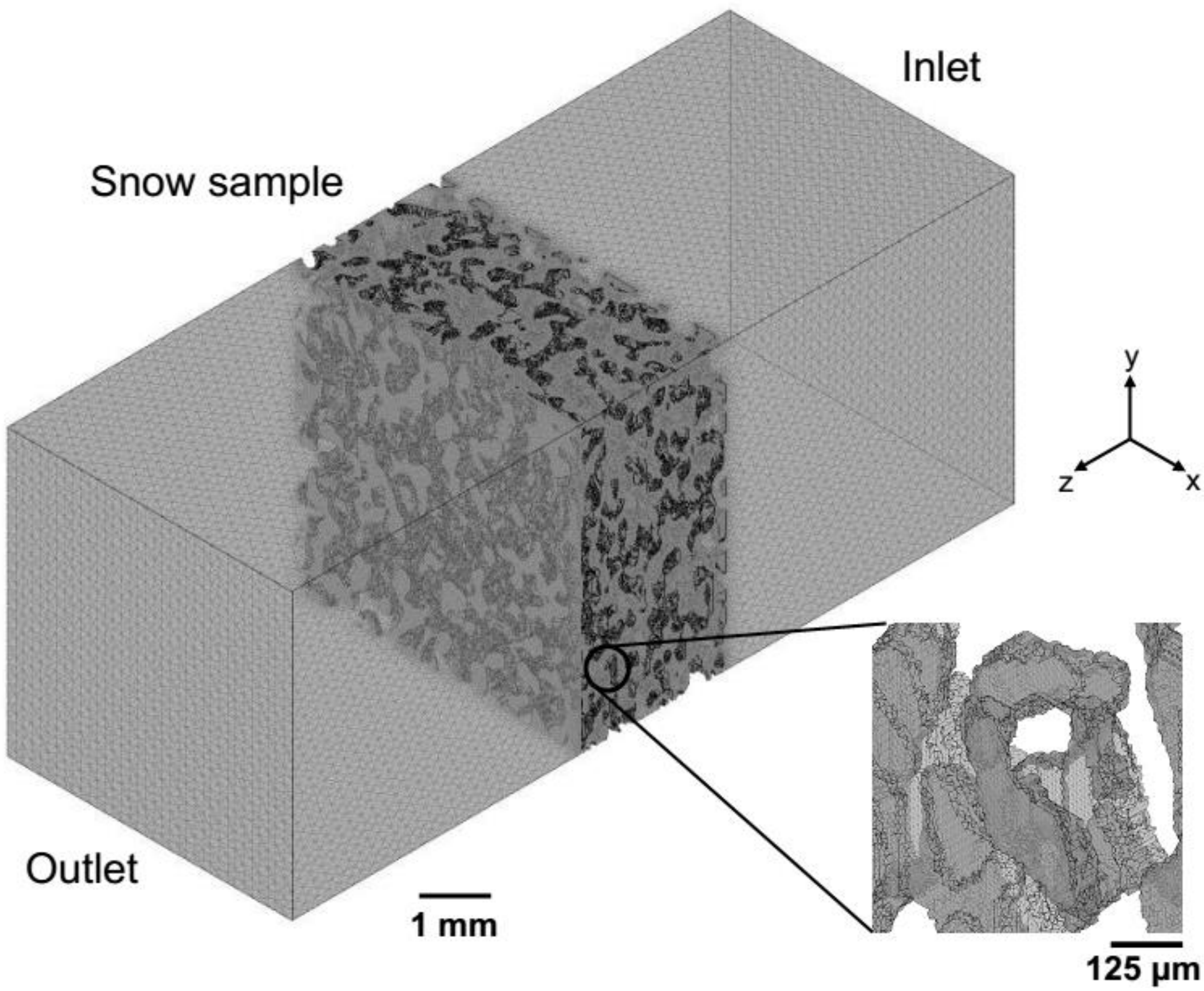
Revision: Text added in the revised paper:

> Line 81: "It is to be noticed that the accurateness of the isothermal conditions between the top and base of the sample was less than 0.2 ºC and a temperature gradient of about 6.7 K m^{-1} was possible. However, this was still in the uncertainty of the thermistors ± 0.2 K (Ebner et al., 2014) and therefore a quasi-isothermal condition was given."

Line 425-427: “The accurateness of the isothermal conditions between the top and base of the sample throughout the experiment is less than 0.2 ºC which is still in the uncertainty of the thermistors ± 0.2 K (Ebner et al., 2014).”

Comment #18: line 458-460; fig2: Presently, only the meshes of the inlet and outlet parts are visible. I suggest providing an enlarged view of the mesh in the snow sample area, which would really allow the reader for estimating the mesh quality.

Revision: Figure 2 replaced in the revised manuscript:



<u>Technical comments or suggestions:</u>

<u>Comment #1:</u> line 38-41: maybe suppress "in isothermal metamorphism".

Revision: Text changed in the revised paper:

> Line 38-41: "Recent studies indicate that sublimation-deposition is the dominant contribution for temperatures close to the melting point, whereas surface diffusion dominates at temperatures far below the melting point (Vetter et al, 2010)."

<u>Comment #2:</u> line 44 and 51: *snow pack*

- ➔ snowpack

Revision: Text changed in the revised paper:

> Line 44: "airflow affect heat and mass transports in the snowpack"
>
> Line 51: "airflow velocities inside a snowpack"

<u>Comment #3:</u> line 51-52: *It is suggested that advective flow of air has a direct effect on snow-air exchange processes related to atmospheric chemistry…*

- ➔ Advective flow of air may have a direct effect on snow-air exchange processes related to atmospheric chemistry…

Revision: Text changed in the revised manuscript:

> Line 51-52: "Advective flow of air may have a direct effect on snow-air exchange processes related to atmospheric chemistry"

<u>Comment #4:</u> line 79-81: please move the reference (Ebner et al, 2014) just after "experimental setup" or change the sentence. Otherwise the referencing seems ambiguous.

Revision: Text changed in the revised manuscript:

> Line 79-81: "Isothermal experiments with fully saturated airflow across snow samples were performed in a micro-CT at laboratory temperatures of $T_{\mathrm{lab}} = -8$ and -15 ºC. Figure 1 shows a schematic of the experimental setup (Ebner et al., 2014)."

Comment #5: line 83-84: *Natural identical snow.*

➔ Nature identical snow

Revision: Text changed in the revised manuscript:

Line 83-84: "Nature identical snow was used for the snow sample preparation"

Comment #6: line 91: uD

➔ u_D

Revision: Text changed in the revised manuscript:

Line 91: "$Pe = u_D d_p/D$ where u_D is the superficial velocity in snow."

Comment #7: line 98: *simulation*

➔ simulations

Revision: Text changed in the revised manuscript:

Line 98: "Higher *Pe* numbers were experimentally not possible, as the shear stress by airflow could destroy the snow structure and we restricted the flow rate to the corresponding maximum $Pe \approx 0.8$ extracted from the simulations of Neumann (2003) and Colbeck (1997)."

Comment #8: line 152-153: *longer sintering duration at higher temperature*

➔ A longer sintering duration at -5 ºC

Revision: Text changed in the revised manuscript:

Line 152-153: "A longer sintering duration at -5 ºC of the snow for experiment 'sa3' and 'sa4' was used to increase the mean thickness of the ice matrix."

Comment #9: line 161: *The initial ice grain didn't change with time.*

➔ The initial ice matrix didn't change significantly with time.

Revision: Text changed in the revised manuscript:

> Line 161: "The initial ice matrix didn't change with time; only coarsening processes on the ice grain surface were observed (Fig. 5)."

<u>Comment #10:</u> line 186: suppress "height" between "snow" and "for"

Revision: Text changed in the revised manuscript:

> Line 186: "The qualitative progression of the spatial SSA of the scanned snow for four discs of $7.2 \times 7.2 \times 1.8$ mm^3 (Fig. 9) did not change significantly with height."

<u>Comment #11:</u> line 195: *(Legagneux and Domine, 2005*)

➔ Legagneux and Domine (2005)

Revision: Text changed in the revised manuscript:

> Line 195: "The model proposed is given by Legagneux and Domine (2005)"

<u>Comment #12:</u> line 203: *real mechanism*

➔ real mechanisms

Revision: Text changed in the revised manuscript:

> Line 203: "Equation (2) gives a very qualitative estimation on the real mechanisms occurring in the snow."

<u>Comment #13:</u> line 251-252: *The experimental observations supported the hypothesis that further densification was limited by coarsening kinetics and further confirmed a constant porosity evolution.*

Maybe change "further densification" into just "densification".

Revision: Text changed in the revised manuscript:

> Line 251-252: “The experimental observations supported the hypothesis that densification was limited by coarsening kinetics and further confirmed a constant porosity evolution (Kaempfer and Schneebeli, 2007).”

Comment #14: line 253-254: *small surface radii*

- ➔ small curvature radii

Revision: Text changed in the revised manuscript:

> Line 253-254: “Curvature caused sublimation of small ice grains and ice structures with small curvature radii leading to a slight decrease in SSA.”

Minor revisions were made throughout the revised manuscript.

We thank the Frédéric Flin for his scrutiny and recommendations.

The authors

Tomography-based monitoring of isothermal snow metamorphism under advective conditions

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Abstract

Time-lapse X-ray microtomography was used to investigate the structural dynamics of isothermal snow metamorphism exposed to an advective airflow. The effect of diffusion and advection across the snow pores on the snow microstructure were analysed in controlled laboratory experiments and possible effects on natural snowpacks discussed. The 3D digital geometry obtained by tomographic scans was used in direct pore-level numerical simulations to determine the effective permeability. The results showed that isothermal advection with saturated air have no influence on the coarsening rate that is typical for isothermal snow metamorphism. Isothermal snow metamorphism is driven by sublimation-deposition caused by the Kelvin effect and is the limiting factor independently of the transport regime in the pores.

Keywords: snow, isothermal, metamorphism, advection, transport properties, tomography

1. Introduction

Snow is a bi-continuous material consisting of fully connected ice and pore space (air) (Löwe et al. 2011). Because of the proximity to the melting point, the high vapour pressure causes a continuous recrystallization of the snow microstructure known as snow metamorphism, even under moderate temperature gradients (Pinzer et al, 2012; Domine et al. 2008). The microstructural changes of snow towards equilibrium under conditions of constant temperature are referred to as isothermal snow metamorphism

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(Colbeck, 1997; Kaempfer and Schneebeli, 2007). This is a coarsening process whose driving force is the reduction of the surface free energy of the complex ice-air interface. The energy reduction is caused by mass transport processes such as vapour diffusion (Neumann et al., 2009), surface diffusion (Kingery, 1960b), volume diffusion (Kuroiwa, 1961), and grain boundary diffusion (Colbeck, 1997a, 1998, 2001; Kaempfer and Schneebeli, 2007). Viscous or plastic flow (Kingery, 1960a), and sublimation-condensation with vapour transport (German, 1996; Hobbs and Mason, 1963; Legagneux and Domine, 2005; Maeno and Ebinuma, 1983) are also suggested to play an important role. The Kelvin effect is seen as the driving force for isothermal snow metamorphism (Bader, 1939; Colbeck, 1980). Recent studies indicate that sublimation-deposition is the dominant contribution for temperatures close to the melting point, whereas surface diffusion dominates at temperatures far below the melting point ~~in isothermal metamorphism~~ (Vetter et al, 2010). Snow has a high permeability, which facilitates diffusion of gases and, under appropriate conditions, airflow (Gjessing, 1977; Colbeck, 1989; Sturm and Johnson, 1991; Waddington et al., 1996). Both diffusion and advective airflow affect heat and mass transports in the snowpack (Cunningham and Waddington, 1993; Albert, 1993; McConnell et al. 1998). In the dry snow zone of an ice sheet, Sowers et al. (1992) described a convective zone located just below the surface in which the air is rapidly flushed by convective exchange with the overlying atmosphere. A rapid decrease of the airflow velocity inside a snow layer (≤ 0.01 m s^{-1}) for high wind speed (≈ 10 m s^{-1}) above the snow surface (pore size ≈ 1 mm) are numerically estimated by Neumann (2003). In addition, Colbeck et al. (1997) confirmed the rapid decrease of airflow velocities inside a snowpack. Advective flow of air may have a direct effect on snow-air exchange processes related to atmospheric chemistry (Clifton et al., 2008; Grannas et al., 2007), and snow metamorphism (Albert and Gilvary, 1992; Albert et al., 2004), and can change the chemical composition of trapped atmospheric gases in ice-cores (Legrand and Mayewski, 1997; Neumann and Waddington, 2004; Severinghaus et al., 2010). However, no prior studies have experimentally analyzed the effect of saturated airflow on the vapour transport and the recrystallization of the snow crystals using non-destructive technique in time-lapse experiments. Over- or undersaturated air leads to a rapid growth or shrinkage of snow structures exposed to such conditions, as exemplified in the growth of surface hoar (Stössel et al., 2010). However, saturation vapour density of the air is reached in the pore space within the first 1 cm of the snow sample, regardless of temperature or flow rate (Neumann et al., 2009; Ebner et al., 2014). The change in shape of the snow crystals during metamorphism also affects the permeability, which, in turn, will continue to affect the shape of the snow structure. Although long-term isothermal metamorphism occurs in nature only in the centre of the polar ice caps (Arnaud et al., 1998), it is important to reduce physical complexity of experiments in order to understand the basic mechanisms governing metamorphism.

The objective of this paper is to study the effect of saturated airflow on the vapour transport and the coarsening rate of snow under isothermal conditions. We designed experiments in a controlled refrigerated laboratory and used time-lapse computed tomography (micro-CT) to obtain the discrete-scale geometry of snow (Schneebeli and Sokratov, 2004; Kaempfer and Schneebeli, 2007; Pinzer and Schneebeli, 2009; Chen and Baker, 2010; Pinzer et al., 2012; Wang and Baker, 2014; Ebner et al., 2014). The extracted 3-D digital geometry of the snow was used to calculate the specific surface area and porosity. Direct pore-level simulations (DPLS) were applied to determine the effective permeability by solving the corresponding mass and momentum conservation equations (Zermatten et al., 2011, 2014).

2. Methodology

Isothermal experiments with fully saturated airflow across snow samples were performed in a micro-CT ~~(Ebner et al., 2014)~~ at laboratory temperatures of $T_{\mathrm{lab}} = -8$ and -15 ºC. Figure 1 shows a schematic of the experimental setup (Ebner et al., 2014). It is to be noticed that the accurateness of the isothermal conditions between the top and base of the sample was less than 0.2 ºC and a temperature gradient of about 6.7 K m^{-1} was possible. However, this was still in the uncertainty of the thermistors ± 0.2 K (Ebner et al., 2014) and therefore a quasi-isothermal condition was given. Two different snow types with high specific surface area were considered to evaluate the structural change in the earlier stage of isothermal metamorphism of new snow, more in detail. Partly decomposed snow (DFdc) was used for low flow rate (‘sa1’ and ‘sa2’) whereas large rounded snow (RGlr) was used for higher flow rate (‘sa3’ and ‘sa4’) to prevent destruction of the fragile snow structure (Fierz et al., 2009). Nature identical snow was used for the snow sample preparation (water temperature: 30 ºC; air temperature: −20 ºC) (Schleef et al., 2014). It was sieved with a mesh size of 1.4 mm into two boxes, and sintered for 13 and 27 days at −15 and −5 ºC, respectively, for increasing strength and coarsening (Kaempfer and Schneebeli, 2007). A cylinder cut out (diameter: 53 mm; height: 30 mm) from the sintered snow was filled into the sample holder (Ebner et al., 2014). The snow samples were analysed during 96 h with time-lapse micro-CT measurements taken every 8 h, producing a sequence of 13 images. Table 1 summarizes the morphological parameters of the snow. Four different runs were chosen based on the Peclet number ($Pe = u_D d_p / D$ where u_D is the superficial velocity in snow, d_p is the pore diameter, and $D = 2.036 \cdot 10^{-5}$ m^2 s^{-1} is the diffusion coefficient of water vapour in air) to compare the advective and diffusive transport rates inside the pore space. Experimental runs were performed at 1 atm pressure and volume flow rates of 0 (no advection), 0.36, 3.0, and 5.0 L min^{-1}, corresponding to Pe = 0, 0.05, 0.47, and 0.85. Higher Pe numbers were experimentally not possible, as the shear stress by airflow could destroy the snow structure and we restricted the flow rate to the corresponding maximum $Pe \approx 0.8$ extracted from the simulations of Neumann (2003) and Colbeck (1997). Assuming an isothermal snowpack, $Pe > 1$ is unlikely in nature because of: 1) low density snow, which has always a very low strength, will be destroyed due to the high airflow velocity; 2) Pe depends on the temperature due to changing diffusivity. Seasonal temperature fluctuations of -60 ºC to -30 º C are typical for surface snow layer in Antarctic regions, and lead to Pe variations of up to 25%. Theoretically, $Pe \approx 1.2$ could be realistic at -60 ºC for a superficial velocity of ≈ 0.06 m s^{-1} (experiment 'sa4'). However, simulations by Neumann (2003) showed a rapid decrease of the airflow velocity inside the snow layer (≤ 0.01 m s^{-1}) for a high wind speed (≈ 10 m s^{-1}) above the snow surface (pore size ≈ 1 mm). This leads to a maximum $Pe \approx 0.8$. 3) $Pe > 1$ would be possible for depth hoar, but this snow type is typically found at depth and rarely exposed to high windspeed (Colbeck, 1997). Depth hoar founded close to the surface (Alley et al., 1990; Gallet et al., 2014) were formed under light winds conditions. According to the reported Beaufort number (in Alley et al., 1990), this will be a maximum wind speed of ≈ 2-3 m s^{-1} (see also Gallet et al., 2014) above the surface. In addition, the depth hoar developed in the slopes of older dunes, leading to an additional decrease of the actual wind speed (≈ 1 m s^{-1}) above the depth hoar layer. Based on the simulations of Neumann (2003) an airflow velocity inside the depth hoar of ≤ 0.002 m s^{-1} would be realistic. To reach a Peclet number > 1 under this condition, the mean pore size must be at least 10 mm, which would be a very extreme case for depth hoar formed close to the surface. Additionally, Adams and Walters (2014) showed that the top layer of such depth hoar consists of long slender needle crystals connected in a cross-hatch pattern which has a low strength and will be destroyed by such a strong flow.

The acceleration voltage in the X-ray tube was 70 kV, with an intensity of 114 μA, and a nominal resolution of 18 μm. The samples were scanned with 2000 projections per 360 degree, with an integration time of 200 ms per projection, taking 1.5 hour per scan. The innermost 36.9 mm of the total 53 mm diameter were scanned and subsamples with a dimension of $7.2 \times 7.2 \times 7.2$ mm^3 were extracted for further processing. Absolute *z*-position varied up to a maximum of 50 voxels between subsequent scans due to the weight of the sample holder. To correct for the *z*-position a linear encoder was built into the micro-CT. A 3×3×3 median filter and Gaussian filter ($\sigma = 1.4$, support = 3) was applied to the reconstructed images. Otsu's method (Otsu, 1979) was used to automatically perform clustering-based image thresholding to segment the grey-level images into ice and air phase. Morphological properties in the two-phase system were determined based on the geometry obtained by the micro-CT. The segmented data were used to calculate a triangulated ice matrix surface and tetrahedrons inscribed into the ice structure. Morphological parameters such as porosity (ε) and specific surface area (SSA) were then calculated. The opening size distribution with spherical structuring elements on the micro-CT scans was used to estimate the mean pore size (d_p) (Haussener et al., 2012). The effective permeability was calculated using the finite volume technique CFD (Computational Fluid Dynamics simulation software from ANSYS) by solving the continuity and Navier–Stokes equations (Zermatten et al., 2011, 2014) for laminar flow

$$\nabla p = -\frac{\mu}{K} u_D - F \rho u_D^2 - \frac{\gamma \rho^2}{\mu} u_D^3 \qquad (1)$$

where p is the pressure, μ is the dynamic viscosity of the fluid and u_D its superficial velocity, ρ is the fluid density, K is the permeability, F is the Dupuit-Forchheimer coefficient, and γ is a dimensionless factor. The first term is the result of viscous effects, predominant at low velocities, whereas the second and third terms describe the inertial effects, which become important at higher fluid velocities. As the viscous effect was still the dominant case (Re ≈ 1) in the experiment, only permeability K was considered for further discussions. A grid convergence study based on the pressure drop (Zermatten et al., 2014) was carried out to find the optimal representative elementary volume (REV) (6.0 x 6.0 x 3.0 mm^3). An in-house tetrahedron-based mesh generator (Friess et al.

2013) was used to create the computational grid on the segmented data. The computational domain consisted of a square duct containing a sample of snow. The boundary conditions consisted of uniform inlet velocity, temperature and outlet pressure, constant wall temperature at the solid-fluid interface, and symmetry of the sample at the lateral duct walls. The square duct was 5 times the length of the sample to ensure a fully developed velocity profile at the entrance of the snow sample (Fig. 2). The largest mesh element length was 0.153 mm and the smallest possible mesh element measured 9.56 µm, with average 60 million volume elements for each segmented snow sample.

3. Results and Discussion

The discussions of the observed results are only based on the investigated volume. Influences of the flow on the base, top and lateral boundaries of the overall sample were not considered due to lack of structural observations.

A representative temporal temperature profile of the snow sample for both laboratory temperatures of T_{lab} = -8 ˚C and -15 ˚C is shown in Figure 3. Variations in temperature up to 1.7 ˚C and 1.4 ˚C were due to heat dissipated by the X-ray tube and temperature fluctuations inside the cold laboratory (Ebner et al., 2014). A longer sintering duration at -5 ºC of the snow for experiment ‘sa3’ and ‘sa4’ was used to increase the mean thickness of the ice matrix. This avoided the destruction of the snow structure due to shear stresses caused by the airflow. The structural analysis of the snow samples was conducted on the complete tomography domain (7.2 × 7.2 × 7.2 mm^3). A smaller sub-set of 110 × 42 × 110 voxels (2 × 0.75 × 2 mm^3) was selected to visualize the 3D evolution (Fig. 4). It showed no significant change in the grain shape, even for different airflow velocities, and only a slight rounding and coarsening was seen for experiments ‘sa1’ and ‘sa2’. A strong translation effect due to settling of sub-layering snow was visible for ‘sa1’ and ‘sa2’. The initial ice matrix didn’t change with time; only coarsening processes on the ice grain surface were observed (Fig. 5). Sublimation of 4.5 % and 4.9 % of the ice matrix and deposition of 4.1 % and 5.9 % on the ice matrix were observed for ‘sa3’ and ‘sa4’ (Fig. 6). The data were extracted by superposition of vertical cross-sections at 0 and 96 hours with an uncertainty of 6 %. The mass sublimated preferentially at locations of the ice grain with low radii due to Kelvin-effect and was relocated on the grain leading to a smoothing of the ice grain. Our observed results were supported by the vapour-pressure map simulated by Brzoska et al. (2008) and the applied airflow velocity did not affect the relocation process.

The well-sintered snow showed very little settling under its own weight (Kaempfer and Schneebeli, 2007) and, consequently, no significant change in porosity was observed. This supports the hypothesis that further densification is limited by coarsening kinetics (Kaempfer and Schneebeli, 2007, Schleef et al., 2013). A spatially constant porosity distribution at t = 0 days and t = 4 days is seen in Fig. 7. Thus, spatial change in the flow field due to different interfacial velocities can be neglected. Consequently, *Pe* was constant with time, and therefore the advective and diffusive mass transfer regime. The average deviation between t = 0 days and t = 4 days was 0.5%, 1.8%, 0.5% and 0.5% for 'sa1', 'sa2', 'sa3' and 'sa4'.

Our segmented 3D-data accurately reproduced the original snow sample and the temporal porosity distribution confirmed that no settling and densification occurred in the investigated volume (Fig. 8). The gravimetric porosity $\varepsilon_{\mathrm{grav}}$ at the beginning and at the end of each experiment was measured by weighing. The measured density values were converted to porosity ($\varepsilon_{\mathrm{grav}} = 1 - \rho_{\mathrm{s}}/\rho_{\mathrm{ice}}$), and compared to the value of porosity computed by DPLS on the micro-CT geometry. The computed values differed from the measured ones by 1.4% and 0.1% at the beginning and 4.1% and 2.3% at the end for experiments 'sa3' and 'sa4'.

The qualitative progression of the spatial SSA of the scanned snow height for four discs of 7.2 × 7.2 × 1.8 mm^3 (Fig. 9) did not change significantly with height. This suggested that the snow properties were homogeneous throughout the sample and duration of the experiments. The slight decrease of the spatial SSA for experiment 'sa4' is explained by the distribution not initially being completely homogeneous.

The coarsening process led to a decrease of the SSA over time (Fig. 10), which was higher for group 'sa1' and 'sa2' compared to 'sa3' and 'sa4'. The difference was caused by the 34% lower initial SSA of group 'sa3' and 'sa4'. Applying the theories developed by Legagneux et al. (2004) and Legagneux and Domine (2005), the evolution of SSA of the ice matrix could be modelled well. The model proposed is given by Legagneux and Domine (2005)

$$\mathrm{SSA} = \mathrm{SSA}_0 \left(\frac{\tau}{\tau + t} \right)^{1/n} \tag{2}$$

where SSA_0 is the initial SSA at time $t = 0$, n is the growth exponent, and τ a parameter related to grain growth and a form factor. Table 2 shows the fitted parameters and the corresponding normalized root-mean square error (NRMSE) for each experiment. Equation (2) fits the data of each experiment well with an average NRMSE < 0.21. The computed fit of the SSA is shown in Figure 8. Equation (2) gives a very qualitative estimation on the real mechanism occurring in the snow. This model is based on the physical processes involved in Ostwald ripening (Ratke and Voorhees, 2002). Ostwald ripening describes the coarsening of solid particles with a given size distribution, considering disconnected grains that do not undergo settling. The driving force in the model is the reduction of the SSA and the model hypothesis is based on the concept that mass transfer occurs by sublimation due to curvature effects, transport through the gas phase and deposition. Theoretically, the growth exponent n is approximately 2 when surface processes are rate limiting and 3 when diffusion is rate limiting. Experiment 'sa1' and 'sa2' had a higher value of n, indicating a strong coarsening process due to sintering and that surface processes were rate limiting (Legagneux et al., 2004; Legagneux and Domine, 2005). Experiment 'sa1' and 'sa2', and 'sa3' and 'sa4' had similar fitting parameters and a low value of n, suggesting that surface effects were rate limiting (Legagneux et al., 2004; Legagneux and Domine, 2005). The lower value of n for experiment 'sa3' and 's4' was due to the longer sintering time of 27 days at -5 ºC before the experiments were started leading to a very little change in the microstructure of the snow. When the sintering times of 13 and 27 days were included in the model, the fitting parameters indicated a consistent growth exponent n for each experiment (Table 3) and a good agreement with the theory. They expressed strong coarsening and surface processes for each experiment. Notice, Eq. (2) extremely depends on the initial state, which is well illustrated by the large difference obtained for n values of 'sa3' and 'sa4' between Tables 2 and 3. Concluding, the calculated values indicated that surface processes caused the limiting rate rather than the diffusion step and no significant influence of advective transport could be observed.

The effect of decreasing SSA on the permeability was not elucidated in our experiments. A SSA decrease of at least 5% in the experiments could not be reproduced in the permeability. However, the computational uncertainty up to 16% (Zermatten et al., 2014) in the permeability is still in the range to cover the correlation between SSA and permeability. The effect of increasing airflow velocity had no influence on the flow characteristics (Fig. 11). The temporal evolution of permeability for experiment 'sa2' showed a decrease of 8% for the first 40 hours and remained constant afterwards. Experiments 'sa1', 'sa3' and 'sa4' showed no significant change in the permeability, which is consistent with the negligible change in density. The average fluctuations of the permeability K between each time step and the slight decrease at the beginning in 'sa2' showed small differences that were below the precision of the numerical method with an uncertainty up to 16% (Zermatten et al., 2014). Only the first time step of 'sa3' showed a particularly high difference of 17.3%, but neither the porosity nor SSA showed significant differences reflecting this value. This difference could therefore be due to an error during the measurement or during the meshing procedure.

4. Summary and conclusions

Four isothermal metamorphism experiments of snow under saturated advective airflow were performed, each with duration of four days. The effects of the main transport processes, diffusion and advection, were analysed inside the pore space. The airflow velocities were chosen based on the Peclet number. $Pe > 0.85$ for natural surface conditions were not possible due to the destruction of the snow structure and is not frequent in natural snowpacks due to the low airflow velocities in snow (Neumann, 2003, Colbeck, 1997). Every 8 h the snow microstructure was observed by X-ray microtomography. The micro-CT scans were segmented, and porosity and specific surface area were calculated. Effective permeability was calculated in direct pore-level simulations (DPLS) to analyse the flow characteristic.

The experimental observations supported the hypothesis that further densification was limited by coarsening kinetics and further confirmed a constant porosity evolution (Kaempfer and Schneebeli, 2007). Curvature caused sublimation of small ice grains and ice structures with small curvature radii leading to a slight decrease in SSA. Compared to rates typical for isothermal snow metamorphism, no enhancement of mass transfer inside the pores of isothermal advection with saturated air was observed. Sublimation-deposition caused by the Kelvin-effect was the limiting factor independently of the transport regime in the pores.

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Table 1: Morphological and flow characteristics of the experiments: Volume flow ($\dot{V}$), corresponding Peclet number (Pe), Reynolds number (Re), initial superficial velocity in snow ($u_{D,0}$), initial snow density (ρ_0), initial porosity (ε_0), specific surface area (SSA_0), initial pore diameter (d_p), temperature in the cold laboratory (T_{lab}), and the sintering time of the snow.

Name	$\dot{V}$ litre min^{-1}	Pe –	Re –	$u_{D,0}$ m s^{-1}	ρ_0 kg m^{-3}	ε_0 –	SSA_0 m^2 kg^{-1}	d_p mm	T_{lab} ˚C	Sintering time
sa1	–	–	–	–	229.25	0.75	46.6	0.22	-8.0	13 days at -15˚C
sa2	0.36	0.05	0.07	0.004	201.74	0.78	43.7	0.27	-8.0	13 days at -15˚C
sa3	3.0	0.47	0.6	0.04	320.95	0.65	28.7	0.24	-15.0	27 days at -5˚C
sa4	5.0	0.85	1.1	0.06	265.93	0.71	28.0	0.29	-15.0	27 days at -5˚C

Table 2: Values of the fitted growth rate τ and growth exponent n for the evolution of the SSA and the corresponding normalized root-mean square error (NRMSE).

Name	SSA_0 m^2 kg^{-1}	τ –	n –	NRMSE –
sa1	46.7	632.9	2.10	0.01
sa2	43.6	721.2	2.15	0.04
sa3	27.8	14400	0.32	0.14
sa4	27.8	17380	0.39	0.21

Table 3: Values of the fitted growth rate τ and growth exponent n for the evolution of the SSA including the sintering time of 13 and 27 days, and the corresponding normalized root-mean square error (NRMSE).

Name	SSA_0 m^2 kg^{-1}	τ –	n –	NRMSE –
sa1	64.4	320.9	2.10	0.01
sa2	56.8	409.1	2.15	0.04
sa3	34.5	1229	2.0	0.15
sa4	36.0	1063	1.91	0.27

Figure captions

Fig. 1. Schematic of the experimental setup and the sample holder. A thermocouple (TC) and a humidifier sensor (HS) inside the humidifier measured the air-flow conditions. Two thermistors (NTC) close to the snow surface measured the inlet and outlet temperature of the airflow (Ebner et al., 2014).

Fig. 2. Schematic of the computational domain with an enlarged subsample of snow. In the snow sample, the dark gray part represents the ice, whereas the mesh is built in the pore space.

Fig. 3. A typical temperature profile for experiment 'sa1, sa2' and 'sa3, sa4'. The temperature rise was caused by the X-ray tube and fluctuations inside the cold laboratory (Ebner et al., 2014). The accurateness of the isothermal conditions between the top and base of the sample throughout the experiment is less than 0.2 °C which is still in the uncertainty of the thermistors ± 0.2 K (Ebner et al., 2014).

Fig. 4. Evolution of the 3-D structure of the ice matrix during isothermal metamorphism under advective conditions. Experimental conditions (from left to right) at different measurement times from beginning to the end (top to bottom) of the experiment. The shown cubes are 110 × 42 × 110 voxels (2 × 0.75 × 2 mm^3) large.

Fig. 5. Residence time of ice particles within in a slice (5.7 × 5.7 mm^2) parallel to the flow direction for a) 'sa3' and b) 'sa4' by overlapping time-lapse tomography pictures. The period of 8 h was sufficiently short to calculate the residence time of each ice voxel with an uncertainty of 6 %.

Fig. 6. Superposition of vertical cross-section parallel to the flow direction at time 0 and 96 hours for (a) 'sa3' and (b) 'sa4'. Sublimation and deposition of water vapor on the ice grain were visible with an uncertainty of 6 %.

Fig. 7. Spatial porosity profile of the scanned area at the beginning and at the end of each experiment. The spatial variability within the reconstructed volume was measured in four discs of 7.2 × 7.2 × 1.8 mm^3.

Fig. 8. Evolution of the porosity over time obtained by triangulated structure surface method and the measured gravimetric density (ε_{grav}) at the beginning and at the end of 'sa3' and 'sa4'.

Fig. 9. Spatial SSA profile of the scanned area at the beginning and at the end of each experiment. The spatial variability within the reconstructed volume was measured in four discs of 7.2 × 7.2 × 1.8 mm^3.

Fig. 10. Temporal evolution of the specific surface area, SSA, of the ice matrix obtained by triangulated structure surface method. The computed fit is of the form $\mathrm{SSA}(t) = \mathrm{SSA}_0 \left(\frac{\tau}{\tau+t}\right)^{1/n}$.

Fig. 11. Temporal evolution of the effective permeability by applying DPLS with an uncertainty of 16 % (Zermatten et al., 2014).

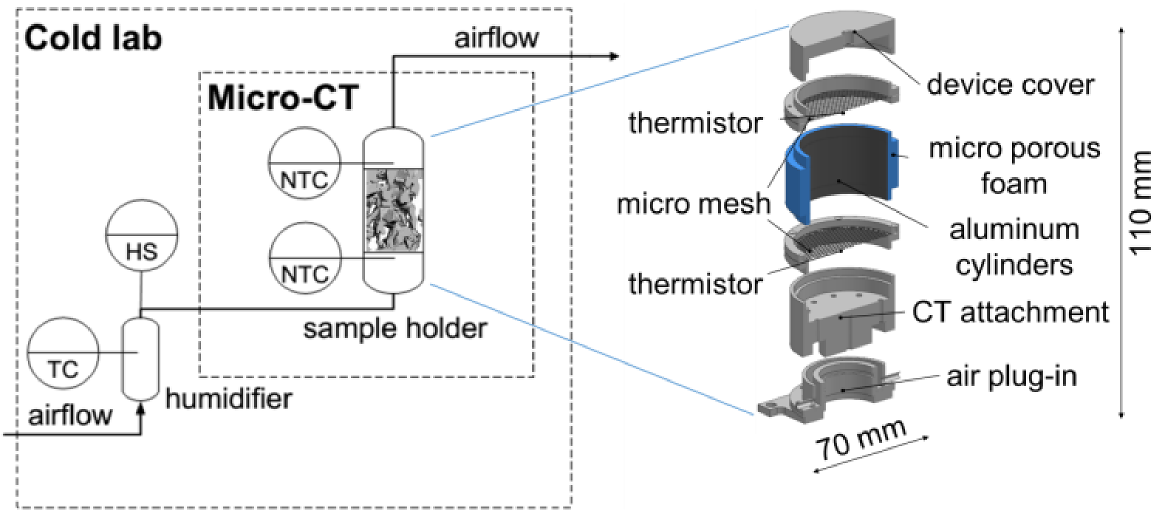

Cold lab
airflow
Micro-CT
NTC
HS
NTC
TC
sample holder
airflow
humidifier
device cover
thermistor
micro porous
foam
micro mesh
aluminum
cylinders
thermistor
CT attachment
air plug-in
110 mm
70 mm

Fig. 1

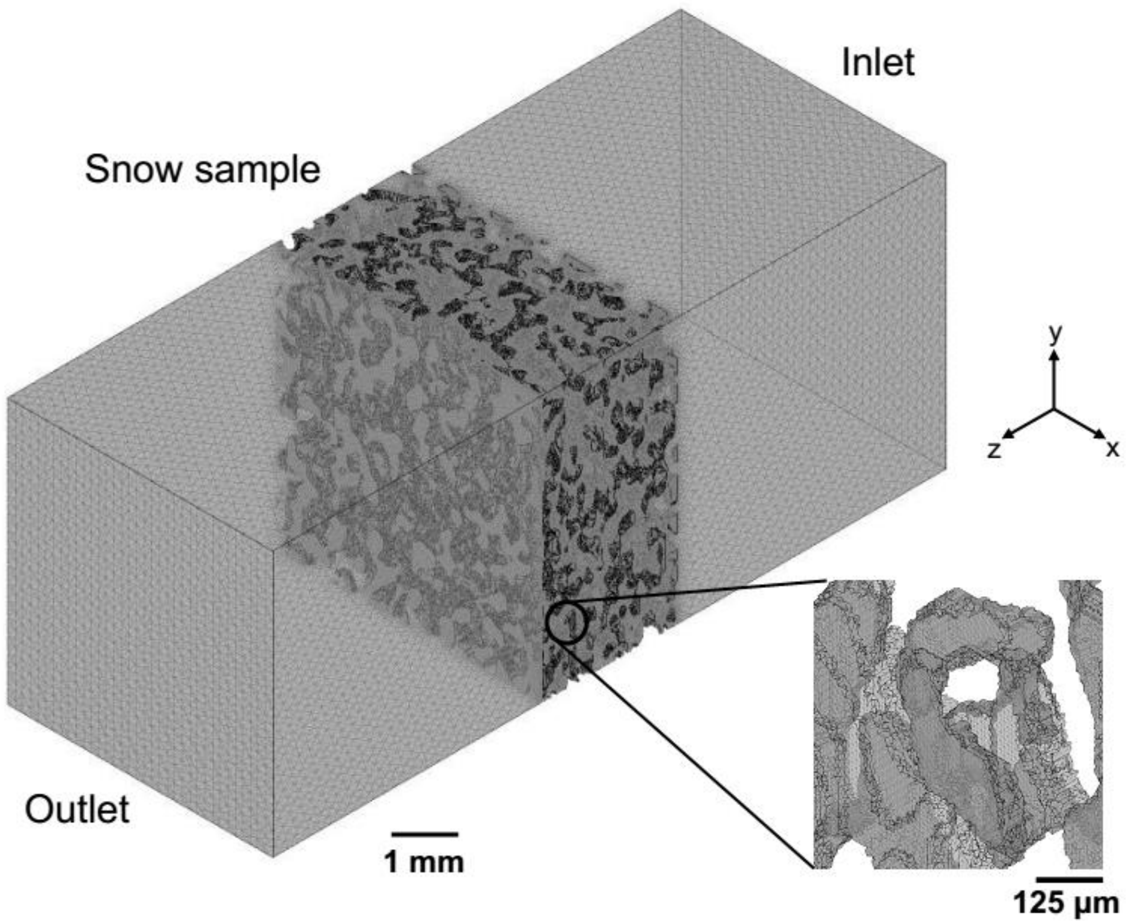
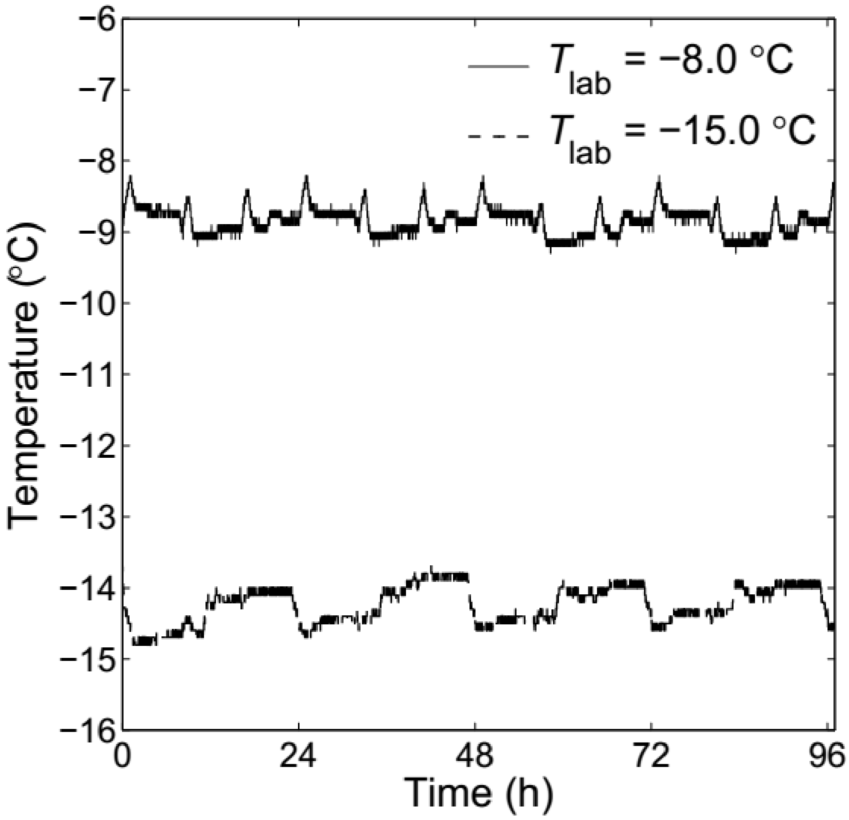


Fig. 2



T_{lab} = −8.0 °C
T_{lab} = −15.0 °C
−6
−7
−8
−9
−10
−11
−12
−13
−14
−15
−16
Temperature (°C)
0
24
48
72
96
Time (h)

Fig. 3

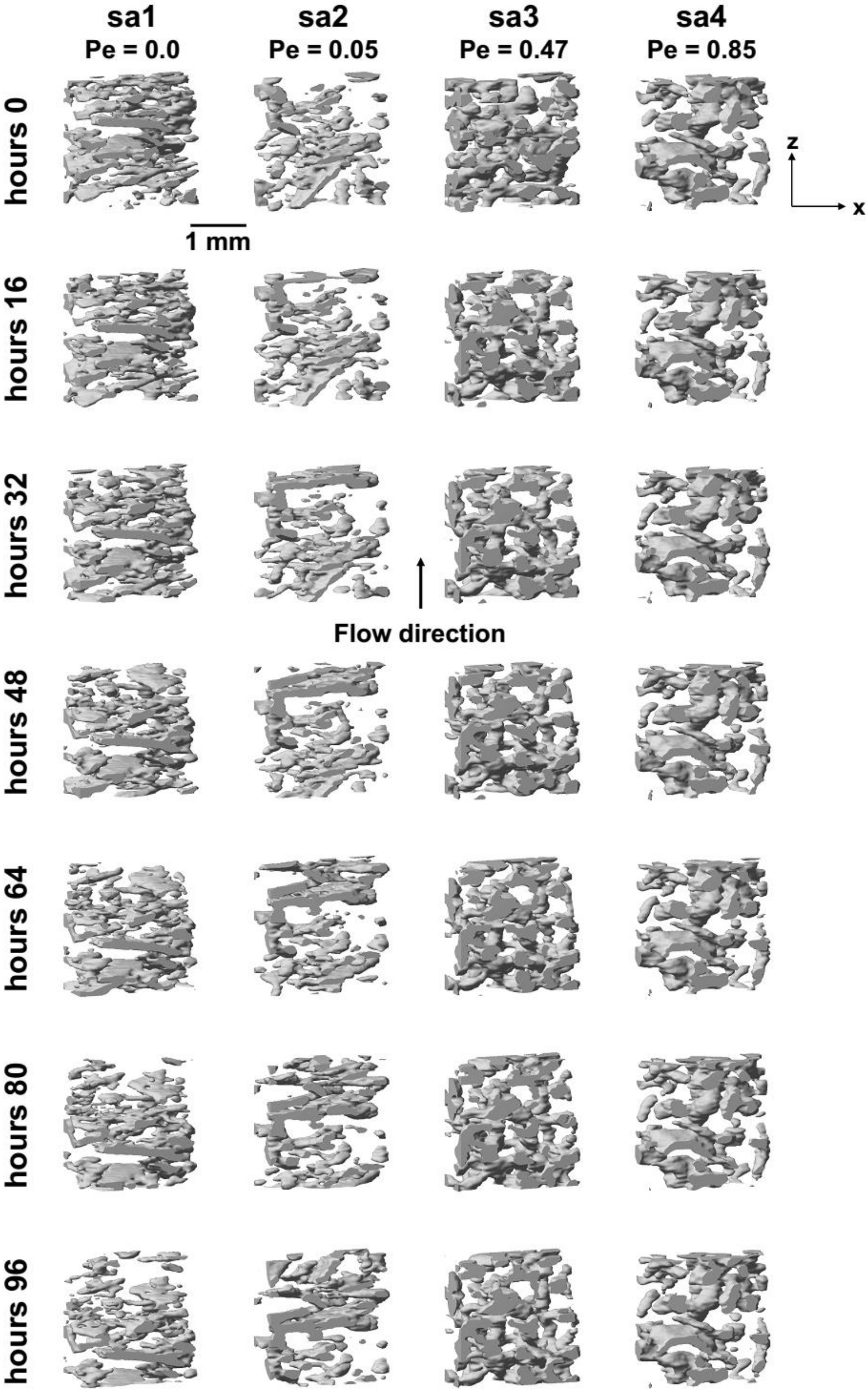

sa1
Pe = 0.0
sa2
Pe = 0.05
sa3
Pe = 0.47
sa4
Pe = 0.85
hours 0
hours 16
hours 32
hours 48
hours 64
hours 80
hours 96
1 mm
z
x
Flow direction

Fig. 4

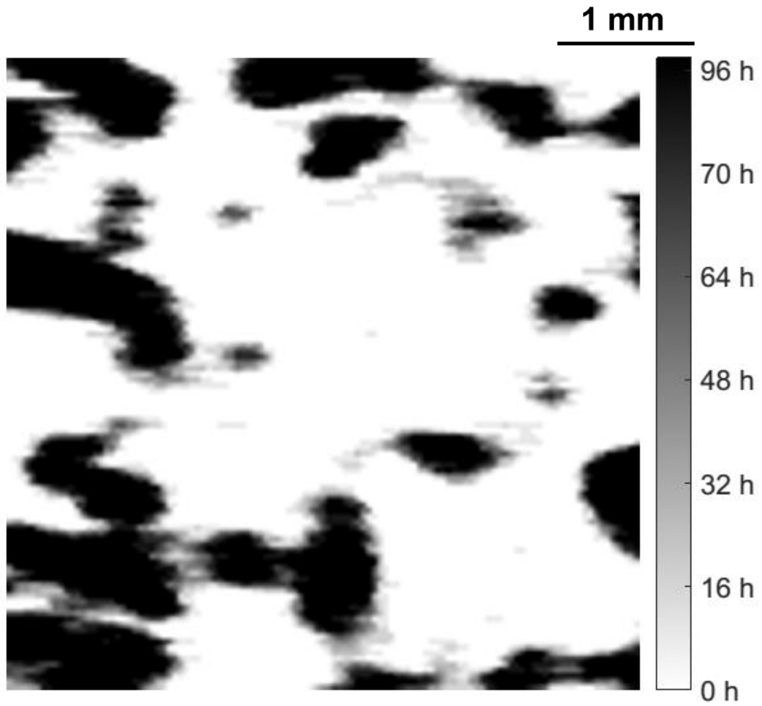


Fig. 5 a)

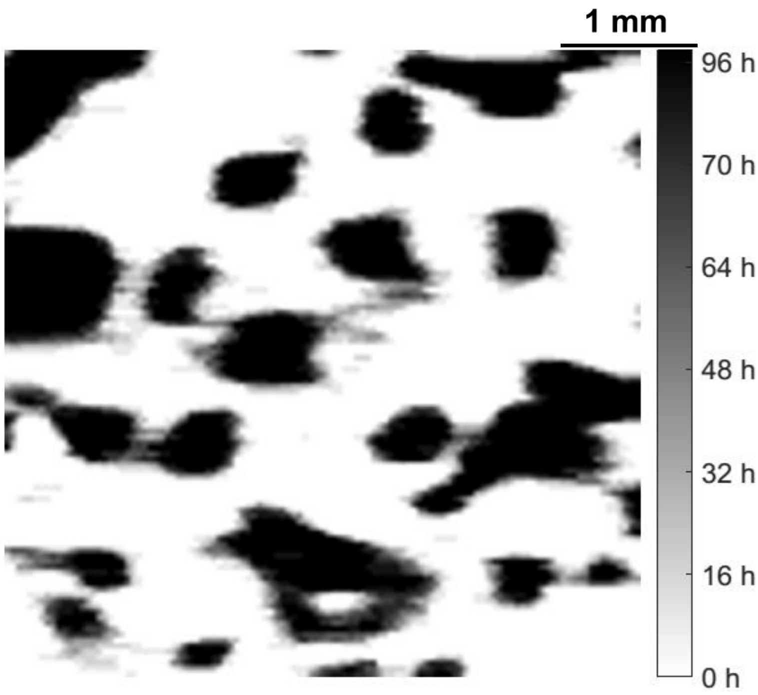


Fig. 5 b)

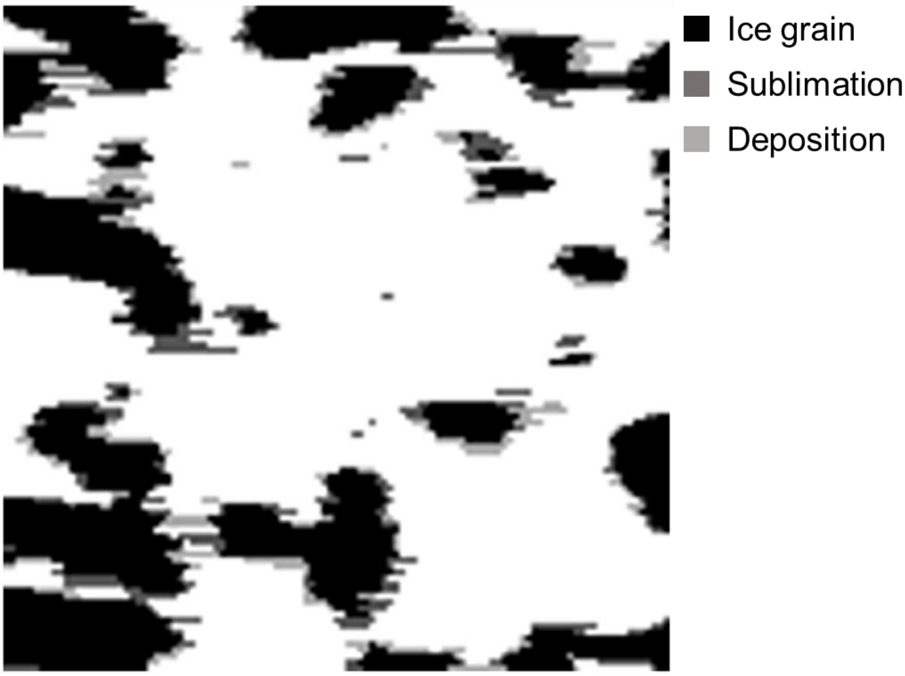


Fig 6 a)

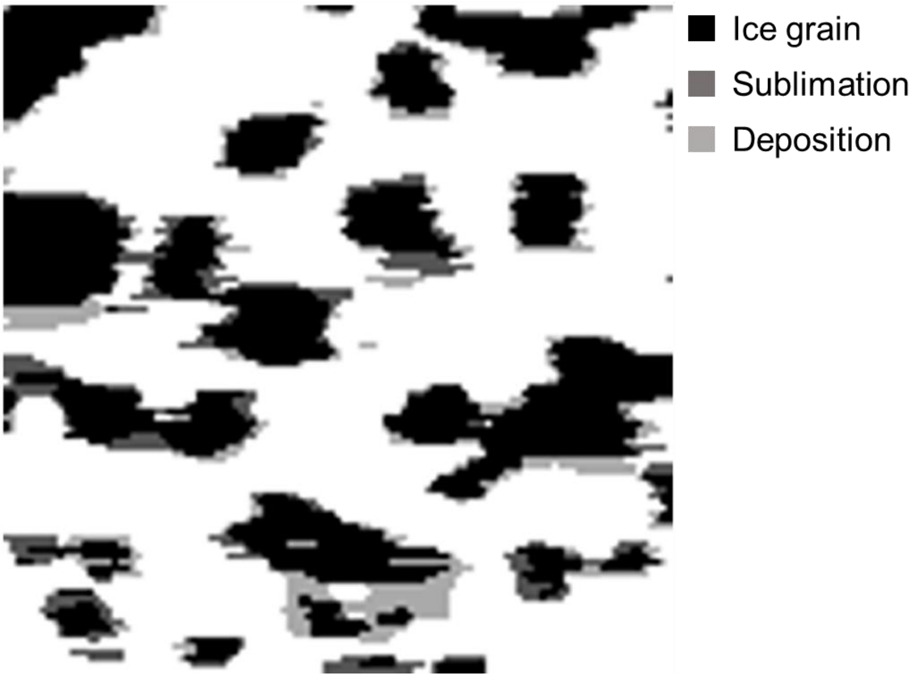


Fig. 6 b)

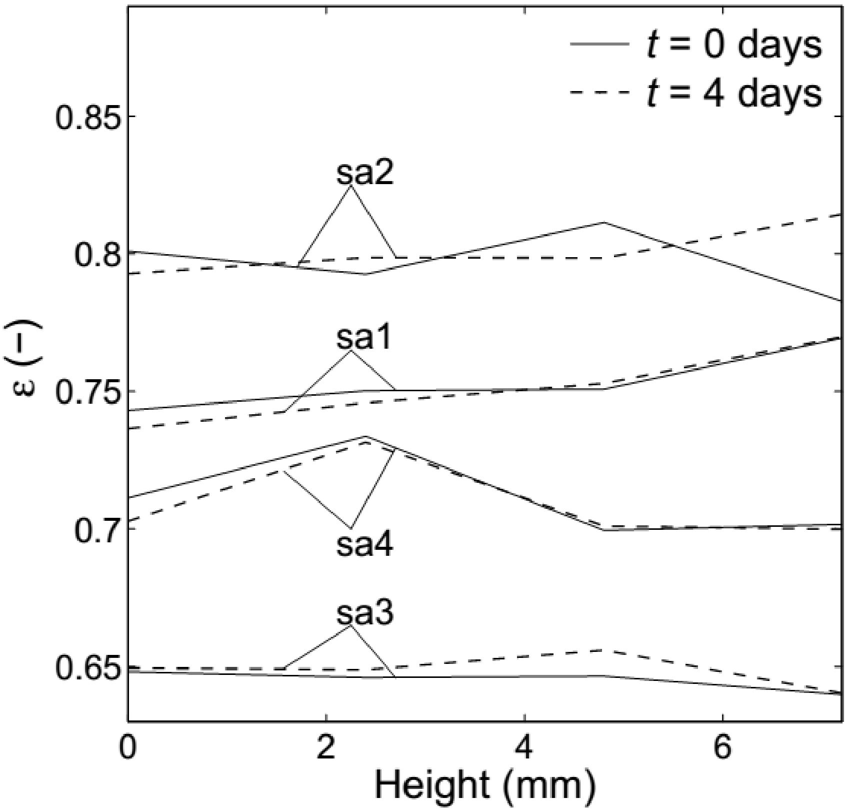

t = 0 days
t = 4 days
0.85
0.8
0.75
0.7
0.65
ε (–)
sa2
sa1
sa4
sa3
0
2
4
6
Height (mm)

Fig. 7

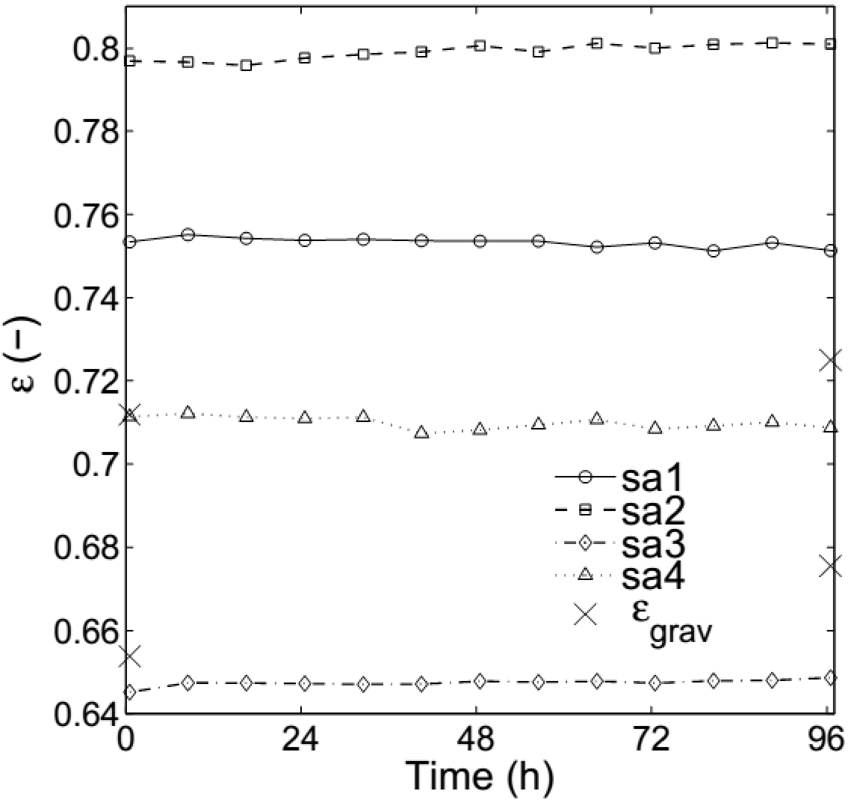
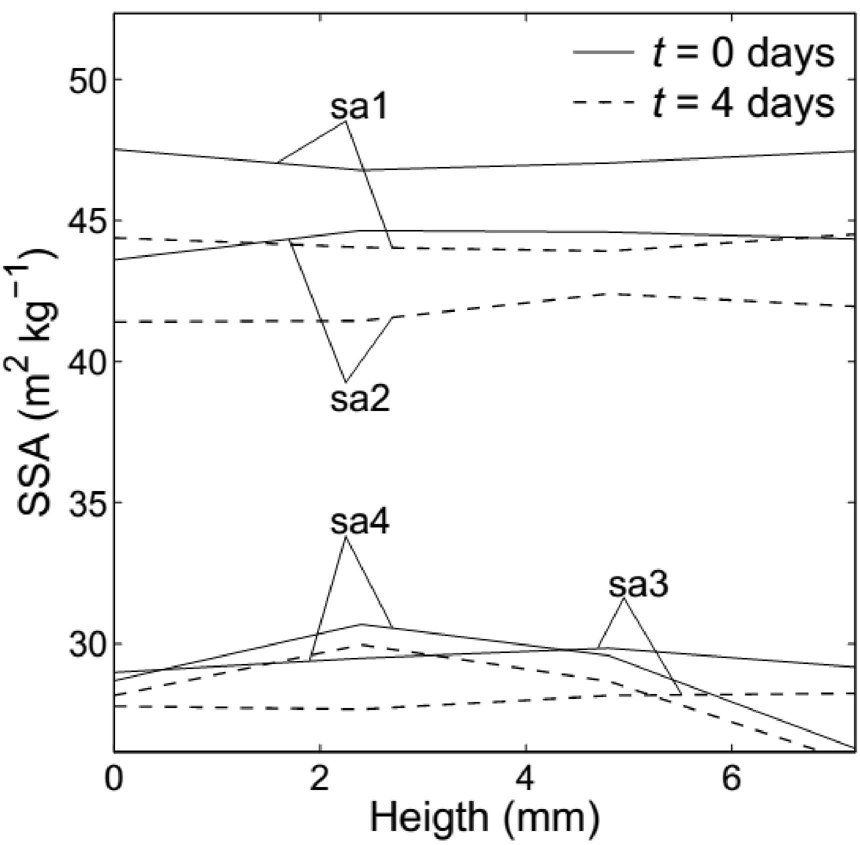
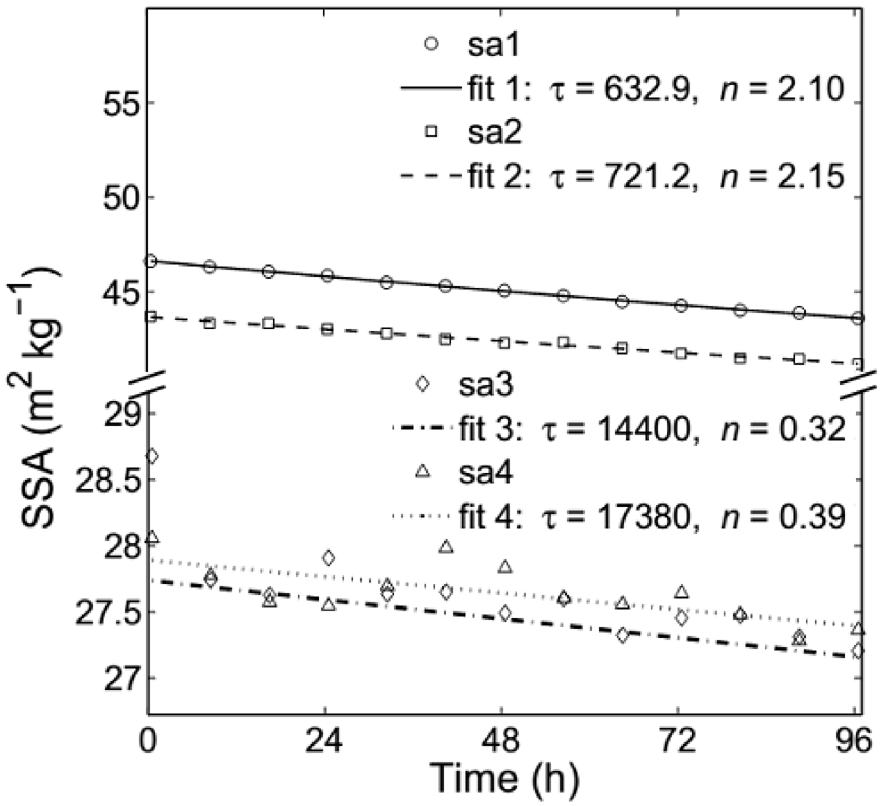

0.8
0.78
0.76
0.74
0.72
0.7
0.68
0.66
0.64
ε (−)
0
24
48
72
96
Time (h)
sa1
sa2
sa3
sa4
ε grav

Fig. 8



t = 0 days
t = 4 days
sa1
sa2
sa3
sa4
SSA (m2 kg−1)
Heigth (mm)
50
45
40
35
30
0
2
4
6

Fig. 9



sa1
fit 1: τ = 632.9, n = 2.10
sa2
fit 2: τ = 721.2, n = 2.15
sa3
fit 3: τ = 14400, n = 0.32
sa4
fit 4: τ = 17380, n = 0.39
55
50
45
29
28.5
28
27.5
27
SSA (m2 kg−1)
0
24
48
72
96
Time (h)

Fig. 10

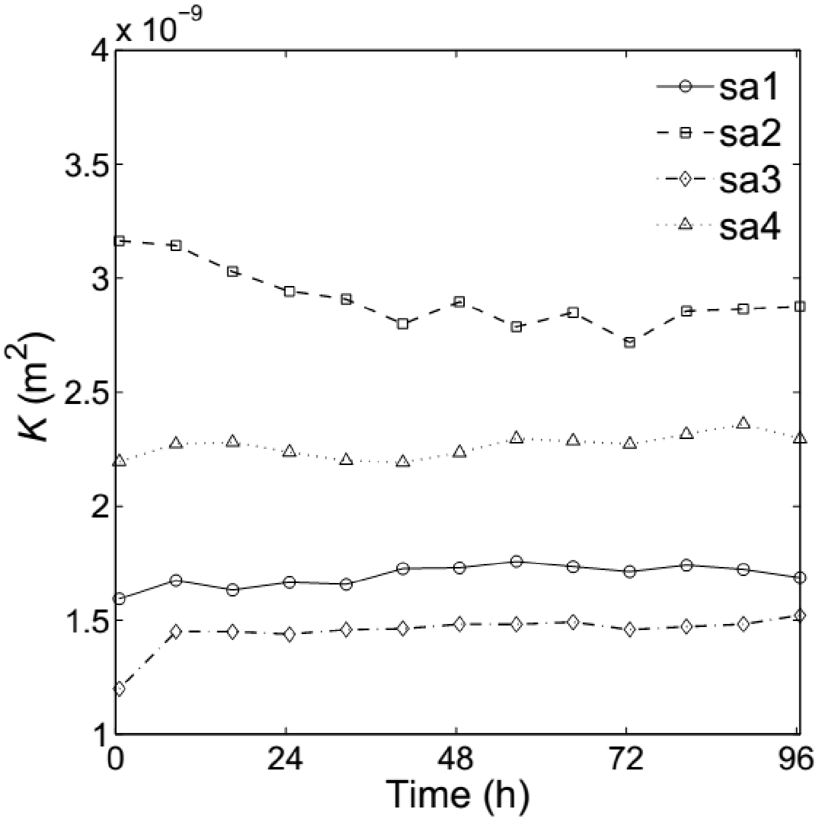


Fig. 11