RESPONSE TO REFEREES' C258 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 the anonymous referee #1 for the constructive comments. All page and line numbers correspond to those of the Discussion Paper.

REVIEWER: Anonymous Referee #1

The paper presents the results of experiments on isothermal metamorphism of snow with presence of saturated water vapor flux in the pore space of snow. The result is simple and interesting: such air flow does not affect the isothermal metamorphism. The methods, observations and results are clearly described. The previous paper of the authors in Geophysical Instrumentations provide more details of the experimental set-up, which saves space in this paper. I am not sure how high can be the impact of the obtained results, because it is difficult to expect some flow in the pore space of snow without presence of some special temperature variability, however, as a boundary condition for modeling the process, the results sounds important.

Response: Flow in the pore space of snow occurs especially under high wind speed above the snow surface but rapidly decreases. Numerical simulations (Neumann, 2003; Colbeck et al., 1997) estimated airflow velocities inside surface snow layer (pore size ≈ 1 mm) of ≈ 0.01 m s^{-1} under high wind speed (≈ 10 m s^{-1}), neglecting an temperature gradient.

Revision: Text added in the revised manuscript:

> On page 1023, line 9: "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 snow pack."

Text added in "References"

> Colbeck, S. C.: Model of wind pumping for layered snow, Journal of Glaciology, 43, 60–65, 1997.

Neumann, T. A.: Effects of firn ventilation on geochemistry of polar snow, (PhD thesis, University of Washington), 2003.

Minor revisions were made throughout the revised manuscript.

We thank the the anonymous referee for his scrutiny and recommendations.

The authors

RESPONSE TO REFEREES' C332 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 the reviewer Frédéric Flin for the constructive comments. We agree with all his comment, and answer them as follows. All page and line numbers correspond to those of the Discussion Paper.

REVIEWER: Frédéric Flin

This work deals with the effect of saturated air circulation in isothermal snow. 4 samples were submitted to different flow velocities and the evolution of their inner parts (about 7x7x7 mm3 volumes) was monitored by X-ray tomography with a pixel size of 18 micrometer during 4 days. The evolution of density, SSA and intrinsic permeability were computed from the 3D images obtained. Based on 3D local observations and the analysis of SSA evolution over this 4 days period, the authors conclude that the circulation of saturated air in isothermal snow does not impact the snow metamorphism. They finally extrapolate their results to all isothermal snowpacks, concluding that diffusion is always the main transport mechanism. This is potentially an excellent paper that proposes an original way to study the impact of air circulation in snow. The fact that the authors restrict to saturated air and isothermal snow conditions, which is a very specific case of air advection in snow, might appear a bit frustrating. However, as a pioneering tomographic approach, it is an important and wise step toward more complicated experiments. Furthermore, this work has also direct implications for a better understanding of the matter redistribution mechanisms occurring in isothermal snow metamorphism (e.g. Kaempfer et al, 2007; Brzoska et al, 2008; Vetter et al, 2010) and potential applications for permeability measurement methods (e.g. Jordan, 1999; Arakawa et al, 2009; Domine et al, 2013).

That said, this paper needs major improvements before publication. Here are my main concerns, with some suggestions (see "detailed comments" for more details):

<u>General comment #1:</u> Diffusion vs. advection: in their analysis, the authors based on the fact that all Pe numbers are below 0.85 to claim that diffusion is the main transport mechanism. This approach is not rigorous enough. When deciding which phenomena are dominant and which ones can be neglected, characteristic numbers should be analyzed depending on the separation of scales of the problem. Using such an approach will show that a Pe number of 0.85 is conceptually not different from 1 (or from 0.08, e.g.) and that experiments sa3 and sa4 at least are in a regime where diffusion and advection contributions are both significant and cannot be neglected (see e.g. Auriault et al, 2009; Calonne, 2014 - chapter 3). It should also be noted that conditions where Pe is “significantly larger” than 1 actually correspond to situations where transfers are driven by advection and dispersion (Bear, 1972 – chapter 10), which is a distinct regime than that of the presently considered regime of diffusion-advection (i.e., for Pe > 1, Darcy’s Law is no more valid and inertial effects should be accounted for).

→ The authors should analyze the considered problem more carefully and adapt their conclusions accordingly.

Response: It is correct, that experiment ‘sa3’ and ‘sa4’ are at least in a regime where diffusion and advection contributions are both significant and cannot be neglected, but our results didn’t show an influence of advective transport on the structural evolution of the snow with increasing velocity. Our results indicated that surface processes are the limiting rates for an isothermal snowpacks. Further, it is correct that there are snow types where the Peclet number could be significantly larger than 1, however, simulation by Neumann (2003) and Colbeck et al. (1997) estimated a maximum velocity of around 0.01 m s^{-1} for a high wind speed of 10 m s^{-1} above the snow surface (pore size ≈ 1 mm). Looking at the Peclet number, this corresponds to a maximum value of Pe ≈ 1. Therefore, we are still in the regime of diffusion-advection.

Revision: Text added in “2. Methodology”:

> “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 destroyed the snow structure and we restricted the flow rate to the corresponding maximum *Pe* ≈ 0.8 extracted from the simulation 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* > 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.”

Text added in “4. Summary and conclusions”:

> “Curvature caused sublimation of small ice grains and ice structures with small surface 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. Evaporation-deposition caused by the Kelvin-effect was the limiting factor independently of the transport regime in the pores.”

<u>General comment #2:</u> There are some inconsistencies concerning the mechanism that is supposed to govern isothermal metamorphism: from their SSA analysis, the authors conclude that surface processes are limiting the metamorphism independently of the transport regime in snow (diffusion or advection). However, they finally conclude that diffusion is the main mechanism at the origin of snow metamorphism.

→ The authors should clarify which mechanisms (diffusion or surface processes) are occurring under the different advection conditions, or at least should present their results in a more consistent way.

Response: It is correct that the surface processes are limiting the metamorphism independently of the transport regime in the pores.

Revision: Text added in “Abstract”:

> “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.”

Text added in “4. Summary and conclusions”:

> “Curvature caused sublimation of small ice grains and ice structures with small surface 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. Evaporation-deposition caused by the Kelvin-effect was the limiting factor independently of the transport regime in the pores.”

<u>General comment #3:</u> Based on 4 samples submitted to saturated air, the authors try to generalize their experimental results to any isothermal snowpack. For this, they argue that Pe numbers higher than 1 are impossible in isothermal snow. Such a claim sounds exaggerated. For instance, Depth hoar can form close to the surface (Alley et al, 1990; Gallet et al, 2013; Adams and Walters, 2014) and then undergo equi-temperature metamorphism due to a change of weather conditions, leading to potentially high Pe numbers, while their microstructures slowly evolve toward more rounded structures.

→ It seems more realistic to restrict to the evidence shown by the experiments and not to extrapolate to conditions that have not yet been properly investigated.

Reponse: It is possible to extrapolate our results to conditions that have not yet been properly investigated, based on previous studies. For example the formation of depth hoar close to the surface (Alley et al., 1990; Gallet et al., 2013; Adams and Walters, 2014). Without going into the details of the papers, there is no solid knowledge to exclude advective vapor transport as a process for the formation of this subsurface depth hoar. First, the formation of this 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.

However, in this paper we treat metamorphism under isothermal conditions, and the case of temperature gradient metamorphism under advective conditions will be treated in a forthcoming paper. If the editor agrees, we suggest not citing these papers and we consider this case of surface depth hoar formation not as relevant for the paper.

General comment #4: Some inconsistencies also appear throughout the paper concerning the settling of snow samples. From the literature (e.g. Schleef et al., 2014), it is obvious that the samples should exhibit at least moderate settling effects. This seems to be confirmed by most of the views of the samples (Fig. 3 and 4) where at least slight translations in the vertical direction are detectable. However, the authors give sometimes contradictory information on this topic.

→ The authors should clarify this point. A possible approach would be to acknowledge settling effects in all experiments but to consider that these effects have negligible impact on their study.

Response: We will acknowledge settling effects in all experiments but to consider that these effects have negligible impact on the study.

Revision: Text added in “3. Results and Discussion”:

> On page 1025, line 19: “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.”

> On page 1026, line 3: “A strong translation effect due to settling of sub-layering snow was visible for ‘sa1’ and ‘sa2’.”
>
> On page 1026, line 18: “no settling and densification occurred in the investigated volume.”

General comment #5: Many appropriate references are missing and several works are inadequately introduced. The paper lacks also some comparisons with previous results of the literature and their in-depth discussion.

→ See detailed comments (and point 6. below, e.g.).

Response: We will adapt the references and introduce the works adequately

Revision: See answer to Detailed comments #3 – #8, #15, #19, #27, and #35.

General comment #6: Permeability computations show evolutions that are not really consistent with those of the density and SSA. This might be due to the inherent difficulty of computing very precise estimations of this property using direct numerical simulations.

→ Comparisons of the results to existing relationships of the literature and a discussion on this topic would strengthen the paper.

Response: In our case, it is not relevant which method was used to calculate the morphological parameters as we wanted to show the trend and the evolution of these parameters to see the influence of advective airflow. We used the method established by Zermatten et al. (2014) to calculate the permeability. We didn’t want to compare the results with other relationship from the literature (e.g. Shimizu (1970), Carman Kozeny formula, etc. - see e.g. Courville et al (2010), Calonne et al (2012) or Domine et al (2013)) again as this was mainly done in the paper by Zermatten et al. (2014). If the editor agrees, we suggest not comparing the different models and we consider this case of different permeability calculations not as relevant for the paper.

It is correct, that an SSA decrease at a constant density would result in an increase of permeability. However, looking at the SSA evolution, it is obvious that there is only a small change in SSA due to the long sintering time. In addition, looking at the accuracy between measured and simulated permeability (e.g. Zermatten et al. (2014)) the uncertainty is still in the range to cover the increase of permeability due to SSA decrease.

Revision: Text added in “3. Results and Discussion”:

> On page 1028, line 2: “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."

<u>General comment #7:</u> A meshing approach has been used to compute most of quantitative parameters (density, SSA, permeability) but very little information is given on the mesh quality. It has, however, a very strong impact on the numerical computations.

→ A graph showing the influence of the mesh quality on the computed properties, and the pertinence of the chosen mesh would be appropriate. At least, for one sample, a figure (3D view) of the mesh used is needed.

Response: We will add more information about the mesh and the calculations in the revised paper

Revision: See answer to Detailed comments #31 and #33.

<u>General comment #8:</u> The local observations of snow structure are a bit deceiving. In particular, Fig. 4 is difficult to read and does not allow really checking the typical nature of Kelvin effect. Vertical displacements of the structure are detectable, but not commented by the authors.

→ The authors should consider replacing Fig. 4 by the superposition of cross-sections between 2 given time steps and discussing it in more details.

Response: We could improve the quality of Fig. 4. We will replace Fig. 4 and add a following up figure showing the superposition of cross-sections between 2 given time steps.

Revision: See answer to Detailed comments #34.

<u>General comment #9:</u> From a presentation point of view, the fact that only cases with Pe <= 1 have been investigated should appear in the important parts of the paper (title, abstract, introduction, etc). In addition, the discussion concerning the Pe numbers appears probably too late in the text.

→ An option would be to discuss and restrict the problem to Pe <= 1 much earlier in the paper.

Response: We will discuss and restrict the problem to Pe <= 1 much earlier in the paper.

Revision: Text added in "1. Introduction":

> On page 1023, line 9: “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 snow pack.”

Text added in “2. Methodology”:

> “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 destroyed the snow structure and we restricted the flow rate to the corresponding maximum *Pe* ≈ 0.8 extracted from the simulation 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* > 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.”

General comment #10: Some basic but important information are missing (height of the samples, anodic current, computation method used for dp, etc.).

→ To be added to the text.

Response: We will add these information in the revised manuscript

Revision: See answer to Detailed comments #10, #11, #12, and #31.

<u>Detailed Comments:</u>

<u>Comment #1:</u> 1022/2-3: *Diffusion and advection across the snow pores were analysed in controlled laboratory experiments.*

It is difficult to understand to which part of the work this sentence refers. Does it refer to the theoretical interpretation of Pe numbers or just to the fact that several experiments with different regimes where experimented? Furthermore, the authors do not have access to the diffusion nor advection fields, but just to their effect on the snow microstructure. A slight reformulation of the sentence would clarify these points.

Revision: Text changed in the revised manuscript:

> On page 1022, line 2-3: "The effect of diffusion and advection across the pores on the snow microstructure was analysed in controlled laboratory experiments and further elaborate on natural snowpacks."

<u>Comment #2:</u> 1022/8-10: *Diffusion originating in the Kelvin effect between snow structures dominates and is the main transport process in isothermal snow packs.*

Can we still talk about transport by diffusion when the Peclet number Pe is so close to one? Do the results not tend to show that the isothermal metamorphism is rather driven by evaporation-deposition phenomena (i.e., probably what the authors also call "surface processes"), independently of the transport process actually used (diffusion for low Pe, advection for Pe closer to 1) –see the n-exponent analysis. In addition, the generalisation of the experiments done on 4 specific samples in saturation conditions to all isothermal snowpacks seems clearly exaggerated. I suggest reformulating this last sentence.

Response: According to the Peclet number, it is not possible to talk about transport only by diffusion when Pe is close to one. However, looking at the experimental results it is obvious that advective transport showed no additional effect on the structural change.

It is also correct that isothermal metamorphism is driven by evaporation-deposition phenomena caused by the Kelvin-effect, independently of the transport process actually used. However, there is no obvious influence of increasing velocity on the structural change.

Revision: Text changed in the revised manuscript:

> On page 1022, line 8-10: "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."

Comment #3: 1022/24-25: *The energy reduction is achieved 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), evaporation-condensation with vapour transport (German, 1996; Hobbs and Mason, 1963; Legagneux and Domine, 2005; Maeno and Ebinuma, 1983), and the Kelvin effect (Bader, 1939; Colbeck, 1980) are also suggested to play an important role.*

These sentences sound strange for several reasons:

- The Kelvin effect is not really a mechanism for isothermal metamorphism but the "driving force" of this metamorphism. It is consensually known to be the cause of isothermal metamorphism and it should not be confused with the way (transport phenomena or other mechanisms) by which the mass redistribution occurs (see e.g. Flin et al 2003, Vetter et al 2010).

- To my knowledge, there is a general agreement to consider vapour diffusion, evaporation-condensation and surface diffusion as the most probable dominant mechanisms depending on temperature conditions (see e.g. Hobbs, 1974; Maeno and Ebinuma, 1983; Brzoska et al, 2008; Vetter et al, 2010)

Revision: Text changed in the revised manuscript:

> On page 1022, line 24-25: "The energy reduction is achieved 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 evaporation-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)."

Comment #4: 1022/26-1023/2: *Recent studies indicate that vapour transport caused by the Kelvin effect is most important in isothermal metamorphism (Vetter et al., 2010).*

It seems that this is not exactly what is written in Vetter et al, 2010. Please check.

Revision: Text changed in the revised manuscript:

> On page 1022, line 26 – page 1023, line 2: "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)."

Comment #5: 1023/14-17: *However, no prior studies have described the effect of airflow on the vapour transport and the recrystallization of the snow crystals.*

As far as tomography is concerned, this subject seems clearly new, indeed. However, several studies have been devoted to air flow effects on vapour transport and recrystallization (actually, phase changes) using other approaches (e.g., Neumann et al, 2009; Albert, 2002; Albert and Schultz, 2002; Calonne, 2014). Please correct the sentence accordingly.

Revision: Text changed in the revised paper:

> On page 1023, line 14-17: "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."

Comment #6: 1023/17-20: *However, saturation vapour density of the air is reached in the pore space within the first 1 mm of the snow sample, regardless of temperature or flow rate (Neumann et al., 2009; Ebner et al., 2014).*

From Neumann et al, 2009 (conclusions), it actually appears that this length is not 1 mm but 1 cm.

Revision: Text changed in the revised paper:

> On page 1023, line 17-20: "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)."

Comment #7: 1024/10: Please give the numerical value used for D.

Revision: Text added in the revised manuscript:

> On page 1024, line 10: "and $D = 2.036 \cdot 10^{-5}$ m^2 s^{-1} is the diffusion coefficient of water vapour in air"

Comment #8: 1024/26-30: *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; Pinzer et al., 2012; Ebner et al., 2014).*

Please consider adding some appropriate references to non-SLF studies (e.g., Chen and Baker, 201 0). This would help to situate the present work in the international contest.

Revision: Text changed in the revised manuscript:

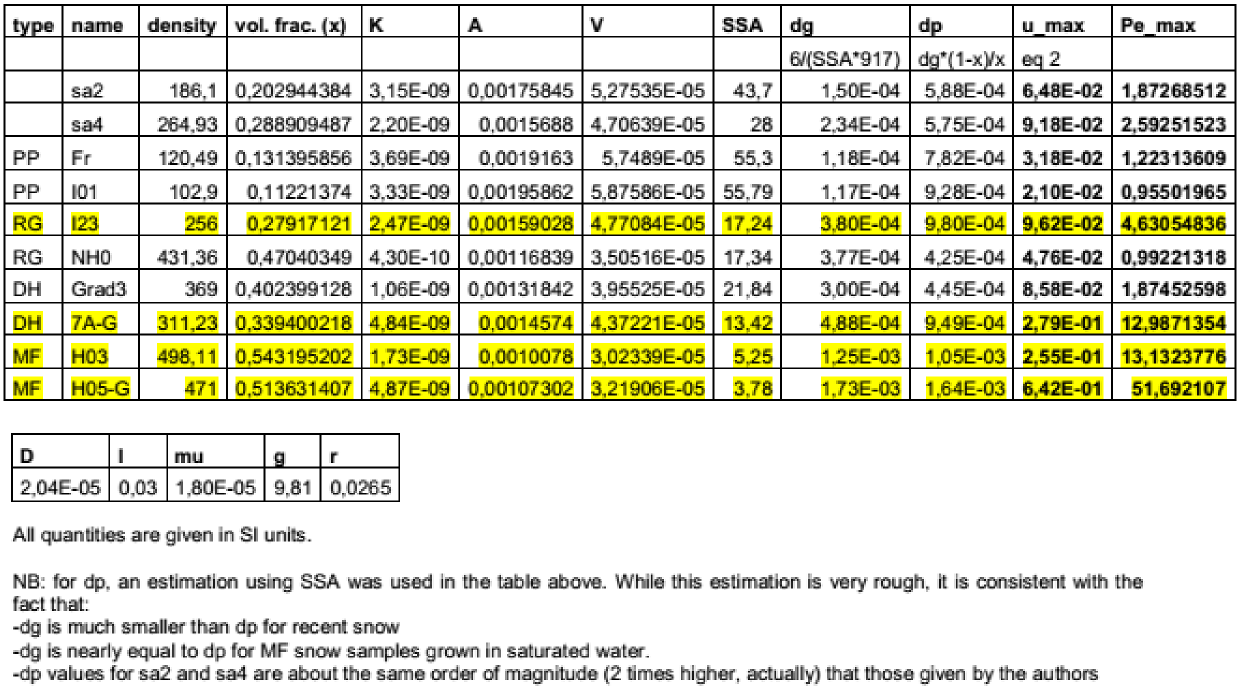
> On page 1024, line 26-30: "We designed experiments in a controlled refrigerated laboratory and used time-lapse computed tomography (micro-CT) to obtain the discrete-scale geometry of snow (Schneebeli and Sokratov, 2004; Kaempfer and Schneebeli, 2007; Pinzer and Schneebeli, 2009; Chen and Baker, 2010; Pinzer et al., 2012; Wang and Baker, 2014; Ebner et al., 2014)"

Following references will be added in the revised manuscript:

> "Chen, S. and Baker, I.: Evolution of individual snowflakes during metamorphism, Journal of Geophysical Research, vol. 115, 1–9, 2010."
>
> "Wang, X. and Baker, I.: Evolution of the specific surface area of snow during high-temperature gradient metamorphism, Journal of Geophysical Research Atmospheres, vol. 119, 13690 – 13703, 2014."

Comment #9: 1024/14-15: *Higher Pe numbers were experimentally not possible, as the shear stress by airflow would destroy the snow structure*.

Maybe I missed something important, but this assertion does not seem convincing: refrozen MF samples, DH samples, or even "old" RG samples would probably have allowed higher Pe numbers without any significant problem. See table below, were I computed some 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.thecryosphere.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: That's correct but the calculations are based on the assumption that the fragile microstructure of the snow sample will not be destroyed. However, in the experiments we saw a destruction of the snow structure for high Peclet number. Further we decided to perform experiments with snow with high SSA to see better the structural evolution. And according to the simulation of Neumann (2003), the maximum Peclet number will be less than 1.

Revision: Text changed in the revised manuscript:

> On page 1024, line 6-22: "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. 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. Natural 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. 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 destroyed the snow structure and we restricted the flow rate to the corresponding maximum $Pe \approx 0.8$ extracted from the simulation 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) $Pe > 1$ 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, $Pe \approx 1.2$ 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 $Pe \approx 0.8$. Table 1 summarizes the experimental conditions."

Comment #10: 1024/23-24: *The acceleration voltage in the X-ray tube was 70 keV with a nominal resolution of 18 μm.*

Please change 70 keV into 70 kV and add information about current in μA.

Revision: Text changed in the revised manuscript:

> On page 1024, line 23-24: "The acceleration voltage in the X-ray tube was 70 kV, with an intensity of 114 μA, and with a nominal resolution of 18 μm."

Comment #11: 1024/24-25: *The samples were scanned with 1000 projections per 180 degree, with an integration time of 200ms per projection.*

Does it mean 2000 projections were done per sample, or that half of a rotation was used to scan the specimen? In the latter case, please specify if there are specific reasons for this choice (360° rotations are much more common, as they better allow checking the consistency of the image reconstruction).

Response: 2000 projections were done per sample (360º).

Revision: Text changed in the revised manuscript:

> On page 1024, line 24-25: "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."

Comment #12: 1024/25-27: *The innermost 36.9mm of the total 53mm diameter were scanned and subsamples with a dimension of 7.2mm×7.2mm×7.2mm were extracted for further processing.*

Please add information about the total height of the snow sample (and that of the snow sample holder) in the text.

Revision: Text changed in the revised manuscript:

> On page 1024, line 19-21: "A cylinder cut out (diameter: 53 mm; height: 30 mm) from the sintered snow was filled into the sample holder (Ebner et al., 2014)."

Comment #13: 1026/1 -3: *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"*

Please comment in the paper on the strong translation effect (settling or sublimation of the sublayering snow?) that is obviously visible for sa1 and sa2 (Fig. 3).

Revision: Text added in revised manuscript:

> On page 1026, line 3: "A strong translation effect due to settling of sub-layering snow was visible for 'sa1' and 'sa2'."

Comment #14: 1026/5-6: *The sublimated mass was relocated to bigger grains but the airflow velocity did not affect this relocation process.*

Was the mass preferentially relocated to bigger grains or to concavities? Which kind of vapour transport is actually occurring? Where are the vapour sources and the corresponding sinks? Could not directional effects that are due to the flow direction be observed on the microstructure? Cross sections (residence time graphs of Fig. 4 are poorly informative).

Response: See answer to Comment #34 (1040/Fig 4).

Comment #15: 1026/9-10: *after sintering, further densification is limited by coarsening kinetics.*

This sentence seems strange. To my understanding, sintering and densification are inherently coupled in metamorphism processes (see Flin et al, 2003; Vetter et al, 2010; Schleef et al, 2014).

Revision: Text changed in the revised manuscript:

> On page 1026, line 9-10: "This supports the hypothesis that further densification is limited by coarsening kinetics (Kaempfer and Schneebeli, 2007; Schleef et al., 2013)."

Comment #16: 1026/11 -12: *Thus, spatial change in the flow field due to different interfacial velocities can be neglected.*

This is true for the imaged volume, but what about the base, top and lateral boundaries of the overall sample, particularly prone to flow changes and heterogeneities?

Revision: Text added in the revised paper to clarify that all the observed results only are based on the investigated volume:

> On page 1025, line 19: "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."

Comment #17: 1026/13-14: *Consequently, Pe was constant with time, and diffusion was still the dominant mass transfer mechanism.*

The relationship with the preceding sentences is not obvious for me. Concerning diffusion as a dominant mechanism, it seems the authors need to check and clarify this point throughout the paper: is really diffusion the dominant vapor transport mechanism? Is advection really negligible? Are these two phenomena not strongly coupled for Pe approaching 1 (sa3 and sa4)?

Response: Your concern about our conclusion for Pe approaching 1 is justified. Advection is not negligible. However, it has also no influence on the structural evolution of the snow.

Revision: Text changed in the revised paper:

> On page 1026, line 13-14: "Consequently, *Pe,* and therefore the advective and diffusive mass transfer regime, was constant with time."

Comment #18: 1026/18: *no settling and densification occurred*

Please add at least "in the investigated volume". This assertion seems quite questionable as far as the whole sample is concerned. Recent snow undergoing isothermal metamorphism, such as sa1 and sa2, are known to undergo settling and densification due to their own weight. See here for instance: Calonne et al 2013, Schleef et al 2014. At least, strong translation effects can be seen on Fig. 3 (sa1 and sa2) and are also detectable on Fig. 4 (s3 and s4).

Revision: Text added in the revised paper to clarify that all the observed results are based on the investigated volume:

> On page 1025, line 19: "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."
>
> On page 1026, line 18: "no settling and densification occurred in the investigated volume."

Comment #19: 1027/eq 1 :

This formula results from a very basic mean field approach. In particular, it considers disconnected grains that do not undergo settling. Consequently, equation (1) may give very qualitative estimation on the real mechanisms occurring in snow (for a discussion on some of these aspects, see e.g. Legagneux et al 2004, who mention different non-integer exponents for several experiments and the introduction of Taillandier et al, 2007). It is also known to be extremely dependent to the initial state, which is well illustrated by the high difference obtained for n values of sa3 and sa4 between tables 2 and 3. At least, a small comment on these topics seems relevant as far as the determination of mechanisms is concerned.

Revision: Text added in the revised paper:

> On page 1027, line 12: "Equation (1) gives a very qualitative estimation on the real mechanism occurring in the snow."
>
> On page 1027, line 13: "Ostwald ripening describes the coarsening of solid particles with a given size distribution, considering disconnected grains that do not undergo settling."
>
> On page 1027, line 25: "Notice, Eq. (1) extremely depends to the initial state, which is well illustrated by the high difference obtained for *n* values of 'sa3' and 'sa4' between Tables 2 and 3."

Comment #20: 1027/16-17: *Theoretically, the growth exponent n is approximately 2 when surface processes are rate limiting*

What does "surface processes" stand for? Is it sublimation-deposition, surface diffusion, or both of them?

Revision: Text changed in the revised paper:

> On page 1027, line 16-17: “Theoretically, the growth exponent *n* is approximately 2 when surface kinetics on a rough interface like sublimation-deposition or surface diffusion are rate limiting and 3 when diffusion in the vapor phase is rate limiting.”

Comment #21: 1027/20-21: *Experiment “sa3” and “sa4” had similar fitting parameters and a lower value of n, suggesting that surface effects were rate limiting.*

Why a lower value of n, namely 0, suggests surface effects are rate limiting?

Response: We had two different snow samples sintered for 13 and 27 days at -15 and -5 ºC, respectively. The growth exponent *n* for experiment “sa3” and “sa4” is close to zero because there was a very little change in the microstructure of snow due to the long sintering time (27 days at -5 ºC) before the experiments started. Only a slowly SSA decrease of 1.5% was observed.

Revision: Text changed in the revised manuscript:

> On page 1027, line 20-21: “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. 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.”

Comment #22: 1028/1-4: *The effect of decreasing SSA on the permeability was not elucidated in our experiments. […] The value of the effective permeability was higher than the one determined in a previous study (Zermatten et al., 2011, 2014), although, our measured SSA was higher by a factor of at least 2.4. The temporal evolution of permeability for experiment “sa2” showed a decrease of 8% for the first 40 h and remained constant afterwards.*

An SSA decrease at a constant density would result in an increase of permeability (see e.g. Calonne et al 2014). This does not seem to be in accordance with the results of Fig. 9. As the authors have access to both SSA and density, they could plot permeability estimations using existing relationships from the literature (e.g. Shimizu (1970), CarmanKozeny formula, etc. - see e.g. Courville et al (2010), Calonne et al (2012) or Domine et al (2013)) and discuss how these estimations compare with their numerical results.

Response: We used the method established by Zermatten et al. (2014) to calculate the permeability. We didn’t want to compare the results with other relationship from the literature (e.g. Shimizu (1970), CarmanKozeny formula, etc. - see e.g. Courville et al (2010), Calonne et al (2012) or Domine et al (2013)) again as this was mainly done in the paper by Zermatten et al.

(2014). If the editor agrees, we suggest not comparing the different models and we consider this case of different permeability calculations not as relevant for the paper.

It is correct, that an SSA decrease at a constant density would result in an increase of permeability. However, looking at the SSA evolution, it is obvious that there is only a small change in SSA due to the long sintering time. In addition, looking at the accuracy between measured and simulated permeability (e.g. Zermatten et al. (2014)) the uncertainty is still in the range to cover the increase of permeability due to an SSA decrease.

Revision: Text added in the revised manuscript:

> On page 1028, line 2: "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."

<u>Comment #23:</u> 1028/13-14: *This difference could therefore be due to an error during the measurement.*

Please clarify this point. What kind or measurement error? Is this inconsistency not rather due to problems in permeability computations (meshing, impact of the borders of the image file, choice of boundary conditions, REV)?

Response: No, this inconsistency cannot be due to problems in permeability computations as all the other permeability calculations of the µ-CT scans didn't show this big change. Therefore, there was a problem with the first scan, but this was not reflected in porosity and SSA.

<u>Comment #24:</u> 1028/15-16: *As Pe < 1, diffusion was consequently the dominant component.*

The interpretation of Pe numbers in terms of transport mechanisms seems biased. I agree that a Pe value of 0.85 is smaller than 1, but 0.85 can be seen also as nearly equal to 1 depending on the separation of scales of the problem (typically, here: pores of 0.3 mm in a sample of size 50 mm). This means that for sa3 and sa4 experiments, diffusion and advection, which are concurrent mechanisms, both play a non-negligible role in vapour transport. Actually, given the scale separation of the problem (about 1/100), it seems Pe should be of the order of 10-4 to neglect advection effects in the transport phenomena (see e.g. Auriault et al, 2009; Calonne, 2014).

Response: Your concern about our conclusion for Pe approaching 1 is justified. Advection is not negligible. However, it has also no influence on the structural evolution of the snow. We will change the sentences.

Revision: Text changed in the revised manuscript:

> On page 1028, line 15-16: “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 surface 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. Evaporation-deposition caused by the Kelvin-effect was the limiting factor independently of the transport regime in the pores.”

<u>Comment #25:</u> 1028/21 -23: *(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, 1997b)*

This is not really true: depth hoar often forms close to the surface and could then be exposed to air advection (Alley et al 1990). See also Gallet et al (2013) and Adams and Walter (2014) concerning radiation recrystallized snow. Also, refrozen wet snow or “old” rounded grains may be suitable to Pe > 1. See comment 1024/14-15.

Response: Without going into the details of the papers, there is no solid knowledge to exclude advective vapor transport as a process for the formation of this subsurface depth hoar. First, the formation of this 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.

However, in this paper we treat metamorphism under isothermal conditions, and the case of temperature gradient metamorphism under advective conditions will be treated in a forthcoming paper. If the editor agrees, we suggest not citing these papers and we consider this case of surface depth hoar formation not as relevant for the paper.

<u>Comment #26:</u> 1029/7-8: *Pe > 0.85 were not possible due to the destruction of the snow structure.*

See comment 1024/14-15. In any case, such information as well as the discussion concerning the Pe number could appear explicitly earlier in the paper (title, abstract and introduction). For the title, replacing « advective conditions » by « moderate advective conditions » could be an option.

Response: We will discuss this earlier in the paper, see the revised manuscript. We will add more information about the Peclet number.

Revision: Text added in the revised manuscript:

> On page 1023, line 9: "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 snow pack."
>
> On page 1029, line 7-8: "$Pe > 0.85$ were not possible due to the destruction of the snow structure and is not realistic in natural snowpacks."

<u>Comment #27:</u> 1029/12-13: *after sintering, further densification was limited by coarsening kinetics.*

See comment 1026/9-10

Revision: Text changed in the revised manuscript:

> On page 1029, line 12-14: "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)."

<u>Comment #28:</u> 1029/16-18: *no enhancement of mass transfer inside the pores was observed and diffusion through the pores was the main driving force.*

Is really diffusion the "driving force" of the metamorphism? What about Kelvin effect? What about the role of « surface processes » mentioned in the paper (see 1027/25-27)?

Response: Your concern is correct, Kelvin effect and the role of "surface processes" can be seen as a mass source/sinks for the water vapor inside the pores.

Revision: Text changed in the revised manuscript:

> On page 1029, line 16-18: "Evaporation-deposition caused by the Kelvin-effect was the limiting factor independently of the transport regime in the pores."

Comment #29: 1029/18-19: *Curvature caused sublimation of small ice grains leading to a slight decrease in SSA*

What about concave shapes?

Response: That's correct, not only small ice grains sublimated but also ice structures with small surface radii.

Revision: Text changed in the revised manuscript:

> On page 1029, line 18-19: "Curvature caused sublimation of small ice grains and ice structures with small surface radii leading to a slight decrease in SSA."

Comment #30: 1029/19-20: *In isothermal snow packs, diffusion through the pores is the dominating part and advective transport processes on the structural dynamics can be neglected.*

Is this sentence really deduced from the experimental work done? Based on the results obtained for 4 samples where Pe was always below 0.85 and the air was always saturated, this assertion seems a bit exaggerated. Using under or over-saturated air (or larger Pe, which is not impossible depending on snow types) may lead to different results.

Response: Clearly, it could be interesting to observe the deposition and sublimation of over- and undersaturated air at the surface by micro-CT, and investigate the thermal effect. However, in order to understand the basic mechanisms governing metamorphism, we reduced the physical complexity of the experiments and restricted here to the isothermal case, and if theory and experiments agree. And based on the experimental results of Neumann et al. (2009), saturation vapor density is reached in the pore space within the first 1 cm of the snow sample.

Revision: Text changed in "Conclusion" section:

> On page 1029, line 12-20: "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 surface 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. Evaporation-deposition caused by the Kelvin-effect was the limiting factor independently of the transport regime in the pores."

Comment #31: 1034: Table 1.

How was dp estimated? Using an estimation based on SSA would give a pore diameter 2 times higher than the presently given values (see comment 1024/14-15): this would then result in an increase of the computed Pe numbers by a factor 2. At least, some information should appear in the text of the paper about the methodology used.

Response: We used the methodology described by Zermatten et al. (2011, 2014), mention in the "2. Methodology".

Revision: Text added in the revised paper:

> On page 1025, line 10-12: "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
>
> $$\nabla p = -\frac{\mu}{K} u_{\mathrm{D}} - F \rho u_{\mathrm{D}}^{2} - \frac{\gamma \rho^{2}}{\mu} u_{\mathrm{D}}^{3} \tag{1}$$
>
> 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 ($\mathrm{Re} \approx 1$) in the experiment, only permeability K was considered for further discussions."

Comment #32: 1038/Fig 2:

This graph does not seem mandatory to me. The authors can just write instead that the temperatures were -7.5+-0.5°C and -14.5+-0.5°C at the top and base of the sample throughout the experiments. If they want to keep this graph, it could be worth plotting both of the NTC measurements to better show the accurateness of the isothermal conditions.

Response: We want to keep this graph to show the temperature signal and the influence of the µ-CT scans on the temperature field. It will not make sense to plot the top and base temperature signal of the NTC because the difference was less than 0.2 ºC and, therefore, inside the uncertainty of the NTC (Ebner et al., 2014).

Revision: Text added in the revised manuscript:

> On page 1038: “The accurateness of the isothermal conditions between the top and base of the sample throughout the experiment is less than 0.2 ºC (Ebner et al., 2014).”

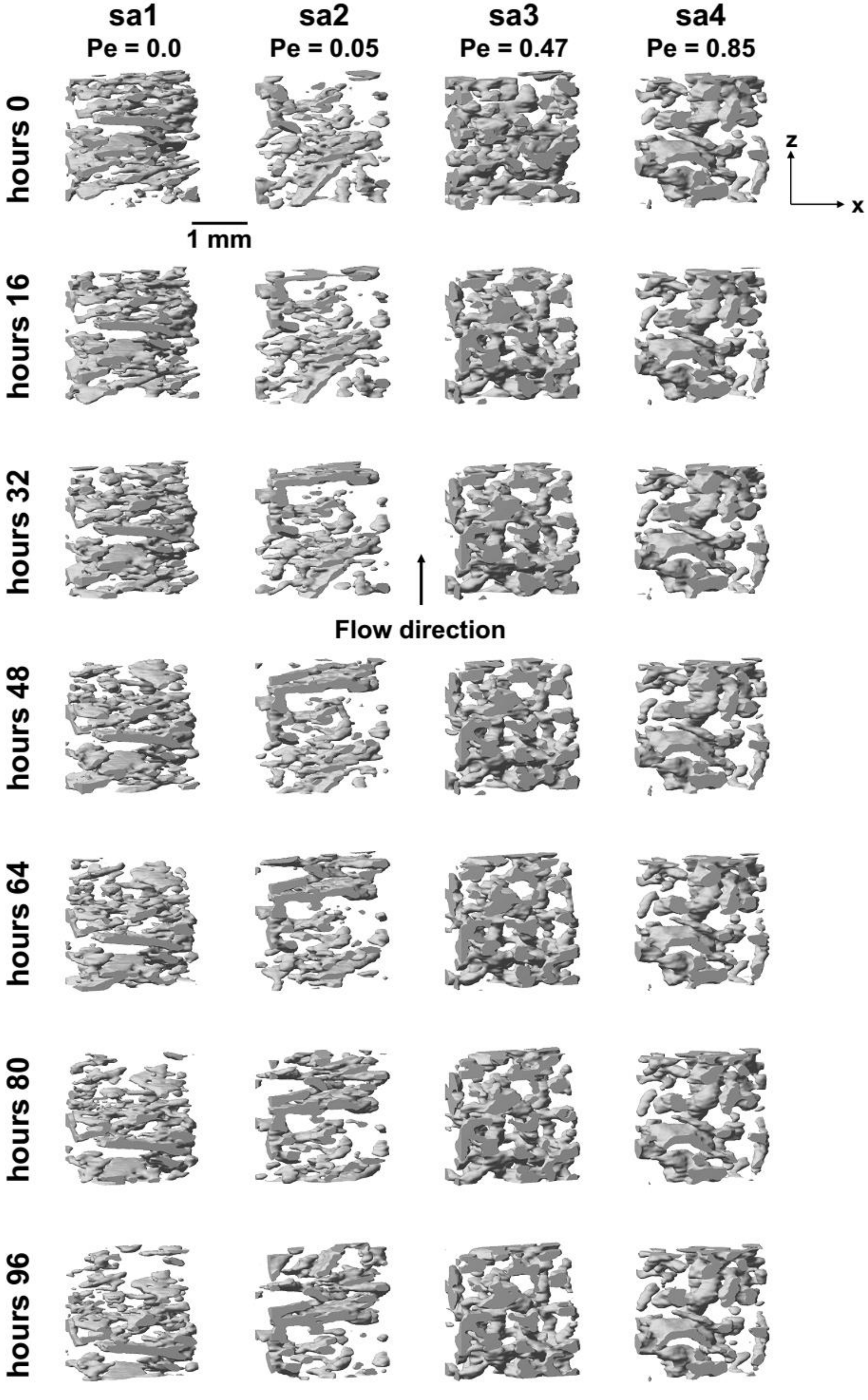
Comment #33: 1039/Fig 3:

It could be worth to recall on the figure:

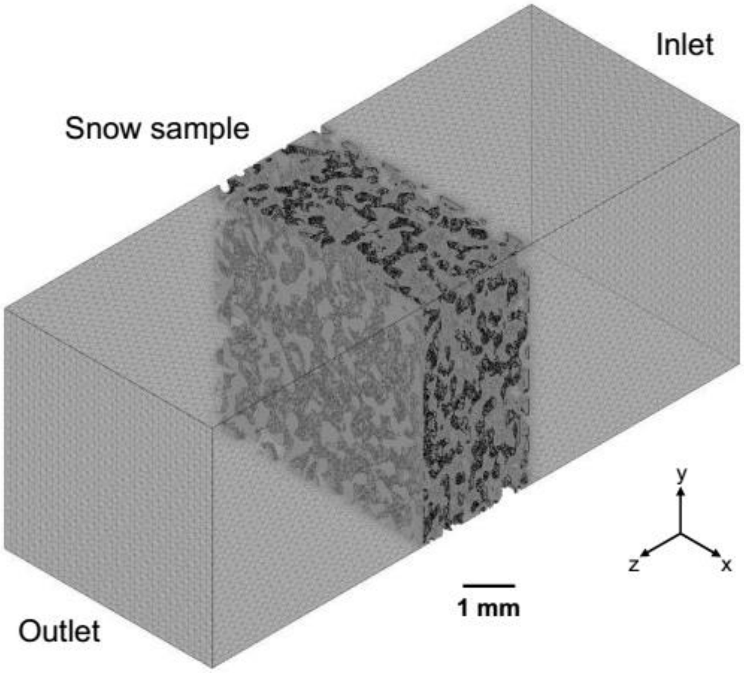
- The direction of the air flow
- The Pe numbers for each experiment

Adding a figure with a full-size view of the surface mesh of a sample would help the reader to be convinced of the meshing accuracy and of those of subsequent computations (density, SSA, permeability, etc.). A graph showing the pertinence of the chosen mesh (e.g. permeability = f (cell number)) should also be considered by the authors.

Revision: Fig. 3 changed in the revised paper:


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

A new figure added between Fig. 1 and Fig. 2:



> Caption 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.”

and text added in the revised paper:

> On page 1025, line 16: “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).”

Text added in the revised paper:

> On page 1025, line 17-18: “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.”

Comment #34: 1040/Fig 4:

Residence time of ice particles within in a slice -> “within a slice”

Due to the acquisition process (slight variability of the X-ray source leading to small differences in the reconstruction parameters, e.g.), the 3D images can generally undergo tiny translations and rotation with time. Has each image that constitutes the figures been spatially repositioned thanks to adequate references?

Residence time views are interesting, but do not show really how the snow evolves over time (i.e., what parts are growing, what parts are shrinking, and in which directions they are moving). This is, however, of primary importance, as it allows understanding the nature of the driving forces (Kelvin effect) and mechanisms in process. Please consider replacing these graphs with the superposition of vertical cross-sections at time 0 and 96 hours (or another time). See e.g. Calonne et al 2013.

From the present graphs, a vertical displacement can be noticed. Is it due (1) to minor settling effects in the snow sample, (2) to the effect of the vertical air flux, or (3) to a combination of these phenomena?

Adding the direction of the air flux would also be useful.

Response: Yes, we repositioned the images to adequate reference. However, there was an error in the procedure for the residence time.

Revision: Fig. 4 changed in the revised manuscript:

On page 1040, Fig. 4:

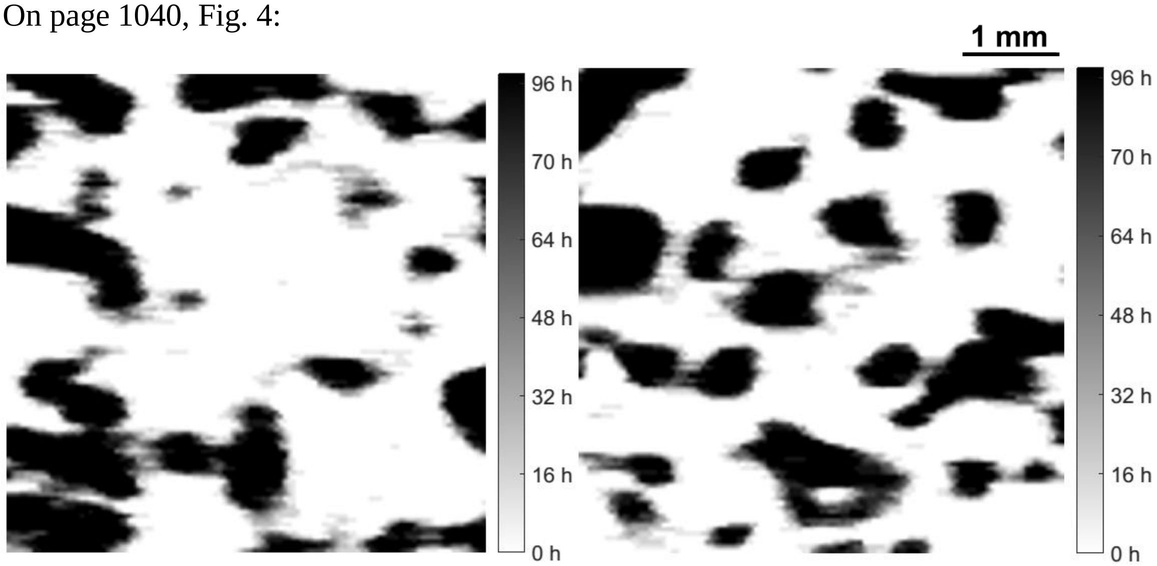
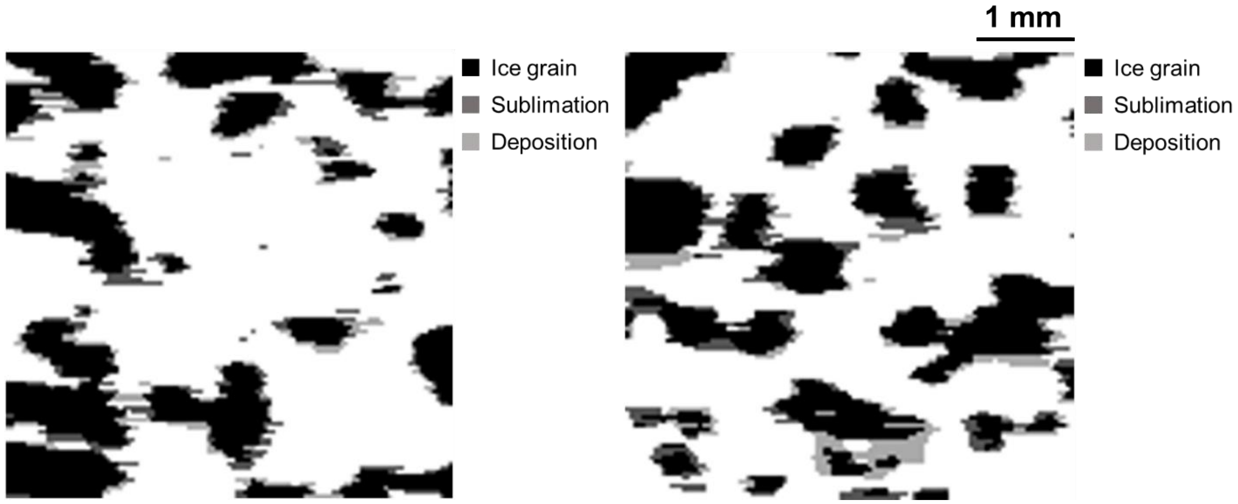


Fig. 4 a) Fig. 4 b)

Further, new figure added between Fig. 4 and Fig. 5 showing the superposition of a vertical cross-section at 0 and 96 hours.



> Caption 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 %.”

Texted changed in the revised manuscript:

> On page 1026, line 3-6: “The initial ice grain didn’t change with time, only coarsening processes on the ice grain surface were visible observed, shown in Fig. 4. 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-section at 0 and 96 hours with an uncertainty of 6 %. The mass sublimated preferred at location 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. The relocation process was not affected by the airflow velocity.”

Comment #35: 1042/Fig 6 + 1043/Fig 7 + 1044/Fig 8:

How were the errors on density and SSA actually estimated? The authors refer to Zermatten et al 2014, but it seems the method used in the work of Zermatten (two-point correlation function) was significantly different from that used in the present paper (triangulation). Note also that the error given by Zermatten et al was estimated based on the comparison with stereological estimations from horizontal cross-sections. Another point to consider is that triangulation methods are potentially prone to systematic overestimations for SSA. At least, this is the case for simple Marching Cubes estimations (see e.g. Flin et al, 2011; Hagenmuller, 2014).

Response: In our case, it is not relevant which method was used to calculate the morphological parameters as we wanted to show the trend and the evolution of these parameters to see the influence of advective airflow. The errors were estimated by comparing the results of the µ-CT images with experimental measurements. It’s correct that Zermatten et al. (2014) used the two-point correlation function to estimate the density and SSA and is different compared to our triangulation methods. However, we could reproduce the results of Zermatten et al. (2014), without a significant variation. Nevertheless, we will delete the errors value to confuse the reader not too much.

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 further elaborated on natural snowpacks. The 3D digital geometry obtained by tomographic scans was used in direct pore-level numerical simulations to determine the effective transport properties. 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 evaporation-deposition caused by the Kelvin effect and is the limiting factor independently of the transport regime in the pores. ~~Diffusion between the snow structures dominates and is the main transport process in long-term isothermal snowpacks.~~

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

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conditions of constant temperature are referred to as isothermal snow metamorphism (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 evaporation-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 snow pack (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 snow pack. It is suggested that advective flow of air has 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 °C. Figure 1 shows a schematic of the experimental setup. 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. Natural identical snow was used for the snow sample preparation (water temperature: 30 °C; air temperature: −20 °C) (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 °C, 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. Four different runs were chosen based on the Peclet number ($Pe = u_{\mathrm{D}} d_{\mathrm{p}}/D$ 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 simulation 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) $Pe > 1$ 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, $Pe \approx 1.2$ 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 ($\leq$ 0.01 m s^{-1}) for a high wind speed ($\approx$ 10 m s^{-1}) above the snow surface (pore size $\approx$ 1 mm). This leads to a maximum $Pe \approx 0.8$. Table 1 summarizes the experimental conditions.

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 × 7.2 × 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 (σ = 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 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

$$\nabla p = -\frac{\mu}{K} u_{\mathrm{D}} - F \rho u_{\mathrm{D}}^{2} - \frac{\gamma \rho^{2}}{\mu} u_{\mathrm{D}}^{3} \tag{1}$$

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 higher temperature 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 grain 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. The 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'~~, which was within the range of error of 7.7% as determined by Zermatten et al. (2014)~~.

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 ($\varepsilon_{\mathrm{grav}} = 1\text{-}\rho_s/\rho_{\mathrm{ice}}$), 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)

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

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. The lower value of n for experiment ‘sa3’ and ‘s4’ was due to the longer sintering time of 27 days at -5 °C 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 value of the effective permeability was higher than the one determined in a previous study (Zermatten et al., 2011, 2014), although, our measured SSA was higher by a factor of at least 2.4.~~ 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.

~~No enhanced metamorphism due to the advective process could be observed in any of the experiments. Evaporation-deposition caused by the Kelvin-effect was the limiting factor independently of the transport regime in the pores. Mass transfer in the pores by diffusion was still the dominant component. The time scale of diffusion inside the pores ($t_{\text{diff}} = d_p^2/D$) was in the order of 10^{-3} s. The coarsening process can be considered to be independent of mass transfer by advection, which was in the order of 10^{-2} s ($t_{\text{adv}} = d_p/u_D$). 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 °C to -30 ° 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 °C 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 and diffusion is consequently still the dominant driver for snow metamorphism.~~

4. Summary and conclusions

Four isothermal metamorphism experiments of snow under saturated advective airflow were performed, each with duration of four days. The two 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 were not possible due to the destruction of the snow structure and is not realistic in natural snowpacks. Every 8 h the snow microstructure was observed by X-ray micro-tomography. 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 surface 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. Evaporation-deposition caused by the Kelvin-effect was the limiting factor independently of the transport regime in the pores. ~~As predicted by the values of *Pe*, No enhancement of mass transfer inside the pores was observed and diffusion through the pores was the main driving force compared to the advective transport. In isothermal snow packs, diffusion through the pores is the dominating part and advective transport processes on the structural dynamics can be neglected.~~

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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) ~~(± 7.7 %)~~, initial porosity (ε_0) ~~(± 7.7 %)~~, specific surface area (SSA_0) ~~(± 18.8 %)~~, initial pore diameter (d_p), temperature in the cold laboratory (T_{lab}), and the sintering time of the snow.

Name	$\dot{V}$	Pe	Re	$u_{D,0}$	ρ_0	ε_0	SSA_0	d_p	T_{lab}	Sintering time
	litre min^{-1}	–	–	m s^{-1}	kg m^{-3}	–	m^2 kg^{-1}	mm	°C	
sa1	–	–	–	–	226.43	0.75	46.6	0.22	-8.0	13 days at -15°C
sa2	0.36	0.05	0.07	0.004	186.1	0.78	43.7	0.27	-8.0	13 days at -15°C
sa3	3.0	0.47	0.6	0.04	325.43	0.65	28.7	0.24	-15.0	27 days at -5°C
sa4	5.0	0.85	1.1	0.06	264.93	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	τ	n	NRMSE
	m^2 kg^{-1}	–	–	–
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	τ	n	NRMSE
	m^2 kg^{-1}	–	–	–
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 airflow 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 (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 ~~with an uncertainty of 7.7 % (Zermatten et al., 2014)~~. 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 ~~with an uncertainty of 7.7 % (Zermatten et al., 2014)~~ and the measured gravimetric density ($\varepsilon_{\mathrm{grav}}$) 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 ~~with an uncertainty of 18.8 % (Zermatten et al., 2014)~~. The spatial variability within the reconstructed volume was measured in four discs of $7.2 \times 7.2 \times 1.8\ \mathrm{mm}^3$.

Fig. 10. Temporal evolution of the specific surface area, SSA, of the ice matrix obtained by triangulated structure surface method ~~with an uncertainty of 18.8 % (Zermatten et al., 2014)~~. 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).

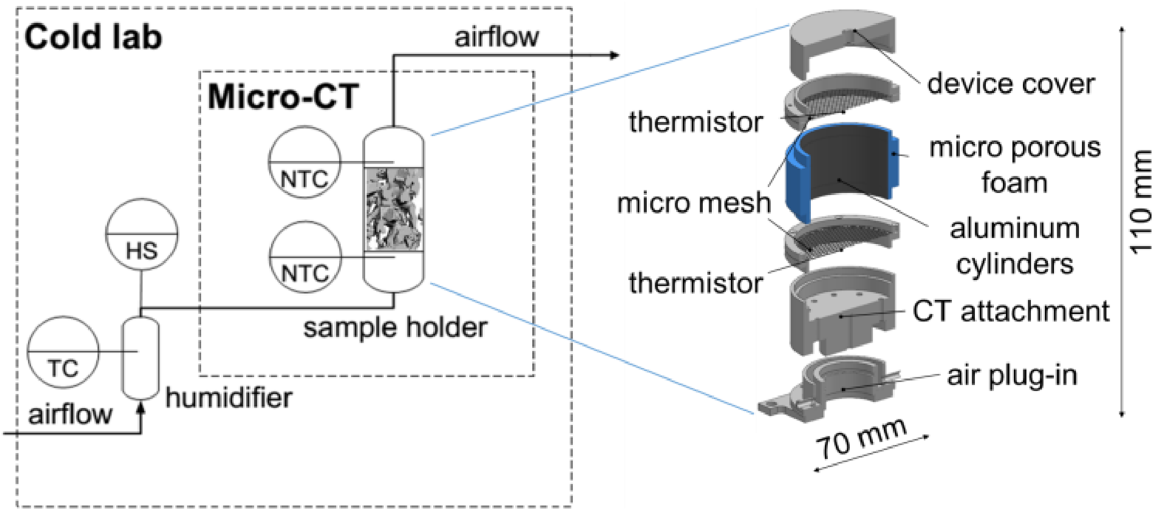

Cold lab
airflow
Micro-CT
NTC
NTC
HS
TC
airflow
humidifier
sample holder
device cover
thermistor
micro porous foam
micro mesh
aluminum cylinders
thermistor
CT attachment
air plug-in
110 mm
70 mm

Fig. 1

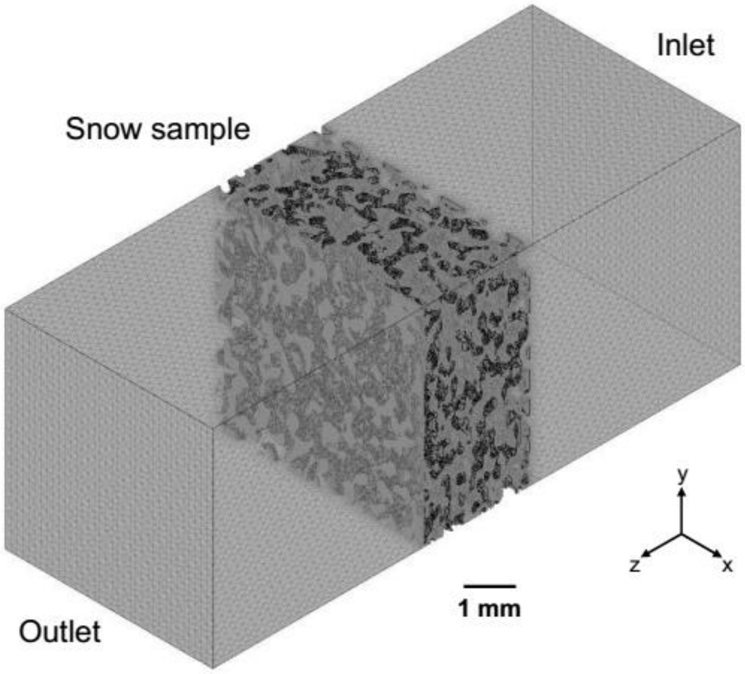
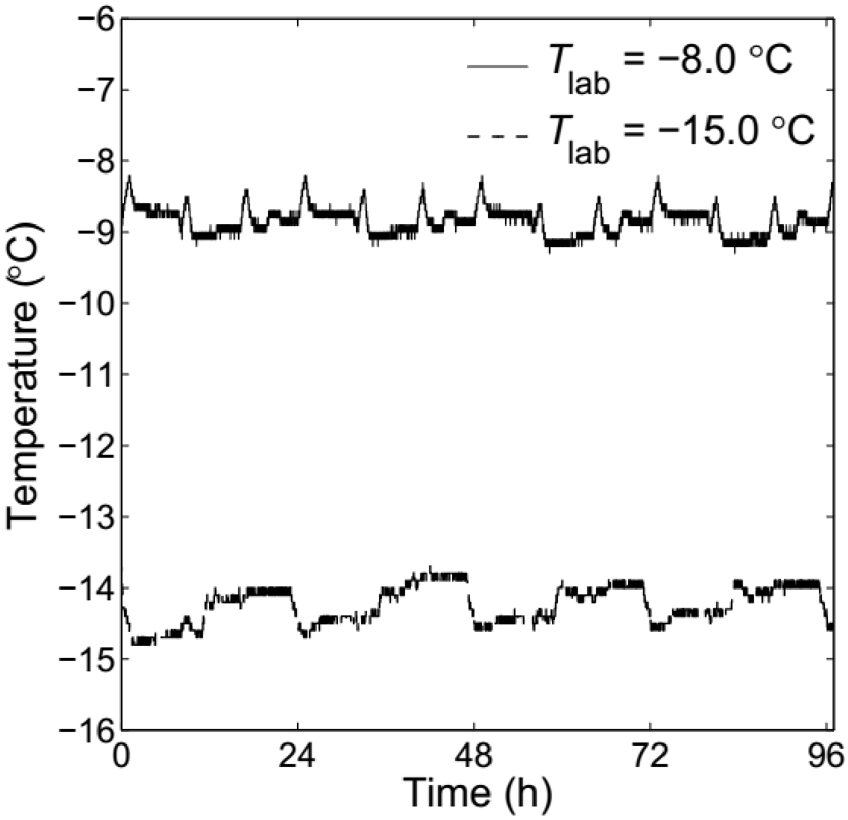


Fig. 2



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

Fig. 3

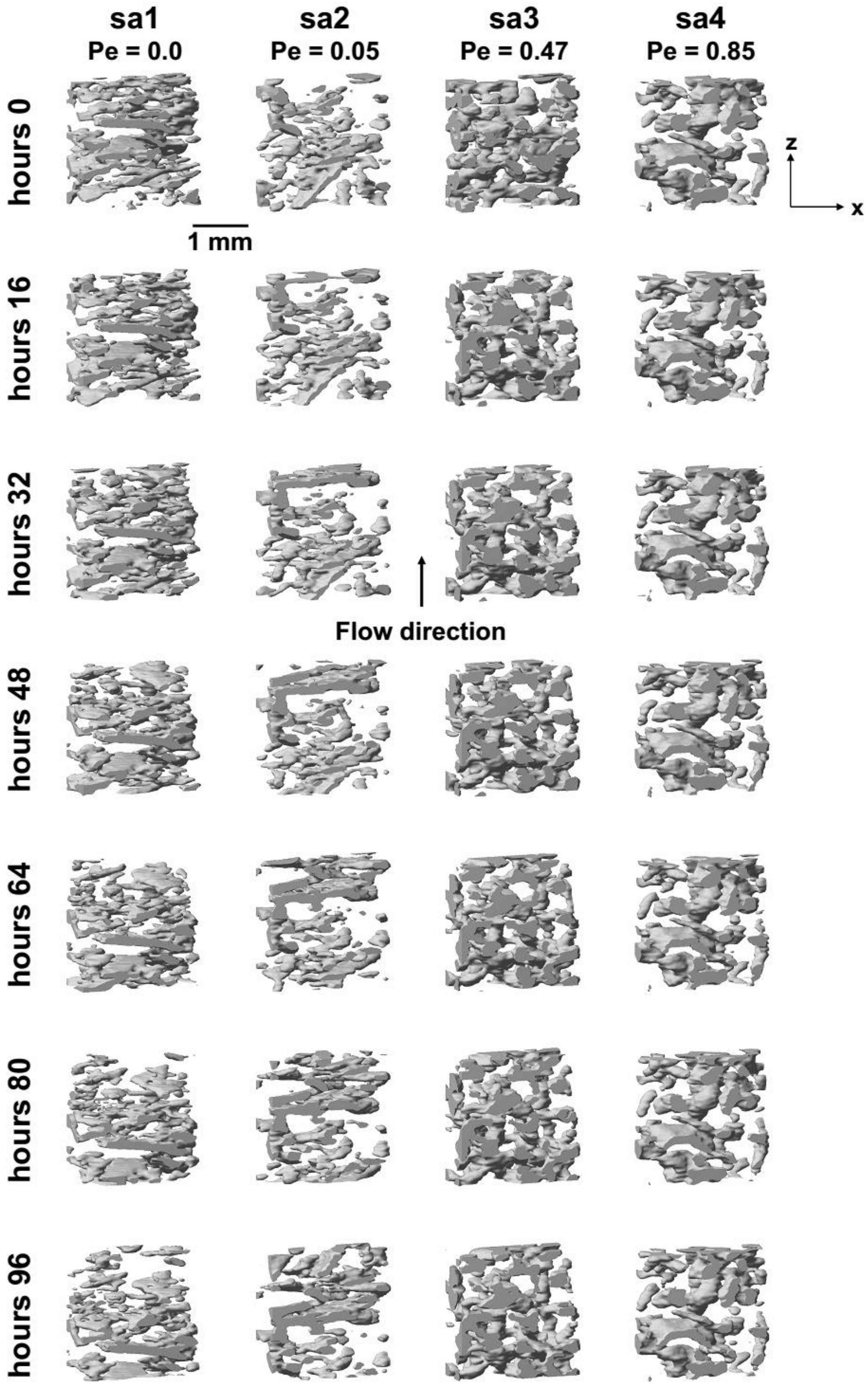

sa1
Pe = 0.0
sa2
Pe = 0.05
sa3
Pe = 0.47
sa4
Pe = 0.85
hours 0
hours 16
hours 32
hours 48
hours 64
hours 80
hours 96
1 mm
z
x
Flow direction

Fig. 4

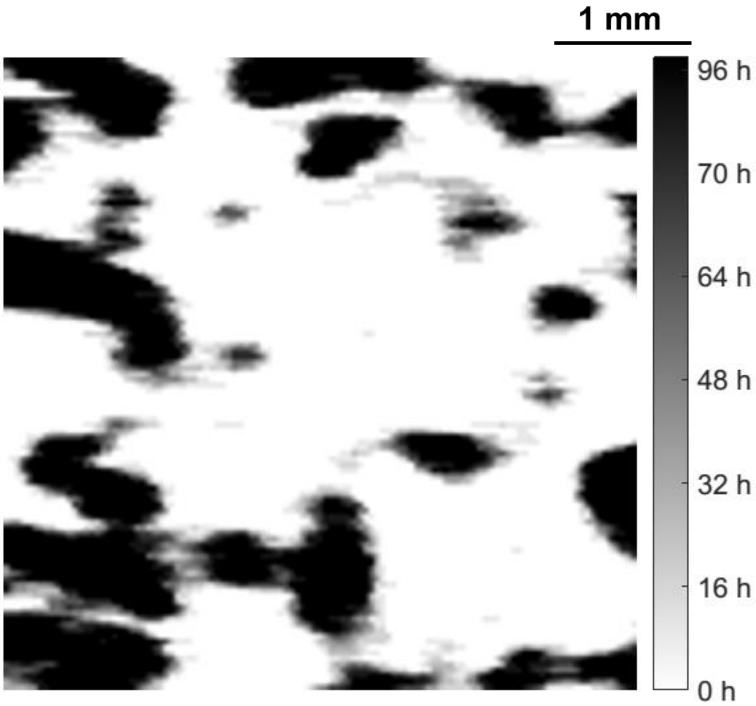
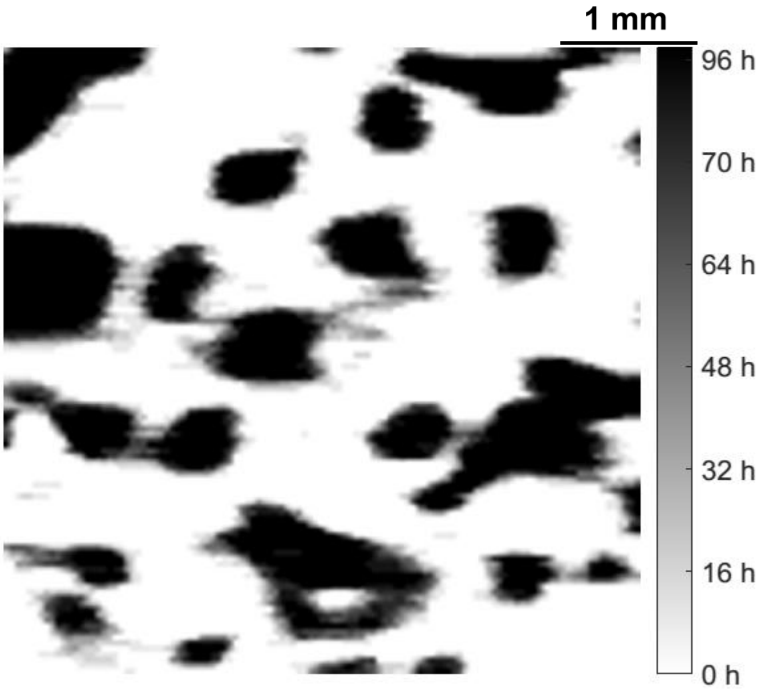


Fig. 5 a)

496



497 Fig. 5 b)

498

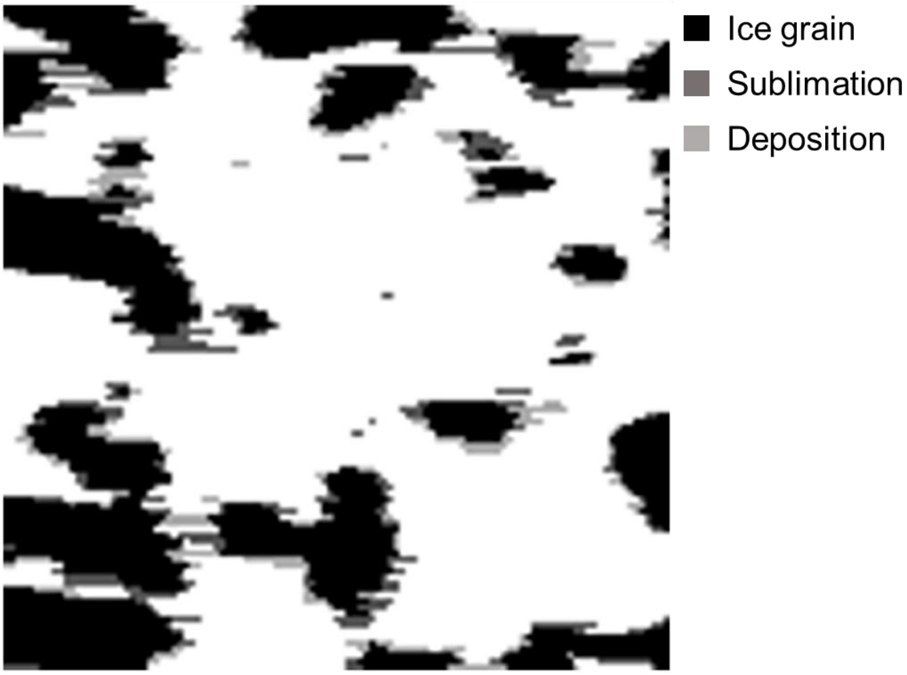


Fig 6 a)

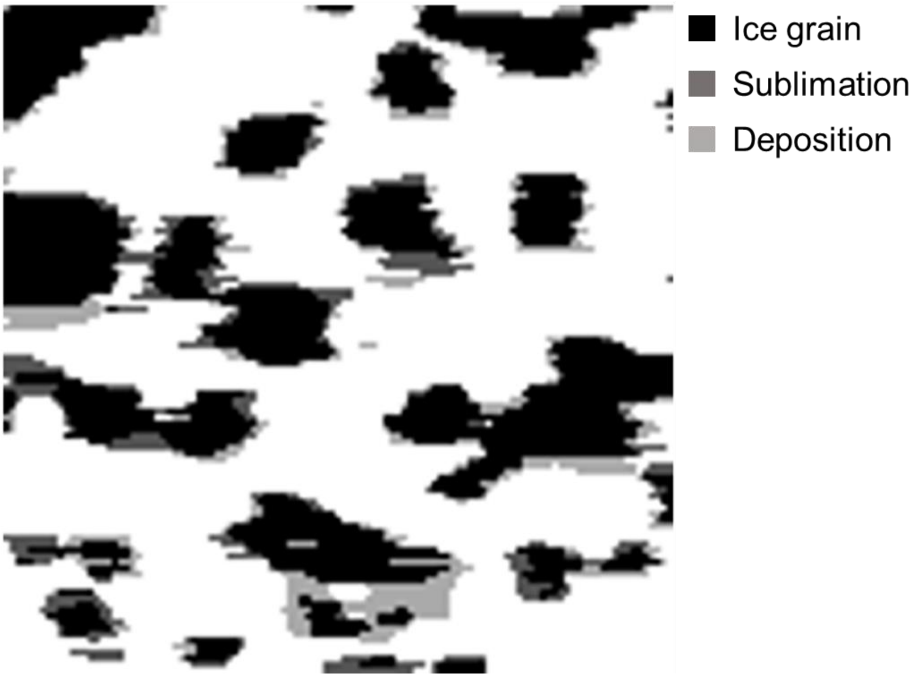


Fig. 6 b)

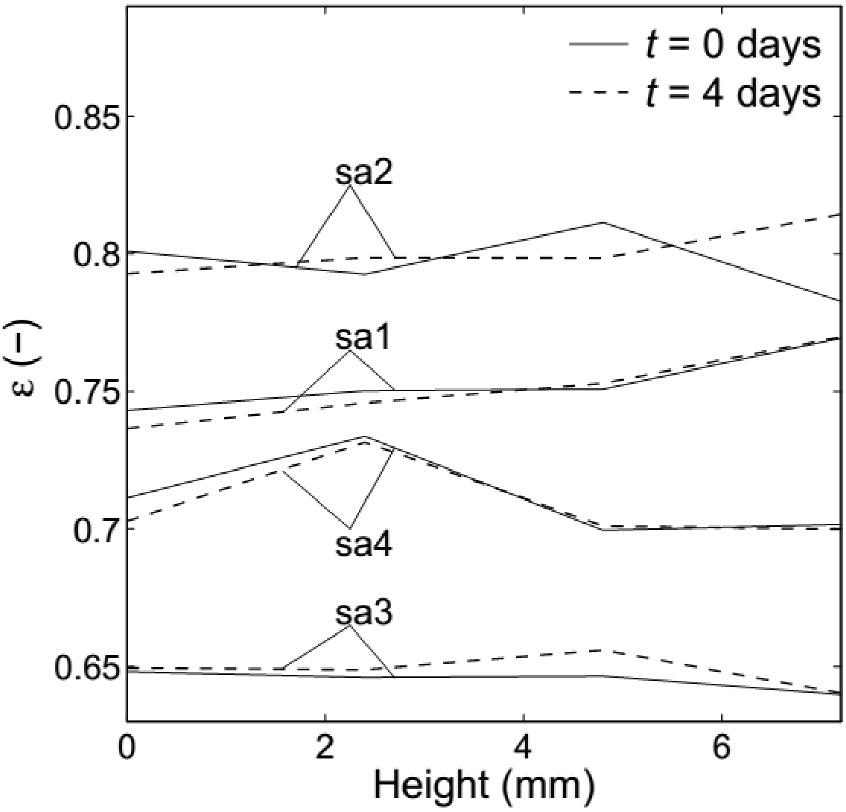

t = 0 days
t = 4 days
sa2
sa1
sa4
sa3
ε (–)
0.85
0.8
0.75
0.7
0.65
0
2
4
6
Height (mm)

Fig. 7

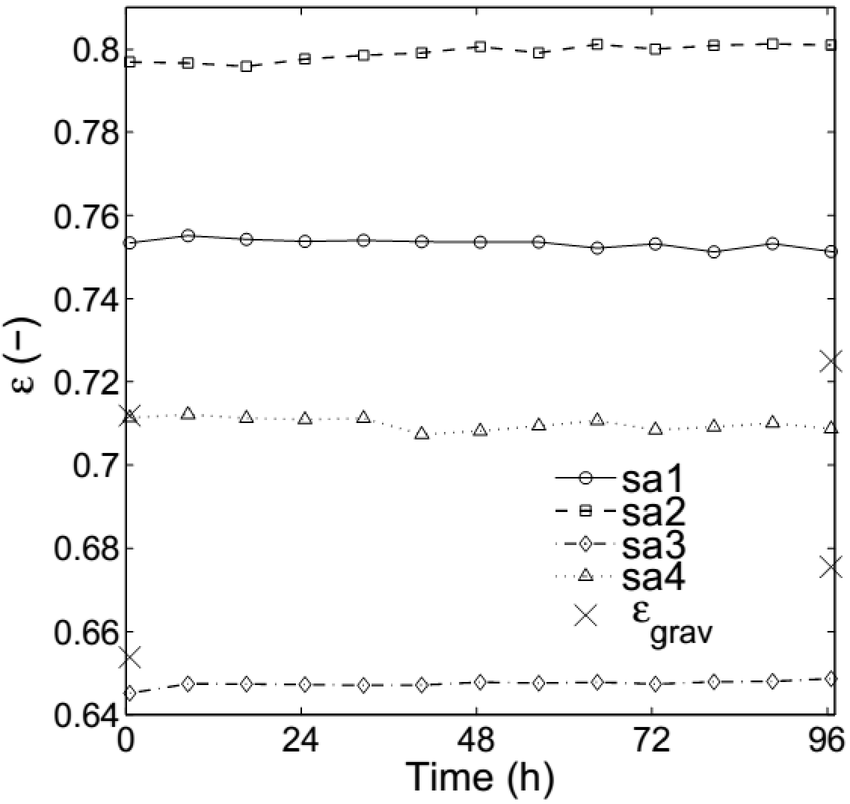

0.8
0.78
0.76
0.74
0.72
0.7
0.68
0.66
0.64
ε (–)
0
24
48
72
96
Time (h)
sa1
sa2
sa3
sa4
ε_{grav}

Fig. 8

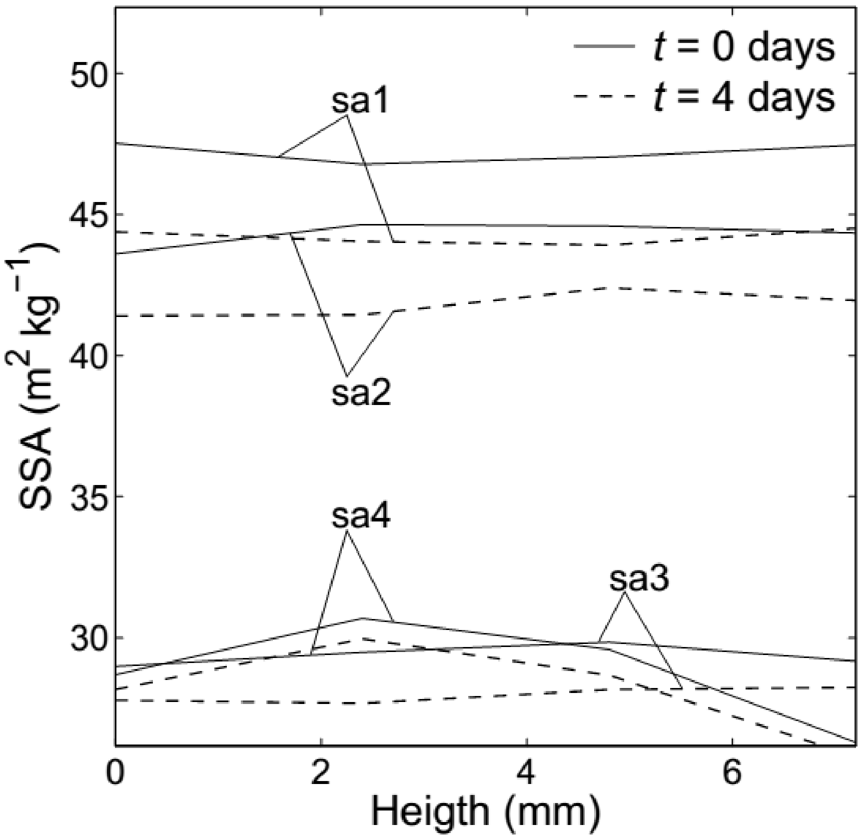

t = 0 days
t = 4 days
sa1
sa2
sa3
sa4
50
45
40
35
30
SSA (m^2 kg^{-1})
0
2
4
6
Heigth (mm)

Fig. 9

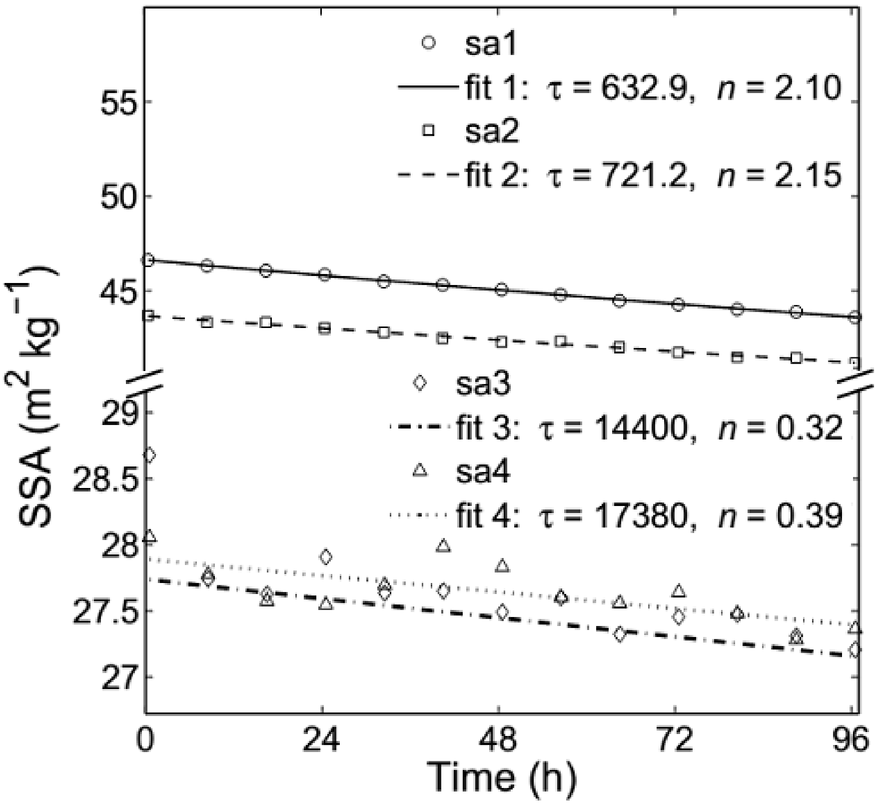

sa1
fit 1: τ = 632.9, n = 2.10
sa2
fit 2: τ = 721.2, n = 2.15
sa3
fit 3: τ = 14400, n = 0.32
sa4
fit 4: τ = 17380, n = 0.39
SSA (m^2 kg^−1)
55
50
45
29
28.5
28
27.5
27
0
24
48
72
96
Time (h)

Fig. 10

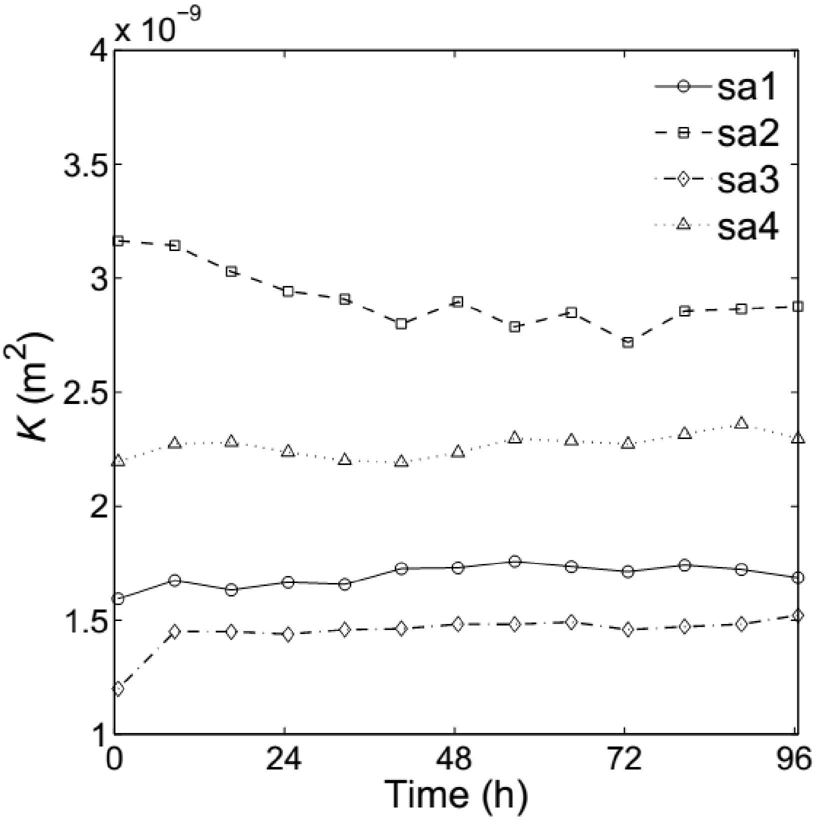


Fig. 11