RESPONSE TO REFEREES' F. FLIN COMMENTS

TO MANUSCRIPT TC-2015-158

Title: Metamorphism during temperature gradient with undersaturated advective airflow in a snow sample

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

We thank the referee F. Flin for the constructive comments. All page and line numbers correspond to those of the Discussion Paper.

We reply to the general questions of the reviewer specifically in the section "Specific comments", as all general questions of the review are given with more details in this section.

REVIEWER: F. Flin

The authors have improved the original version of the manuscript, leading to a better presentation of the experiments realized and of the subsequent scientific argumentation. However, the paper really needs an additional revision before it can be published. In particular:

Comment #1: Some of my previous requests have not been addressed adequately. It is especially the case of requests #3.x concerning the post-processing and reliability of the data:

3. Data post-processing and reliability: The experiment is really interesting, but some "unusual" results obtained need to be checked, clarified or discussed. It is in particular the case of:

> *- 3.1. Some erratic translations or changes that can be observed in the image series (see the enlarged version of Fig. 2 in supplementary materials). Has each image that constitutes Fig. 2 been spatially repositioned thanks to adequate references? The beginning of the series ota3 is especially problematic. For most series, some slight but persistent downward translations are observed and should also be commented. See e.g. comment 4862/Fig 2.*
>
> *- 3.2. Fig. 3, which is a bit difficult to "read" (no classical rounding or TG effect) and exhibits some post-processing artifacts. See comments 4863/Fig. 3 for suggestions.*

- 3.3. The ota1 series, which does not show any increase of the vertical component of its conductivity when submitted to a TG only. At least a comment should be written on this topic. See comment 4852/27-4853/2.

- 3.4. Ideally, a characterization of the structural anisotropy of the snow samples would be appropriate. See comment e.g. 4850/7-8.

-> At least, point 3.1 should be accurately addressed before publication (see specific comments 91-92, 118-119 and 416)

Response: There was a mistake in the image position correction which we corrected. However, this had not an effect on the numerical results (porosity, SSA, conductivity …) because the parameters were extracted from the total scan sample and not from the cut-out of Figure 2. Also, it did not affect Figure 3. More details are given in “Specific comments”.

Comment #2: I am now also concerned with some of the physical interpretations of the experiments, which do not seem sufficiently convincing to me. In particular, some conclusions of the paper (e.g. about the "preference" for deposition to sublimation [lines 253-255], or the limiting mechanisms occurring at microscale [lines 176-180]) are based on the fact that little effect can be observed on the snow microstructure in the described experiment as compared to that of Ebner et al 2015b. However, as mentioned by the authors themselves, this fact can just been explained by the settings of the present experiment, where TG and air flow counteract.

Actually, the authors just mention 2 TG and air flow configurations in their paper but 4 important configurations are possible:

1. air mainly **supersaturated** with respect to the entire sample (typically, Td = -12.5 when the sample is between T_base = -12.5 and T_top = -14) and TG and air flow acting in the **same direction** (Ebner et al 2015).
2. air mainly **undersaturated** with respect to the entire sample (typically, Td = -14 when the sample is between -14 and -12.5) and TG and air flow acting in the **opposite direction** (this paper).
3. air mainly **supersaturated** with respect to the entire sample (typically, Td = -12.5 when the sample is between T_base = -12.5 and T_top = -14) and TG and air flow acting in the **opposite direction**.
4. air mainly **undersaturated** with respect to the entire sample (typically, Td = -14 when the sample is between -14 and -12.5) and TG and air flow acting in the **same direction**.

I am puzzled by the fact that the authors, by comparing cases 1 and 2, try to reach conclusions about local sublimation and deposition processes in snow. However, these conclusions might only be achieved from a precise comparison between 1 and 4 (or also 2 and 3). It should be also noticed, that for case 2 and 3, TG and air flow effects clearly counteract and an increased observation time (or increased resolution) would probably be necessary to infer reliable conclusions on the physical mechanisms involved. See also comment 162-163.

-> Complimentary experiments, or at least, complimentary explanations seem mandatory to assert some of the authors' conclusions.

Response: Your configuration 3 and 4 are correct for snow layers close to the surface (< 1 cm) where we can have a mixing zone changing from under- to supersaturation of the airflow and vice versa. However, we performed experiments in snow depth (> 1 cm) where the snow and air have “quasi” the same temperature (We called it “quasi” because the snow structure continuously changes and therefore the equilibrium conditions change). As the temperature of the snow at the inlet and outlet is controlled, and snow has a high heat capacity, a high specific surface area, and therefore a high convective heat transfers to the air, we have again the conditions of case 1 or 2 in the scanned area only with a different temperature gradient. In general, this is a good point to analyze the transition between under- to supersaturation of an airflow (and vice versa) on the structural change of the ice matrix in further experiments.

Revision: Text added in the revised manuscript.

> Line 35: “In general, in natural snowpack close to the surface (< 1cm) two additional conditions can occur: (1) warm air enters a snowpack having a positive temperature gradient leading to a supersaturation of the air at the entrance, and (2) cold air enters a snowpack having a negative temperature gradient leading to an undersaturation of the air at the entrance. However, because snow has a high heat capacity compared to the air, a high specific surface area, and therefore a high convective heat transfers to the air, a “quasi” thermal equilibrium (the term “quasi” is used because normally the snow structure continuously changes and therefore the equilibrium conditions as well) is usually assumed inside the snowpack (> 1 cm). In this paper, only conditions deeper than > 1 cm inside a snowpack are considered.”

Specific comments:

Comment #1: 15-16: *The temperature gradient in the sample was around 50 K m-1 at maximum airflow velocity.*

> -> Is really TG dependent on the airflow velocity? If not, I suggest modifying the sentence to prevent any misinterpretation.
>
> -> Giving the quantitative value of the maximum airflow in L/min would be more informative.

Revision: Text changed in the revised manuscript.

> Line 14-16: “Cold saturated air at the inlet was blown into the snow samples and warmed up while flowing across the samples with a temperature gradient of around 50 K m^{-1}.

<u>Comment #2:</u> 16-20: *The sublimation of ice for saturated air flowing across the snow sample was experimentally determined via changes of the porous ice structure in the middle-height of the snow sample. Sublimation has a marked effect on the structural change of the ice matrix but diffusion of water vapor in the direction of the temperature gradient counteracted the mass transport of advection. Therefore…*

These sentences are difficult to catch for a reader who tries to understand the principle of your experiment. Here is a suggestion: "Changes of the porous ice structure were observed in the middle-height of the snow sample. Sublimation occurred due to the slight undersaturation of the incoming air into the warmer ice matrix. Diffusion of water vapor opposite to the direction of the temperature gradient counteracted the mass transport of advection. Therefore…"

Revision: Text changed in the revised manuscript.

> Line 16-20: “Changes of the porous ice structure were observed at mid-height of the snow sample. Sublimation occurred due to the slight undersaturation of the incoming air into the warmer ice matrix. Diffusion of water vapor opposite to the direction of the temperature gradient counteracted the mass transport of advection. Therefore, …”

<u>Comment#3:</u> 19-20: *diffusion of water vapor in the direction of the temperature gradient*

Strictly speaking, this sentence is wrong: from the Fick's Law, the water vapor diffusion occurs in the opposite direction of the temperature gradient (j = -k **grad** P = -K **grad** T). Actually, in the whole paper, there seem to be a constant mistake with the direction of the temperature gradient (respectively, the vapor pressure gradient), which actually is in the direction of the growing temperature (respectively, growing vapor pressure). This has, of course, no impact on the general meaning of the paper but it needs to be corrected for a sake of clarity. Please check the whole text and figures, especially Fig. 1 (see also comment 412/Fig1).

Response: Your comment is correct, we constant mistake with the direction of the temperature gradient (respectively, the vapor pressure gradient). We changed it in the revised manuscript.

Revision: Text changed in the revised manuscript.

> Line 19-20: “Diffusion of water vapor opposite to the direction of the temperature gradient counteracted the mass transport of advection.”

Comment #4: 34-35: *Various airflow conditions in a snow sample occur, namely: isothermal airflow, temperature gradient along the flow direction, and temperature gradient opposite to the airflow (Fig. 1).*

Please check these lines according to comment 19-20.

Revision: Text changed in the revised manuscript.

> Line 34-35: "Various airflow conditions in a snow sample occur, namely: isothermal airflow, air cooling by a negative temperature gradient along the airflow leading to local supersaturation of the air, and air warming by a positive temperature gradient along the airflow leading to local undersaturation of the air (Fig. 1)"

Comment #5: 56-60*: Albert (2002) suggest that condensation of water vapor will have a noticeable effect on the microstructure of snow using airflow velocities, vapor transport and sublimation rates calculated using a two-dimensional finite-element model, which is also confirmed by a 3D phase-field model of Kaempfer and Plapp (2009).*

Actually, Kaempfer and Plapp (2009) did not consider any airflow in their 3D phase field model, while Albert (2002) did. Please change the way the citation is introduced to make it clearer to the reader.

Revision: Text changed in the revised manuscript.

> Line 56-60: "Kaempfer and Plapp (2009) suggest that condensation of water vapor will have a noticeable effect on the microstructure of snow using a 3D phase-field model, which is also confirmed by a two dimensional finite-element model using airflow velocities, vapor transport and sublimation rates of Albert (2002)."

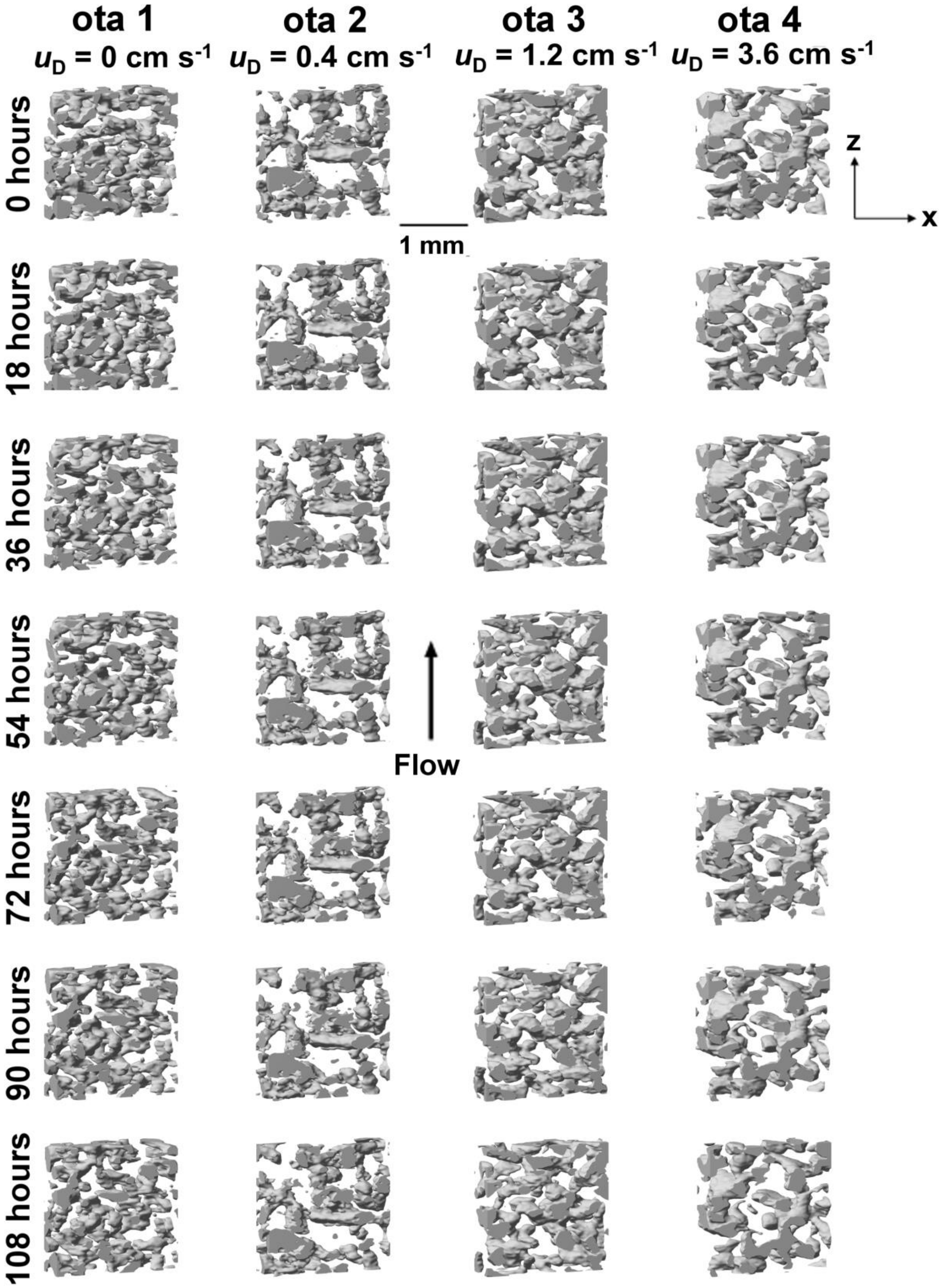
Comment #6: 91-92: *A linear encoder with a resolution of less than 1 voxel was used to verify that the scans were taken at the same position.*

From Fig. 2, it is obvious to any reader that this method failed to provide the same region of interest with time. As pointed out in my preceding review (see general comment 3.1 and comments #17-4850/3-4 and #22-4862/Fig 2.) large and erratic vertical translations (reaching sometimes about 50 voxels) are observable. Some images are even not recognizable from one step to another (e.g., ota3, 30hours), and this has potential impacts on the evolution of the provided numerical results (porosity, SSA, conductivity…). The authors should really ensure the data they provide are reliable. They can just suppress all erroneous (or "suspicious") data from their dataset, or choose to numerically correct the image position as it is usually done in tomographic time-lapse imaging. However, providing obviously erroneous (or poor quality) data is not acceptable in a journal like TC.

Response: There was a mistake in the image position correction which we corrected. However, this had not an effect on the numerical results (porosity, SSA, conductivity …)

because the parameters were extracted from the total scan sample and not from the cut-out of Figure 2.

Revision: Figure 2 changed in the revised manuscript.



Comment #7: 118-119: *The change of structural change "ota 3" at 30 h is due to an error in the scan.*

See comment 91-92.

Response: An error was found in the image position correction and now everything is correct. Text deleted in the revised manuscript.

Comment #8: 162-163: *As thermally induced diffusion was opposite to the airflow gradient, a backflow of water vapor occurred and the two opposite fluxes cancelled each other out.*

I basically agree with this sentence, but is it fully compatible with the fact that the snow evolution is completely independent of the flow velocity? To my understanding, the TG is always fixed: if the opposite fluxes cancel out each other for a low velocity e.g., the airflow effect should be dominant as it increases. At least some comments and explanations should be added to the text.

Revision: Text added in the revised manuscript.

> Line 160: "The entering air warmed up, allowing vapour sublimating from the snow sample to be incorporated into the airflow. As time passed, the snow grains in the sample became more rounded as convexities sublimated. As a result of the reduced curvature, the rate of sublimation decreased and less vapour was deposited in concavities and therefore the surface asperities persisted longer. Finally, the "Kelvin-effect" had a longer impact on the structural change of the ice grains and the reposition of water molecules."

Text changed in the revised manuscript.

> Line 162-163: "As thermally induced diffusion was opposite to the airflow gradient, a backflow of water vapor occurred and the two opposite fluxes counteracted each other."

Comment #9: 167: *diffused along the temperature gradient*

See comment 19-20 -> "diffused along the opposite direction to the temperature gradient"

Revision: Text changed in the revised manuscript.

> Line 167: "Therefore, water molecules were diffused along the opposite direction of the temperature gradient and …"

Comment #10: 176-178: *Our results support the hypothesis of Neumann et al. (2009) that sublimation is limited by vapor diffusion into the pore space rather than sublimation at crystals faces.*

Why? Is it only justified by the lines 178-180 (in that case, suppress the word "also" in these lines), or by other reasons?

Revision: Text changed in the revised manuscript.

> Line 178: "This is supported by the temporal evolution of the …"

<u>Comment #11:</u> 178-180: *This is also supported by the temporal evolution of the porosity (Fig. 4 b)) and the SSA (Fig. 4 c)), as no velocity dependence was observed and the structural changes were too small to be detected by the micro-CT.*

See general comment #2. Complimentary experiments, or at least, complimentary explanations seem necessary to justify the authors' conclusions.

Revision: Text added in the revised manuscript.

> Line 35: "In general, in a natural snowpack close to the surface (< 1cm) two additional conditions can occur: (1) warm air enters a snowpack having a positive temperature gradient leading to a supersaturation of the air at the entrance, and (2) cold air enters a snowpack having a negative temperature gradient leading to an undersaturation of the air at the entrance. However, because snow has a high heat capacity compared to the air, a high specific surface area, and therefore a high convective heat transfer to the air, a "quasi" thermal equilibrium (the term "quasi" is used because normally the snow structure continuously changes and therefore the equilibrium conditions as well) is usually assumed inside the snowpack (> 1 cm). In this paper, only conditions deeper than > 1 cm inside a snowpack are considered."

<u>Comment #12:</u> 214-216: *The model by Neumann et al. (2009) does not consider the influence of a temperature gradient and the additional vapor pressure gradient was not analyzed.*

It is important to specify that point. But is it realistic to draw definitive conclusions from the comparison between a TG experiment and a model that does not really account for the important specificities (TG) of the experimental conditions?

Response: On one point it is realistic to draw conclusions from the comparison between the TG experiment and the model because in both cases we have sublimation of ice. It's correct that the model does not account for the temperature gradient, however, we can still conclude that the temperature gradient has an additional impact. We reformulated the text in the revised manuscript.

> Line 214-216: "The model by Neumann et al. (2009) does not consider the influence of a temperature gradient and the additional vapor pressure gradient was not analyzed. But our results conclude that a positive temperature gradient along the airflow has a significant impact on the sublimation rate decreasing the rate by two orders of magnitude."

<u>Comment #13:</u> 232: *This indicates that advective cold airflow opposite to a temperature gradient…*

-> "This indicates that advective cold airflow along a temperature gradient…"

(or "This indicates that advective cold airflow opposite to the TG-induced vapor diffusion…")

Revision: Text changed in the revised manuscript

> Line 232: "This indicates that air warming by a positive temperature gradient along the airflow and …"

<u>Comment #14:</u> 232: *...and an open system…*

The meaning of this wording and its implications is difficult to catch without any additional explanations. Please consider adding a more detailed comment such as your private response to comment #20-4852/27-4853/2

Revision: Text changed in the revised manuscript.

> Line 231-234: "Thermal conductivity changed insignificantly in these experiments, especially an increase of the vertical component of the thermal conductivity was not observed for 'ota 1'. This indicates that air warming by a positive temperature gradient along the airflow and an open system reduces or suppresses the increase in thermal conductivity usually observed by temperature gradient metamorphism (Loewe et al., 2013; Calonne et al., 2014). Compared to closed temperature gradient experiment, the applied temperature gradient and the open system induced an air movement and therefore reduced the impact on the thermal conductivity, at least on the short term."

<u>Comment #15:</u> 233-234: *the increase in thermal conductivity usually observed by temperature gradient metamorphism (Riche and Schneebeli, 2013).*

To my knowledge, Riche and Schneebeli (2013) do not report any increase in thermal conductivity during TG metamorphism. Citing e.g. Löwe et al., 2013 (Fig 4) or Calonne et al., 2014 (Fig. 6) might be more appropriate.

Revision: Citation changed to (Loewe et al., 2013; Calonne et al., 2014).

Reference added:

> Calonne, N., Flin, F., Geindreau, C., Lesaffre, B. and Rolland du Roscoat, S.: Study of a temperature gradient metamorphism of snow from 3-D images: time evolution of microstructures, physical properties and their associated anisotropy, The Cryosphere, 8, 2255-2274, 2014.

<u>Comment #16:</u> 253-255: *The kinetic phase-change from gas to solid is preferable as energy is released compared to solid to gas where energy is required, thus leading to more water molecule deposition than water molecule sublimation.*

This sentence still does not make sense for me (see previous comment #16-4850/16-18). Again, I suggest removing it (or justifying it with proper argumentation, references, etc).

Revision: Text removed in the revised manuscript.

<u>Comment #17:</u> 405: please specify the sizes of the volumes used for the computation of each property (7.2 x 7.2 x 7.2 mm3 in all cases?)

Revision: Text added in the revised manuscript

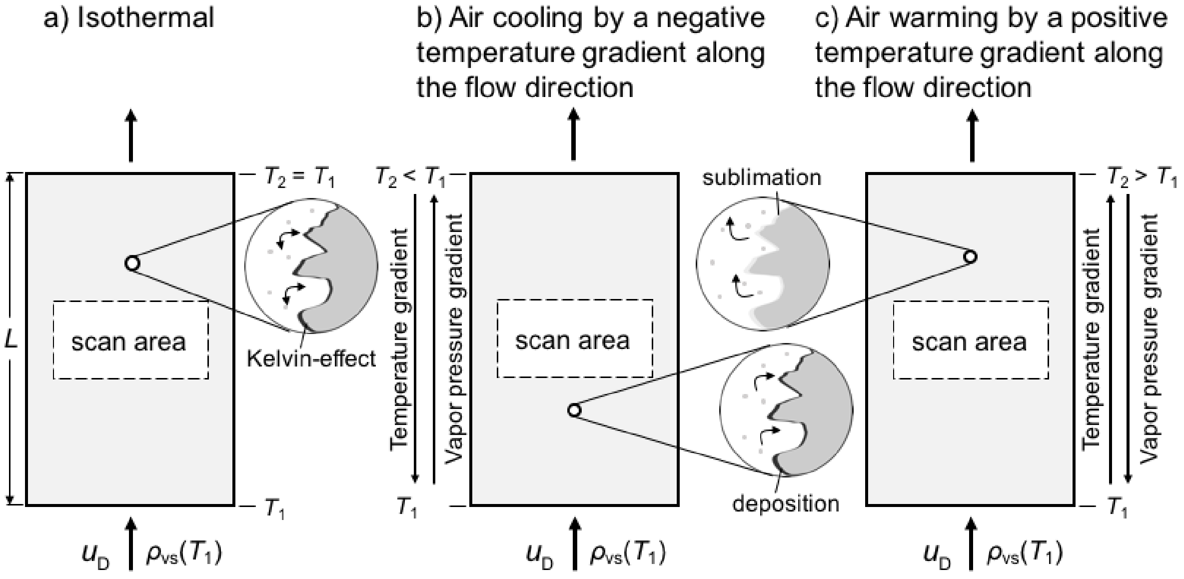
> Line 410: “The sizes of the volumes used for the computation of each property are 350 × 350 × 350 voxels (6.3 × 6.3 × 6.3 mm^3).”

<u>Comment #18:</u> 406: *obtained by opening-size distribution* -> "obtained by an opening-based morphological operation"

Revision: Text changed in the revised paper:

<u>Comment #19:</u> 412/Fig1: The direction of the arrows for temperature and vapor pressure gradients should be changed in the opposite direction. Arrows corresponding to the direction of the vapor diffusion (effect of TG) could be added (j = -k **grad** P = -K **grad** T) to help the reader.

Revision: Fig. 1 and caption of Fig. 1 changed in the revised manuscript.

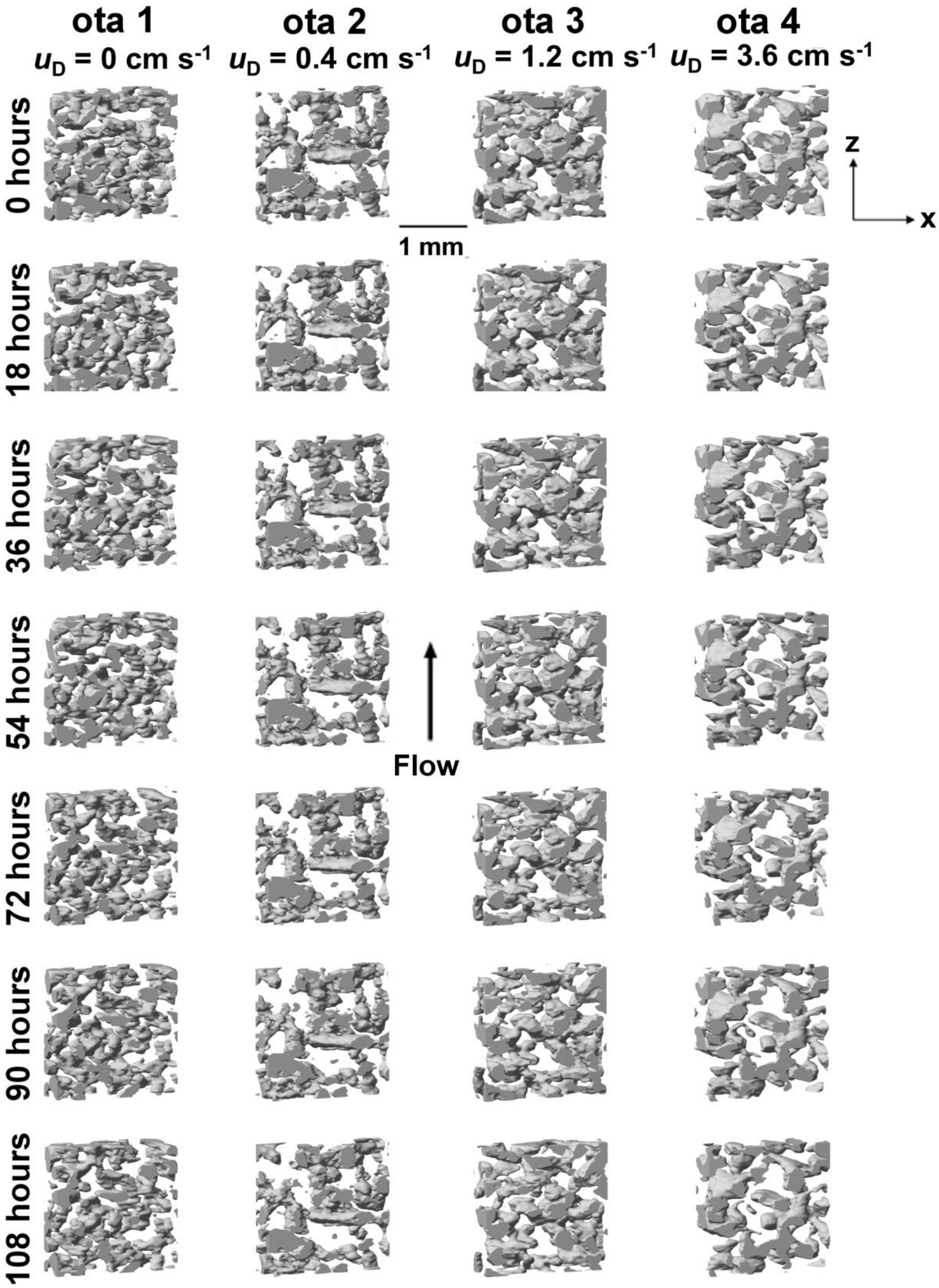


> Figure 1 caption: “Schematic of the ice-air interface transport processes: a) Under isothermal conditions Kelvin-effect leads to a saturation of the pore space in the snow

> bud did not affect the structural change (Ebner et al., 2015a); b) Air cooling by a negative temperature gradient along the flow direction leads to a change in the microstructure due to deposition (Ebner et al., 2015b); c) Air warming by a positive temperature gradient along the flow direction has a negligible total mass change of the ice but a strong reposition effect of water molecules on the ice grains, shown in this paper.

Comment #20: 416/Fig 2: see previous comment #22-4862/Fig2 and current comment 91-92.

Revision: Figure 2 changed in the revised manuscript.



Comment #21: 423/Fig 4 (a to d): to update according to specific comment 91-92.

Response: See comment #6.

Technical comments or suggestions:

Comment #1: 35-38: *Under isothermal condition, the continuous sublimation and deposition of ice due to higher vapor pressure over convex surfaces and lower vapor pressure over concave surfaces, respectively (Kelvin-effect).*

A verb seems to be missing in this sentence: *due* -> "is due" (?)

Revision: Text changed in the revised paper:

Comment #2: 63: *dynamic* -> dynamics

Revision: Text changed in the revised paper:

Comment #3: 83: *the strength* -> its strength

Revision: Text changed in the revised paper:

Comment #4: 88: *18 µm3* -> 18 µm (or 18 x 18 x 18 µm3)

Revision: Text changed in the revised paper:

Comment #5: 123: *ice grain* -> ice matrix (or ice grains)

Revision: Text changed in the revised paper:

Comment #6: 124: *ice grain* -> ice surface (or ice grains)

Revision: Text changed in the revised paper:

Comment #7: 150*: in the pore* -> in the pores

Revision: Text changed in the revised paper:

Comment #8: 178: *crystals faces* -> crystal faces

Revision: Text changed in the revised paper:

Comment #9: 192: *by (Neumann et al., 2009)* -> by Neumann et al. (2009)

Revision: Text changed in the revised paper:

Comment #10: 260: *under isothermal conditions Kelvin-effect…* -> under isothermal conditions, Kelvin effect…

Revision: Text changed in the revised paper:

Comment #11: 263: *whistler-like* -> whisker-like

Revision: Text changed in the revised paper:

Comment #12: 269: *and seems to* -> and seem to

Revision: Text changed in the revised paper:

Comment #13: 403: *ice grain* -> ice grains

Revision: Text changed in the revised paper:

Minor revisions were made throughout the revised manuscript.

We thank F. Flin for his scrutiny and recommendations.

The authors

RESPONSE TO REFEREES’ G. CHAMBON COMMENTS

TO MANUSCRIPT TC-2015-158

Title: Metamorphism during temperature gradient with undersaturated advective airflow in a snow sample

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

We thank the referee G. Chambon for the constructive comments. All page and line numbers correspond to those of the Discussion Paper.

<u>REVIEWER: G. Chambon</u>

Two additional technical comments related to changes made to the initial version:

<u>Comment #1:</u> Line 47-48: The sentence starting with "A deposition rate..." still remains unclear to me. Consider the following possible reformulation: "A flow rate dependence of the deposition rate of water vapor on the ice matrix was observed, the deposition rate reaching asymptotically..." However, the unit of the asymptotic value provided (kg.m-3.s-1) does not seem to correspond to a deposition rate? The meaning of "asymptotically" here should also be clarified.

Response: The unit is correct; it is a volumetric deposition rate. We clarified the meaning of “asymptotically” in the revised manuscript.

Revision: Text changed in the revised paper:

> Line 47-48: “A flow rate dependence of the deposition rate of water vapor deposition at the ice interface was observed, asymptotically approaching an average estimated maximum volumetric deposition rate on the whole sample of $1.05 \cdot 10^{-4}$ kg m^{-3} s^{-1} (Ebner et al., 2015b).”

<u>Comment #2:</u> Line 106: Do DPLS simulations used to compute the thermal conductivity really solve momentum equations? (for which phase?)

Revision: Text reformulated in the revised paper:

> Line 106: “DPLS determined the effective thermal conductivity by solving the governing steady-state heat conduction equations within the solid phase and the

> stagnant fluid phase (Kaempfer et al., 2005; Petrasch et al., 2008; Calonne et al., 2011, Loewe et al., 2013).”

Minor revisions were made throughout the revised manuscript.

We thank G. Chambon for his scrutiny and recommendations.

The authors

Metamorphism during temperature gradient with undersaturated advective airflow in a snow sample

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Abstract

Snow at or close to the surface commonly undergoes temperature gradient metamorphism under advective flow, which alters its microstructure and physical properties. Time-lapse X-ray micro-tomography is applied to investigate the structural dynamics of temperature gradient snow metamorphism exposed to an advective airflow in controlled laboratory conditions. Cold saturated air at the inlet was blown into the snow samples and warmed up while flowing across the sample with a temperature gradient of around 50 K m^{-1}. ~~The temperature gradient in the sample was around 50 K m^{-1} at maximum airflow velocity~~. ~~The sublimation of ice for saturated air flowing across the snow sample was experimentally determined via changes of the porous ice structure in the middle-height of the snow sample. Sublimation has a marked effect on the structural change of the ice matrix but diffusion of water vapor in the direction of the temperature gradient counteracted the mass transport of advection.~~ Changes of the porous ice structure were observed at mid-height of the snow sample. Sublimation occurred due to the slight undersaturation of the incoming air into the warmer ice matrix. Diffusion of water vapor opposite to the direction of the temperature gradient counteracted the mass transport of advection. Therefore, the total net ice change was negligible leading to a constant porosity profile. However, the strong recrystallization of water molecules in snow may impact its isotopic or chemical content.

Keywords: snow, temperature gradient, metamorphism, advection, sublimation, tomography

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1. Introduction

Snow has a complex porous microstructure and consists of a continuous ice structure made of grains connected by bonds and inter-connecting pores (Löwe et al., 2011). It has a high permeability (Calonne et al, 2012, Zermatten et al., 2014) and under appropriate conditions airflow through the snow structure can occur (Sturm and Johnson, 1991) due to variation of surface pressure (Colbeck, 1989; Albert and Hardy, 1995), simultaneous warming and cooling, and induced temperature gradients (Sturm and Johnson, 1991). Both diffusive and advective airflows affect heat and mass transport in the snowpack and influence chemical concentrations (Gjessing, 1977; Waddington et al., 1996). Various airflow conditions in a snow sample occur, namely: isothermal airflow, air cooling by a negative temperature gradient along the airflow leading to a local supersaturation of the air, and air warming by a positive temperature gradient along the airflow leading to a local undersaturation of the air ~~temperature gradient along the flow direction, and temperature gradient opposite to the airflow~~ (Fig. 1). In general, in a natural snowpack close to the surface (< 1cm) two additional conditions can occur: (1) warm air enters a snowpack having a positive temperature gradient leading to a supersaturation of the air at the entrance, and (2) cold air enters a snowpack having a negative temperature gradient leading to an undersaturation of the air at the entrance. However, because snow has a high heat capacity compared to the air, a high specific surface area, and therefore a high convective heat transfer to the air, a “quasi” thermal equilibrium (the term “quasi” is used because normally the snow structure continuously changes and therefore the equilibrium conditions as well) is usually assumed inside the snowpack (> 1 cm). In this paper, only conditions deeper than > 1 cm inside a snowpack are considered. Under isothermal condition, the continuous sublimation and deposition of ice is due to higher vapor pressure over convex surfaces and lower vapor pressure over concave surfaces, respectively (Kelvin-effect) (Neumann et al., 2008; Ebner et al., 2014). However, applying a fully isothermal saturated airflow across a snow sample has been shown to have no influence on the coarsening rate that is typical for isothermal snow metamorphism independently of the transport regime in the pores at a physically possible Peclet-number (Ebner et al., 2015a). When applying a temperature gradient, the effect of sublimation and deposition in the snow results from interaction between snow temperature and the local relative humidity in the pores. If vapor is advected from a warmer zone into a colder zone, the air becomes supersaturated, and some water vapor deposits onto the surrounding ice grains. This leads to a change in the microstructure creating whisker-like crystals (Ebner et al., 2015b). Whisker-like crystals are very small (~10-30 μm) elongated monocrystals. A flow rate dependence of the deposition rate of water vapor deposition at the ice interface was observed, asymptotically approaching an average estimated maximum volumetric deposition rate on the whole sample of ~~A deposition rate of water vapor on the ice matrix dependence on the flow rate was observed, reaching asymptotically a maximum rate of~~ $1.05 \cdot 10^{-4}$ kg m^{-3} s^{-1} (Ebner et al., 2015b). Contrarily, if the temperature gradient acts in the ~~opposite~~ same direction of the airflow, the airflow through the snow brings cold and relatively dry air into a warmer area, causing that the pore space air becomes undersaturated, and surrounding ice sublimates. Here, we investigate specifically this last effect.

Sublimation of snow is a fundamental process that affects its crystal structure (Sturm and Benson, 1997), and thus is important for ice core interpretation (Stichler et al., 2001; Ekaykin et al., 2009), as well as calculation of surface energy balance (Box and Steffen, 2001) and mass balance (Déry and Yau, 2002). Kaempfer and Plapp (2009) suggest that condensation of water vapor will have a noticeable effect on the microstructure of snow using a 3D phase-field model, which is also confirmed by a two dimensional finite-element model using airflow velocities, vapor transport and sublimation rates of Albert (2002). ~~Albert (2002) suggest that condensation of water vapor will have a noticeable effect on the microstructure of snow using airflow velocities, vapor transport and sublimation rates calculated using a two-dimensional finite-element model, which is also confirmed by a 3D phase-field model of Kaempfer and Plapp (2009).~~ Neumann et al. (2009) determined that there is no energy barrier to be overcome during sublimation, and suggest that snow sublimation is limited by vapor diffusion into pore space, rather than by sublimation at the crystal surface.

In the present work, we studied the surface dynamics of snow metamorphism under an induced temperature gradient and saturated airflow in a controlled laboratory experiments. Cold saturated air at around -14 °C was blown into the snow samples and warmed up to around -12.5 °C while flowing across the sample. Sublimation of ice was analyzed by in-situ time-lapse experiment with microcomputer tomography (micro-CT) (Pinzer and Schneebeli, 2009; Chen and Baker, 2010; Pinzer et al., 2012; Wang and Baker, 2014; Ebner et al., 2014) to obtain the discrete-scale geometry of snow. By using discrete-scale geometry, all structures are resolved with a finite resolution corresponding to the voxel size.

2. Time-Lapse tomography experiments

Temperature gradient experiments with fully saturated airflow across snow samples (Ebner et al., 2014) were performed in a cooled micro-CT (Scanco Medical µ-CT80) ~~at~~ in a cold laboratory temperature of T_{lab} = -15˚C. Cold saturated air was blown into the snow samples and warmed up while flowing across the sample. Aluminum foam including a heating wire was used to ~~generate the~~ warm the side of the snow opposite to the entering airflow. We analyzed the following flow rates: a volume flow of 0 (no advection), 0.3, 1.0, and 3.0 liter/min. Higher flow rates were experimentally not possible as shear stresses by airflow destroyed the snow structure (Ebner et al., 2015a). Nature identical snow produced in a cold laboratory (Schleef et al., 2014) was used for the snow sample preparation (water temperature: 30 ºC; air temperature: −20 ºC). The snow was sieved with a mesh size of 1.4 mm into a box, and was sintered for 27 days at -5˚C to increase ~~the~~ its strength. The sample holder (diameter: 53 mm; height: 30 mm) was filled by cutting out a cylinder from the sintered snow and pushing into the sample holder without mechanical disturbance of the core. The snow samples were measured with a voxel size of 18 µm^3 over 108 h with time-lapse micro-CT measurements taken every 3 h, producing a sequence of 37 images. The size of the cubic voxel size was 18 µm^3. The innermost 36.9 mm of the total 53 mm diameter were scanned, and subsamples with a dimension of 7.2 mm × 7.2 mm × 7.2 mm were extracted for further processing. The imaged volume was in the centre of the sample (Fig. 1 c)). A linear encoder with a resolution of less than 1 voxel (< 2 µm) was used to verify that the scans were taken at the same position. The reconstructed micro-CT images were filtered by using a 3 × 3 × 3 median filter followed by a Gaussian filter (σ = 1.4, support = 3). The clustering-based Otsu method (Otsu, 1979) was used to automatically ~~perform~~ segment ~~clustering-based image thresholding to segment~~ the grey-level images into ice and void phase. Morphological properties of the two-phase system were determined based on the ~~exact~~ 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. An opening-based morphological operation was applied to extract the mean pore size of each micro-CT scan (d_{mean}) (Haussener et al., 2012). ~~Morphological param-~~

~~eters such as porosity, specific surface area and the initial mean pore size were extracted from the micro-CT images to study the ice-air interface dynamic.~~ As additional physical and structural parameter, the effective thermal conductivity k_{cond} was estimated by direct pore-level simulations (DPLS) to determine the influence of changing microstructure. DPLS determined the effective thermal conductivity by solving the governing steady-state heat conduction equations within the solid phase and the stagnant fluid phase ~~corresponding mass and momentum conservation equations~~ (Kaempfer et al., 2005; Petrasch et al., 2008; Calonne et al., 2011; Löwe et al., 2013).

3. Results

Time-lapse tomographic scans were performed with temperature gradients between 43-53 K m^{-1} (Table 1). Small fluctuations of the measured inlet and outlet temperature were due to temperature regulation both inside the cold chamber and inside the micro-CT (Ebner et al., 2014). A shift of $\Delta t < 10$ min between inlet and outlet temperature indicated that a fast equilibrium between the temperature of the snow and the airflow was reached (Albert and Hardy, 1995; Ebner et al., 2015b). The morphological evolution was similar between all four experiments and only a slight rounding and coarsening was visually observed, shown in Fig. 2. ~~The change of structural change “ota 3” at 30 h is due to an error in the scan.~~ The initial ice grains did not change with time and the locations of sublimation and deposition for “ota3” and “ota4” is shown in Fig. 3. Sublimation of 7.7 % and 7.6 % of the ice matrix and deposition of 6.0 % and 9.6 % on the ice matrix were observed. The data were extracted by superposition of vertical cross-sections at 0 and 108 hours with an uncertainty of 6%. The mass sublimated preferentially at locations of the ice ~~grain~~ matrix with low radii and was relocated leading to a smoothing of the ice ~~grain~~ surface and to an increase in the size of pores (Fig. 4 a)). The pore size (uncertainty ~6 %) increased by 3.4 %, 3.6 %, 5.4 % and 6.5 % for ‘ota1’, ‘ota2’, ‘ota3’, and ‘ota4’, respectively.

Loss of ice due to sublimation could not be detected by the micro-CT scans due to limited accuracy and no flow rate dependence was observed during any of the four experiments. The temporal evolution of the porosity, shown in Fig. 4 b), did not change with time and the influence of sublimation of water vapor was not observed. Only ‘ota2’ showed a slight drop in the temporal evolution of the porosity until 18 h into the experiment but kept constant afterwards. This slight drop (≈ 0.5 %) was probably caused by settling of the snow. Coarsening was observed for each experiment but the influence of changing airflow was not visible, confirmed by the temporal SSA evolution, shown in Fig. 4 c).

The repositioning of water molecules led to a smoothing of the ice grains, but did not affect the thermal conductivity of snow. This quantity (standard deviation ~0.025 W m^{-1} ~~(Calonne et al., 2011)~~) slightly increased after applying airflow to the temperature gradient, shown in Fig. 4 d), but no flow rate dependence was observed. Every third scan was used to extract the thermal conductivity and a change of -2.6 %, 3.6 %, 2.2 %, and 2.7 % for ‘ota1’, ‘ota2’, ‘ota3’, and ‘ota4’ was detected.

5. Discussion

The rate of deposition onto the ice surface depends on the flow rate where warm saturated air cooled down while flowing through the sample, as shown in previous experiments (Ebner et al., 2015b). Its deposition rate asymptotically reached a maximum of $1.05 \cdot 10^{-4}$ kg m^{-3} s^{-1}. In this study, changing the temperature gradient leads to a warming up of a cold saturated flow, and resulted in a sublimation rate too small for the analyzed period of the experiment to measure a flow rate dependence by the micro-CT and an influence on the temporal density gradient. A smoothing of ice grains and an increase of the pore space was measured but the airflow velocity did not affect the relocation process of water molecules.

A structural change of the ice grains and repositions of water molecules was observed but the total net flux of the snow was not affected. The superposition of a vertical cross-section in Fig. 3 shows a big effect on reposition of water molecules on the ice structure. However, the temporal porosity (Fig. 4 b) was not affected and the total water vapor net flux was negligible for the analyzed volume. Continued sublimation and deposition of water molecules due ~~the Kelvin-effect~~ the temperature gradient led to a saturation of the pore space. The vapour pressure of the air in the pore was in equilibrium with the water pressure of the ice, given by the local temperature. The entering air warmed up, allowing vapour sublimating from the snow sample to be incorporated into the airflow. As time passed, the snow grains in the sample became more rounded as convexities sublimated. As a result of the reduced curvature, the rate of sublimation decreased and less vapour was deposited in concavities and therefore the surface asperities persisted longer. Finally, the “Kelvin-effect” had a longer impact on the structural change of the ice grains and the reposition of water molecules. ~~However~~ In addition, the uptake of water molecules and their transport due to warming during ~~propagation~~ advection was counteracted by diffusion of water molecules due to the temperature gradient. As thermally induced diffusion was opposite to the airflow gradient, a backflow of water vapor occurred and the two opposite fluxes counteracted each other. ~~cancelled each other out~~ The Peclet numbers ($Pe = u_\mathrm{D} \cdot d_\mathrm{mean}/D$, where D is the diffusion coefficient of water vapor in air), describing the ratio of mass transfer between diffusion and advection, measured during each experiment, showed that diffusion was still dominant (Table 1). Therefore, water molecules were diffused along the opposite direction to the temperature gradient and advected along the flow direction leading to a back and forth transport of water molecules.

As a Peclet higher than 1 is not possible in ~~nature~~ snow (Ebner et al., 2015a), advection of cold saturated air into a slightly warmer snowpack has a significant influence not on the total net mass change but on the structural change of the ice grains due to redistribution of water vapour on the ice matrix. Also the increasing pore size has an influence on the flow field leading to a deceleration of the flow and therefore the interaction of an air-parcel with the ice matrix in the pores increases due to higher residence time. In addition, the diffusive transport rises whereas the advective transport decreases changing the mass transport in the pores. Our results support the hypothesis of Neumann et al. (2009) that sublimation is limited by vapor diffusion into the pore space rather than sublimation at crystal~~s~~ faces. This is ~~also~~ supported by the temporal evolution of the porosity (Fig. 4 b)) and the SSA (Fig. 4 c)), as no velocity dependence was observed and the structural changes were too small to be detected by the micro-CT.

The influence of diffusion of water vapor in the direction of the temperature gradient and the influence of the residence time of an air-parcel in the pores were also confirmed by a low mass change at the ice-air interface. Overlapping two consecutive 3D images, the order of magnitude of freshly sublimated ice was detected. The absolute mass change at the ice-air interface (kg $\mathrm{m}^{-3}\ \mathrm{s}^{-1}$) estimated by the experimental results is defined as

$$S_{\mathrm{m,exp}} = \left| \rho_\mathrm{i} \frac{\Delta(1-\varepsilon)}{\Delta t} \right| \tag{1}$$

where $\Delta(1\text{-}\varepsilon)$ is the change in the porosity between two images separated by the time step Δt, and ρ_i is the density of ice. Albert and McGilvary (1992) and Neumann et al.

(2009) presented a model to calculate sublimation rates directly in an aggregate snow sample

$$S_\mathrm{m} = \left| h_\mathrm{m} \mathrm{SA}_\mathrm{V} (\rho_\mathrm{sat} - \rho_\mathrm{v}) \right| \tag{2}$$

where $\mathrm{SA_V}$ is the specific surface area per volume of snow, and h_m is the mass-transfer coefficient (m s^{-1}) given by ~~(~~Neumann et al., 2009~~)~~

$$h_\mathrm{m} = (0.566 \cdot \mathrm{Re} + 0.075) \cdot 10^{-3} \tag{3}$$

assuming that the sublimation occurs within the first few mm of the sample. Re ($\mathrm{Re} = u_\mathrm{D} \cdot d_\mathrm{mean} / \nu$ where ν is the kinematic viscosity of the air) is the corresponding Reynolds-number of the flow. The absolute sublimation rate is driven by the difference between the local vapor density (ρ_v) and the saturation vapor density (ρ_sat) (Neumann et al., 2009; Thorpe and Mason, 1966). Table 2 shows the estimated absolute sublimation rate by the experiment (Eq. (1)) and the model (Eq. (2)). The very small change in porosity due to densification during the first 18 h for ‘ota2’ was not taken into account. The estimated sublimation rates by the experiment were two orders of magnitude lower than the modeled values and also two orders of magnitude lower than ~~for~~ during ~~the~~ a negative temperature gradient along an airflow experiment (Ebner et al., 2015b). As the air in the pore space is always saturated (Neumann et al., 2009), the back diffusion of water vapor in the opposite direction of the temperature gradient led to a lower mass transfer rate of sublimation. The flow rate dependence for the model described is shown by the mass-transfer coefficient (Eq. 3), increasing with higher airflow. However, the values calculated from the experiment showed a different trend. Increasing the flow rate led to a lower mass transfer rate due to a lower residence time of the air in the pores. Transfer of heat toward and water vapor away from the sublimating interface may also limit the sublimation rate. In general, the results of the model by Neumann et al. (2009) have to be interpreted with care, as ~~the~~ his model was set up to saturate dry air under isothermal conditions. Ice crystals sublimated as dry air enters the snow sample; water vapor was advected throughout the pore space by airflow until saturation vapor pressure was reached, preventing further sublimation. The model by Neumann et al. (2009) does not consider the influence of a temperature gradient and the additional vapor pressure gradient. ~~was not analyzed~~ However, our results concluded that a positive temperature gradient along the airflow has a significant impact on the sublimation rate decreasing the rate by two orders of magnitude.

In the experiments by Neumann et al. (2009), sublimation of snow using dry air under isothermal condition showed a temperature drop for approximately the first 15 min after sublimation ~~began~~ started and stayed constant because the latent heat absorption of sublimation for a given flow rate and heat exchange with the sample chamber equalized each other. Such a temperature drop was not observed in our experiments. In the experiments by Neumann et al. (2009) the amount of energy used for sublimation was between -10 and -40 J min^{-1} for saturation of dry air. Using the expected mass change at the ice-air interface $S_{m,exp}$ (Eq. (1)) and the latent heat of sublimation ($L_{sub} \approx 2834.1 \cdot 10^3$ J kg^{-1}) the energy needed for sublimation ranged between -2 and -12 J min^{-1} for our experiments. Our estimated values are a factor up to five lower than the estimated numbers of Neumann et al. (2009), because the entering air was already saturated (with reference to the cold temperature) at the inlet. The needed energy for sublimation could be balanced between the sensible heat carried into and out of the sample, and the exchange of the snow sample with the air stream and the surrounding prevented a temperature drop.

Thermal conductivity changed insignificantly in these experiments, especially for 'ota 1'. This indicates that ~~advective cold airflow opposite to a temperature gradient~~ air warming by a positive temperature gradient along the airflow and an open system reduces or suppresses the increase in thermal conductivity usually observed by temperature gradient metamorphism (~~Riche and Schneebeli, 2013~~ Loewe et al., 2013; Calonne et al., 2014). Compared to closed temperature gradient experiment, the applied temperature gradient and the open system induced an air movement and therefore reduced the impact on the thermal conductivity, at least on the short term.

6. Summary and conclusion

We performed four experiments of temperature-gradient metamorphism of snow under saturated advective airflow during 108 h. Cold saturated air was blown into the snow samples and warmed up while flowing across the sample. The temperature gradient varied between 43 and 53 K m^{-1} and the snow microstructure was observed by X-ray micro-tomography every 3 h. The micro-CT scans were segmented, and porosity, specific surface area, and the mean pore-size were calculated. Effective thermal conductivity was calculated in direct pore-level simulations (DPLS).

Compared to deposition (shown in Ebner et al., 2015b), sublimation showed a small effect on the structural change of the ice matrix. A change in the pore size was most likely due to sublimation of ice crystals with ~~low~~ small radii but a significant loss of water molecules of the snow sample and mass transfer away from the ice interface due to sublimation and advective transport could not be detected by the micro-CT scans and no flow rate dependence was observed. The interaction of mass transport of advection and diffusion of water vapor in the opposite direction of the temperature gradient and the influence of the residence time of an air-parcel in the pores led to a negligible total mass change of the ice. However, a strong reposition of water molecules on the ice grains was observed.

~~The kinetic phase change from gas to solid is preferable as energy is released compared to solid to gas where energy is required, thus leading to more water molecule deposition than water molecule sublimation.~~ The energy needed for sublimation was too low to see a significant temperature drop because the needed energy was balanced between the sensible heat carried into and out of the sample, and the exchange of the snow sample with the air stream and the surrounding.

This is the third paper of a series analyzing an advective airflow in a snowpack in depth of more than 1 cm. Previous work showed that: (1) under isothermal conditions, the Kelvin-effect leads to a saturation of the pore space in the snow but did not affect the structural change (Ebner et al., 2015a); (2) applying a negative temperature gradient along the flow direction leads to a change in the microstructure and creation of ~~whistler~~ whisker-like structures due to deposition of water molecules on the ice matrix (Ebner et al., 2015b); and (3) a positive temperature gradient ~~opposed~~ along to the flow had a negligible total mass change of the ice but a strong reposition effect of water molecules on the ice grains, shown in this paper. Conditions (1) and (3) showed that they have a negligible effect on the porosity evolution of the ice matrix. ~~and~~ Porosity changes can be neglected to improve models for snow compaction and evolution at the surface. In contrast, conditions (2) showed a significant impact on the structural evolution and seems to be essential for such snowpack models and other numerical simulations. Nevertheless, the strong reposition of water molecules on the ice grains observed for all conditions (1) – (3) can have a significant impact on atmospheric chemistry and isotopic changes ~~contents~~ in snow.

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Table 1: Morphological and flow characteristics of the experiments: Volume flow ($\dot{V}$), initial superficial velocity in snow ($u_{D,0}$), initial snow density (ρ_0), initial porosity (ε_0), specific surface area (SSA_0), initial mean pore size (d_{mean}), average inlet ($T_{in,ave}$) and outlet temperature ($T_{out,ave}$), and the average temperature gradient (∇T_{ave}), corresponding Reynolds number (Re) and Peclet number (Pe).

Name	$\dot{V}$ liter min^{-1}	$u_{D,0}$ m s^{-1}	ρ_0 kg m^{-3}	ε_0 –	SSA$_0$ m^2 kg^{-1}	d_{mean} mm	$T_{in,ave}$ °C	$T_{out,ave}$ °C	∇T_{ave} K m^{-1}	Re –	Pe –
ota1	–	–	284.3	0.69	25.0	0.30	-13.8	-12.5	43.3	–	–
ota2	0.3	0.004	256.8	0.72	26.3	0.33	-14.0	-12.5	50.0	0.07	0.05
ota3	1.0	0.012	256.8	0.72	24.3	0.34	-13.8	-12.3	43.3	0.25	0.19
ota4	3.0	0.036	265.9	0.71	21.7	0.36	-14.6	-13.0	53.3	0.78	0.61

Table 2: Estimated sublimation rate S_m using the mass transfer coefficient h_m determined by Neumann et al. (2009) and the corresponding average surface area per volume $SA_{V,ave}$. S_m can be compared with the measured sublimation rate of the experiment $S_{m,exp}$ (Eq. (1)).

Name	$SA_{V,ave}$ mm^{-1}	h_m m s^{-1}	S_m kg m^{-3} s^{-1}	$S_{m,exp}$ kg m^{-3} s^{-1}
ota1	22.44	$0.75 \cdot 10^{-4}$	$4.83 \cdot 10^{-4}$	$0.68 \cdot 10^{-6}$
ota2	23.98	$1.15 \cdot 10^{-4}$	$2.99 \cdot 10^{-4}$	$4.48 \cdot 10^{-6}$
ota3	21.88	$2.17 \cdot 10^{-4}$	$5.15 \cdot 10^{-4}$	$0.76 \cdot 10^{-6}$
ota4	19.61	$5.16 \cdot 10^{-4}$	$10.9 \cdot 10^{-4}$	$0.08 \cdot 10^{-6}$

Figure captions

Fig. 1. Schematic of the ice-air interface transport processes: a) Under isothermal conditions Kelvin-effect leads to a saturation of the pore space in the snow but did not affect the structural change (Ebner et al., 2015a); b) Air cooling by a negative temperature gradient along the flow direction leads to a change in the microstructure due to deposition (Ebner et al., 2015b); c) Air warming by a positive temperature gradient ~~opposite to~~ along the flow has a negligible total mass change of the ice but a strong reposition effect of water molecules on the ice grains, shown in this paper.

Fig. 2. Evolution of the 3-D structure of the ice matrix with applied temperature gradient and 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 × 40 × 110 voxels (2 × 0.7 × 2 mm^3) large with 18 µm voxel size (a high resolution figure can be found in supplementary material).

Fig. 3. Superposition of vertical cross-section parallel to the flow direction at time 0 and 108 hours for ‘ota3’ (left panel) and ‘ota4’ (right panel). Sublimation and deposition of water vapor on the ice grains were visible with an uncertainty of 6 % (a high resolution figure can be found in supplementary material).

Fig. 4. Temporal evolution of a) the mean pore size, d_{mean}, of the snow samples obtained by an opening-size distribution, b) the porosity, ε, obtained by triangulated structure surface method, c) the specific surface area, SSA, of the ice matrix obtained by triangulated structure surface method, and d) the effective thermal conductivity of the snow sample, k_{cond}, estimated by DPLS simulations. The sizes of the volumes used for the computation of each property are 350 × 350 × 350 voxels (6.3 × 6.3 × 6.3 mm^3).

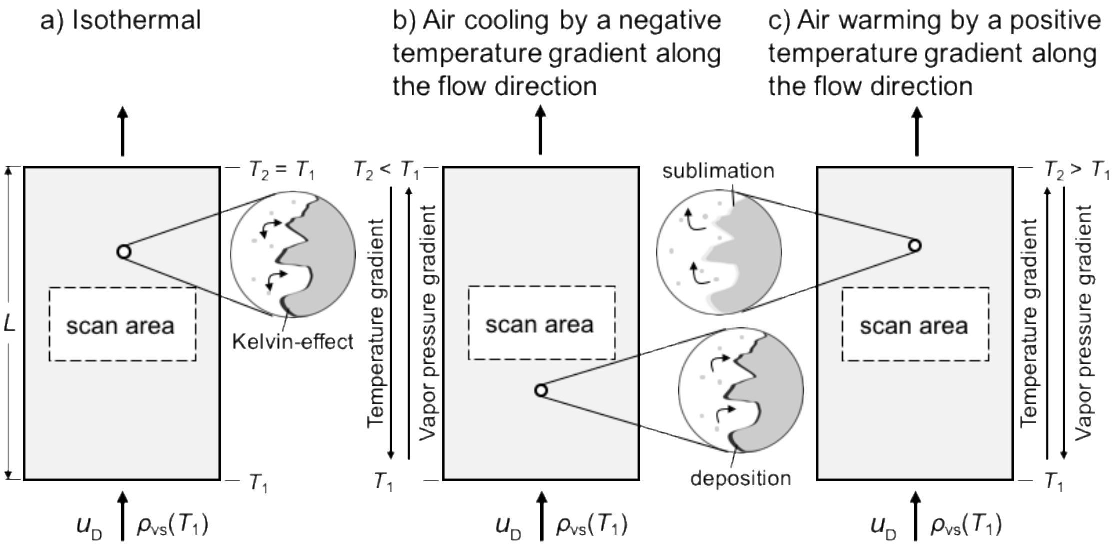

a) Isothermal
b) Air cooling by a negative temperature gradient along the flow direction
c) Air warming by a positive temperature gradient along the flow direction
$T_2 = T_1$
T_1
L
scan area
Kelvin-effect
u_D
$\rho_{vs}(T_1)$
$T_2 < T_1$
Temperature gradient
Vapor pressure gradient
sublimation
deposition
$T_2 > T_1$

Fig. 1

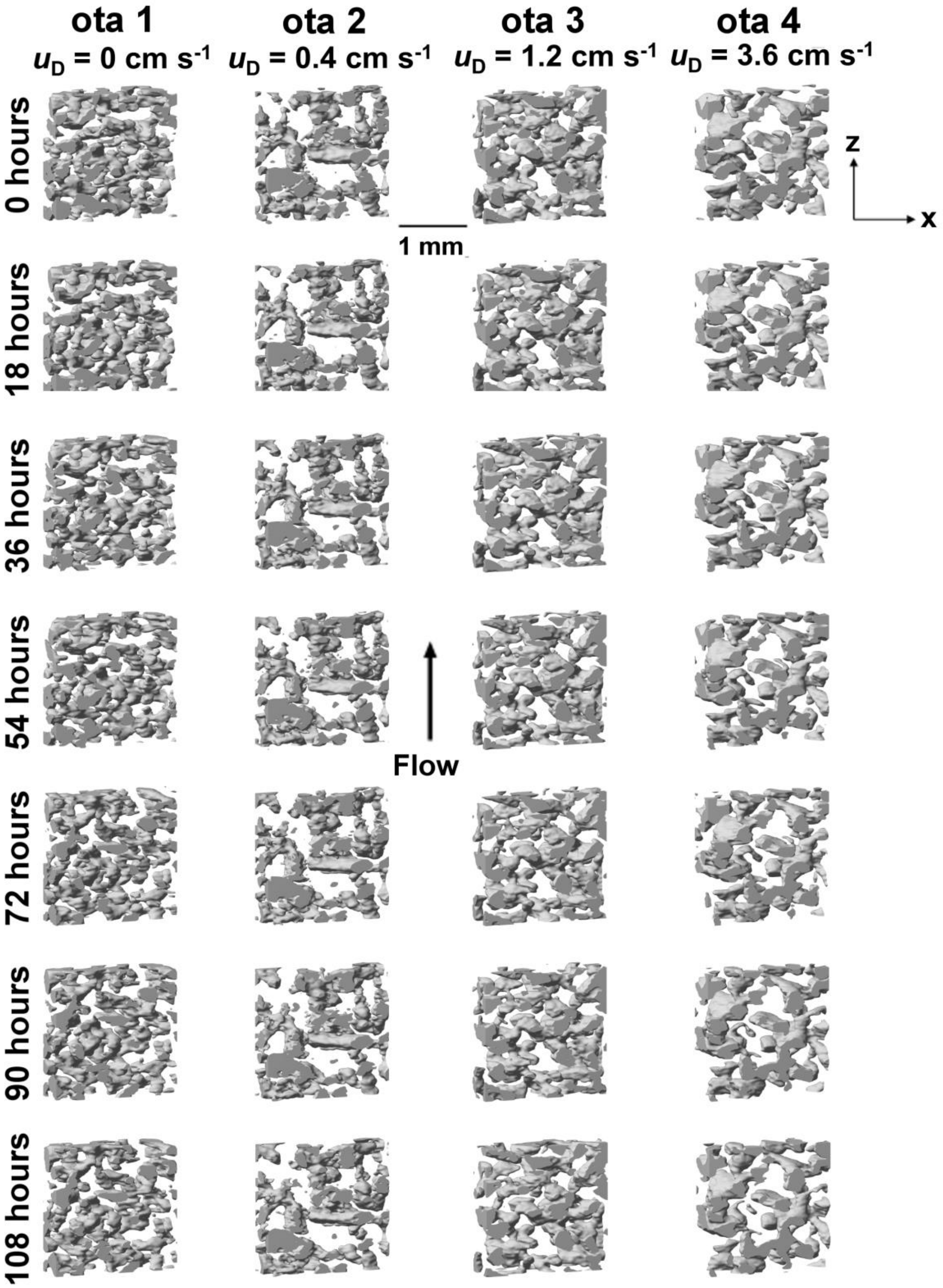

ota 1
u_D = 0 cm s^{-1}
ota 2
u_D = 0.4 cm s^{-1}
ota 3
u_D = 1.2 cm s^{-1}
ota 4
u_D = 3.6 cm s^{-1}
0 hours
18 hours
36 hours
54 hours
72 hours
90 hours
108 hours
1 mm
z
x
Flow

Fig. 2

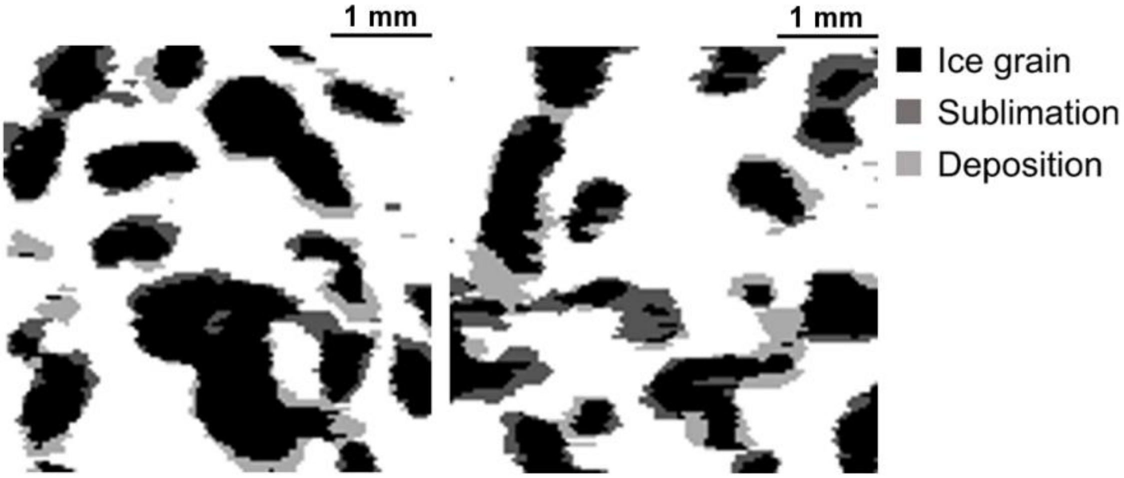


Fig. 3

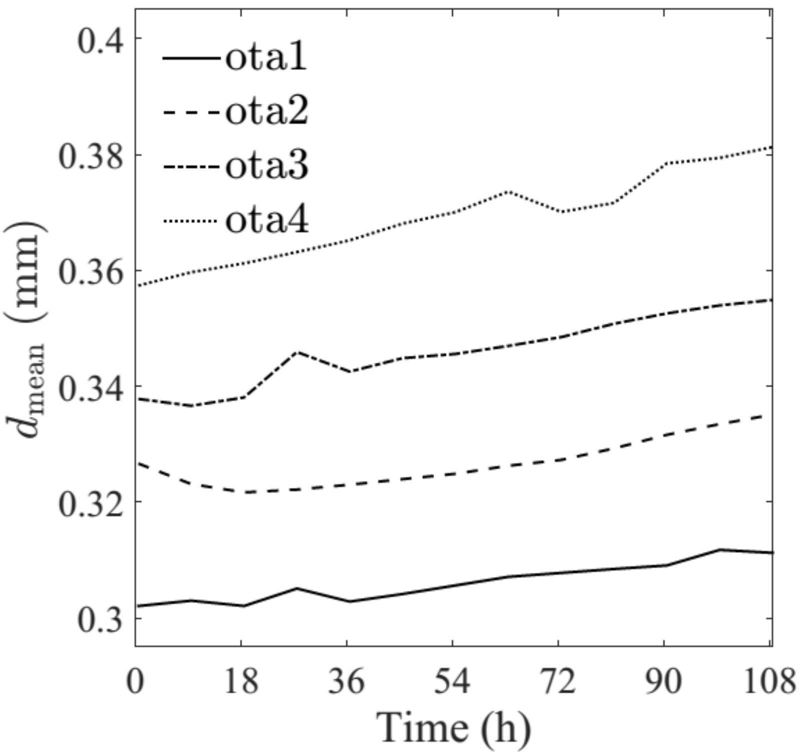

0.4
0.38
0.36
0.34
0.32
0.3
d_{mean} (mm)
0
18
36
54
72
90
108
Time (h)
ota1
ota2
ota3
ota4

Fig. 4 a)

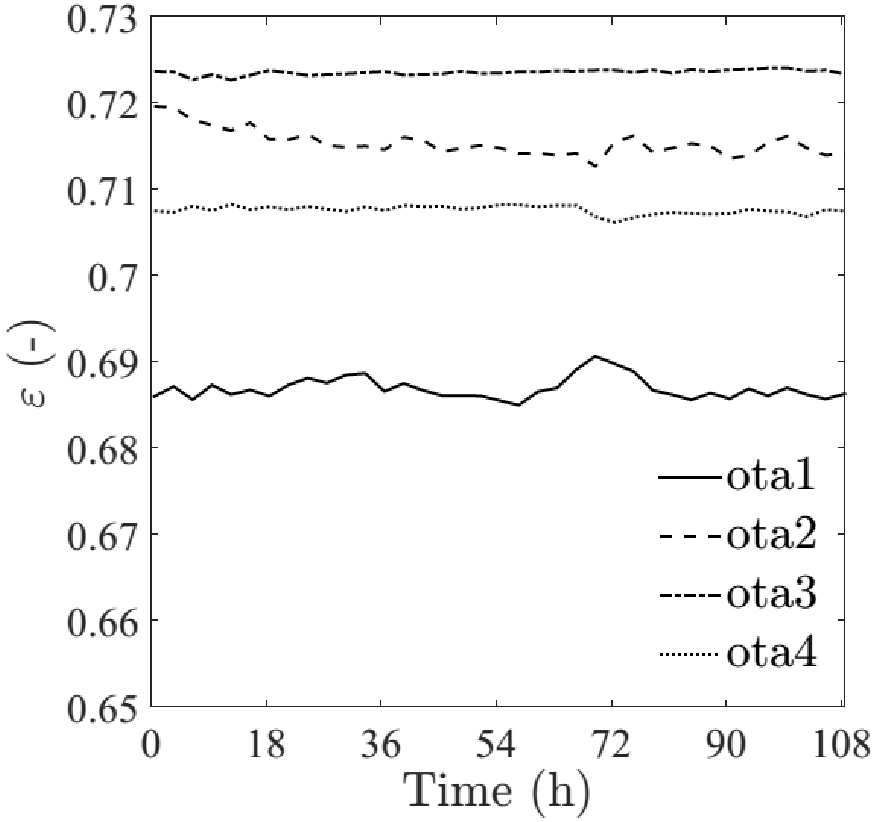

0.73
0.72
0.71
0.7
0.69
0.68
0.67
0.66
0.65
ε (-)
0
18
36
54
72
90
108
Time (h)
ota1
ota2
ota3
ota4

Fig. 4 b)

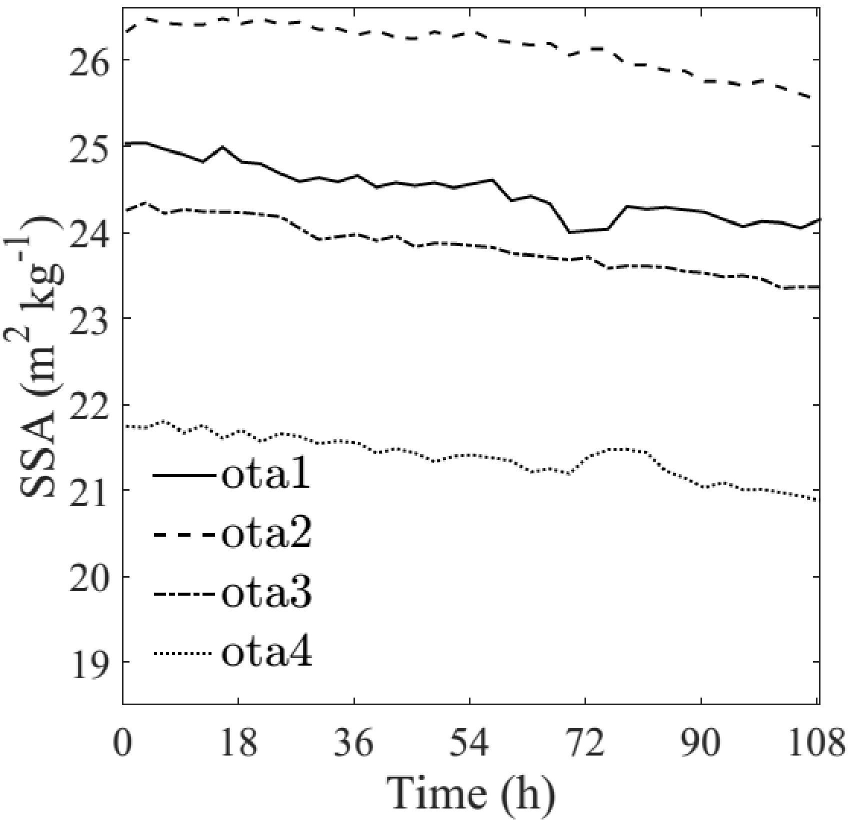
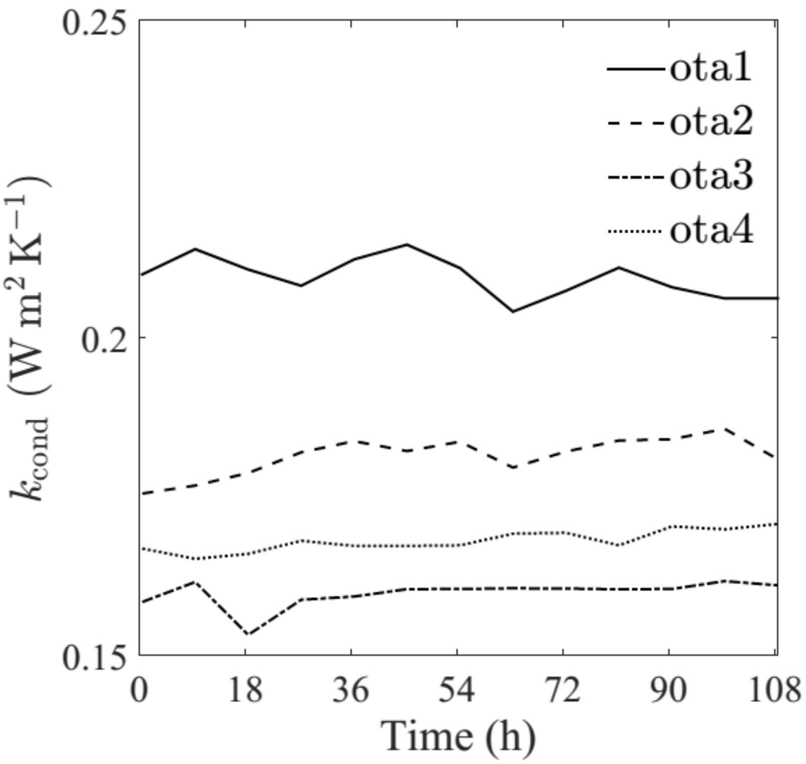

SSA (m^2 kg^{-1})
26
25
24
23
22
21
20
19
Time (h)
0
18
36
54
72
90
108
ota1
ota2
ota3
ota4

Fig. 4 c)



495

496 **Fig. 4 d)**