Temperature gradient metamorphism is not a classical coarsening process

Bernd Pinzer[1,] and Martin Schneebeli[1 *]
[1]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland

ABSTRACT: The current understanding of snow metamorphism distinguishes two classes: equi-temperature metamorphism and temperature gradient metamorphism. The former is an example of a coarsening process similar to Ostwald ripening, i.e. larger particles grow at the expense of smaller particles. Observations of temperature gradient metamorphism in the field and in the laboratory suggested a similar picture for this process. However, we showed that water vapor transfer in snow under a temperature gradient is so large that the entire ice skeleton is renewed within a few days. This means that a "particle" of ice which is usually used to classify snow in the field is completely dissolved after a few days. The concept of growing and shrinking particles does not hold under these circumstances. Instead, the structure must be considered a very dynamic population, where new ice mass "is born" and "dies" continuously.

KEYWORDS: temperature gradient, metamorphism, grain growth, vapor flux

1 INTRODUCTION

The lack of truly three dimensional observation techniques led to the notion of snow as a granular material during the last decades. The most common description and classification of the snow pack involves disassembly of the delicate three-dimensional structure. Parameters like grain size and grain shape are usually recorded in the field. This is reflected in the common models for grain growth under a temperature gradient (Sommerfeld 1983, Colbeck 1983, Gubler 1985). The models rely on simplified geometries, mostly motivated by 2d images. Sommerfeld (1983) assumes that the gradient and therefore the mass flux above and below a grain solely depends on the separation to the next grain, and that the temperature gradient in a pore with mean pore size is equal to the macroscopic gradient. The first assumption can not be justified in a three-dimensional geometry, while the latter assumption contradicts the concept of geometrical gradient enhancement. However, refusing diffusion enhancement, he estimated the time for one complete cycling of all ice grains to be around 12 days. Contrarily, Colbeck (1983) and Gubler (1985) neglected the possibility that all ice grains simultaneously accumulate and loose mass. Colbeck (1983) calculated the growth rate of a single particle next to a vapor source, with a geometrically enhanced temperature gradient between source and sink. The guiding idea behind this model is that some grains grow at the expense of other grains. Gubler (1985) stated that not all particles in a natural arrangement can act as combined sink and source. He considered snow to consist of elongated clusters of grains that are well connected and therefore almost isothermal. Condensation and sublimation in his model only takes place at the “end grains” of such a cluster.

A related controversy is about the bulk diffusion constant of water vapour in snow. Early experiments by Yosida (1955) revealed an enhanced water vapor transport through snow, expressed in the vapor diffusion constant being five times larger than in air. A model to explain this diffusion enhancement was presented by Colbeck (1993), although with a considerably simplified geometry. Field measurements by Sturm and Benson (1997) led to the definition of two different mass fluxes: layer-to-layer and grain-to-grain mass flux. It is not clear how the concept of diffusion enhancement and grain growth can be brought together.

The inconsistencies in the current models of grain growth and the concept of diffusion enhancement show that the processes responsible for temperature gradient metamorphism are still not understood. A truly three-dimensional observation technique is necessary to shed light on this question.

Time-lapse X-ray micro tomography (or 4D tomography) allows for the first time the direct observation of the morphological changes of structural elements within the complicated environment of an undisturbed snow sample. This gives completely new insight into the processes of grain growth and morphological changes.

Corresponding author address: Martin Schneebeli, WSL Institute for Snow and Avalanche Research, Davos, Switzerland;
tel: +41 81 417 0181; fax: +41 81 410 0110;
email: schneebeli@slf.ch

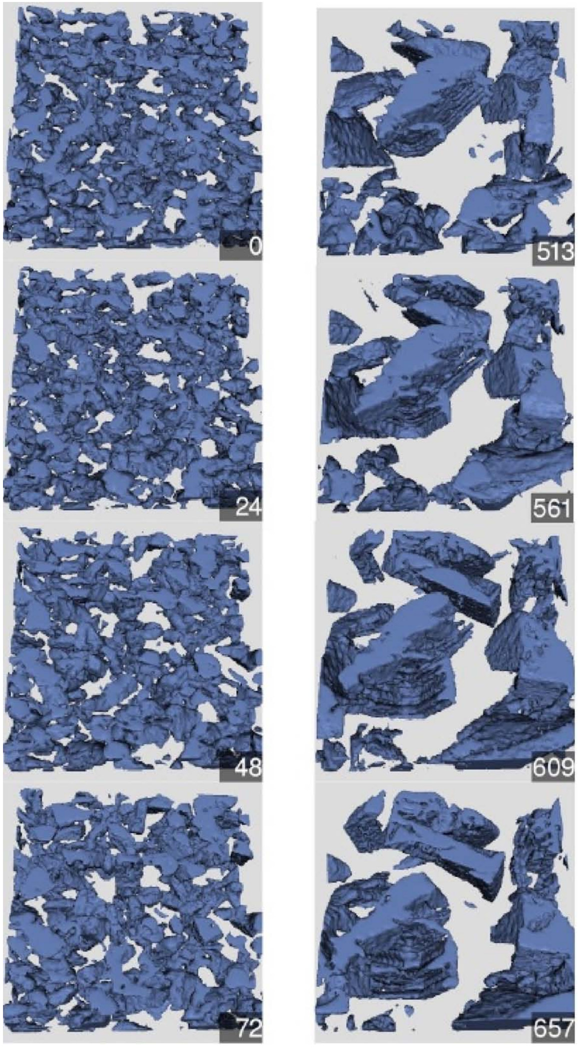

Figure 1. Structural evolution of the sample under a temperature gradient of 50 K m^{-1}. The subvolumes have dimensions 3.6 *x* 3.6 *x* 0.9 mm^3, the numbers indicate time in hours.

2 EXPERIMENT

2.1 Setup

A desktop tomograph (µCT 80, Scanco Medical), residing in a cold laboratory, was equipped with a special sample holder to apply a temperature gradient to a snow sample (Schneebeli and Sokratov, 2004). The scanner was programmed to take an image every 8 hours, with a voxel size of 18 um. Such a resolution is sufficient to capture aged snow, as shown by Kerbrat et al. (2008).

The snow was taken from a natural snow layer with rounded grains, and an undisturbed core of 18 mm height and 55 mm diameter was transferred into the sample holder. The snow sample was subjected to a temperature gradient of 55 K m^{-1} during 665 h (28 days).

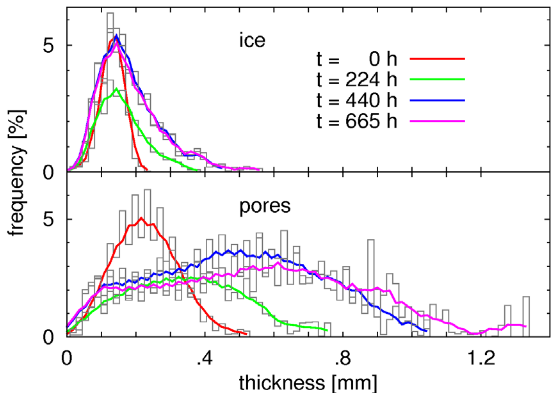

Figure 2. Evolution of ice thickness and pore size of the sample shown in Fig. 1.

2.1 Image Processing

Segmentation: subvolumes of dimensions 300x300x200 voxels were extracted and filtered with a gaussian filter (σ=1, support=2). Partitioning into ice and air phases was done by choosing a threshold that resulted in an ice fraction matching the weighed density of the snow.

Thickness distributions: A distance transform was calculated on the binary image, followed by

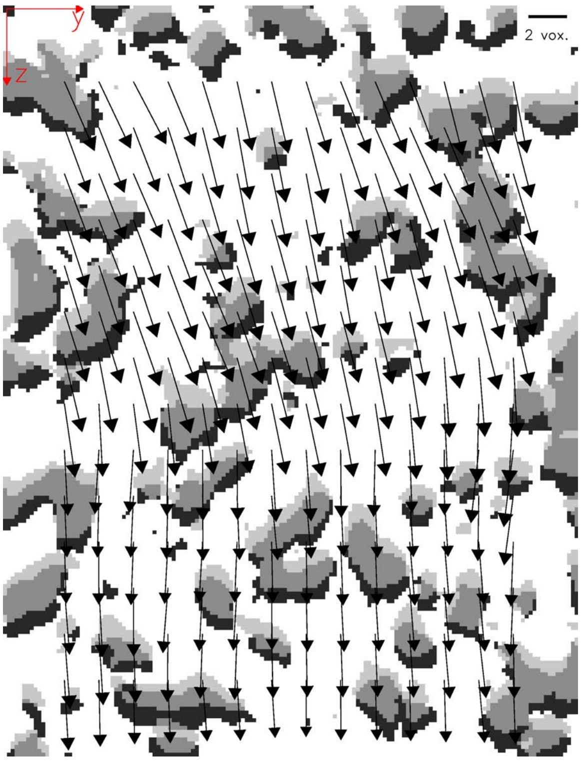

Figure 3: The apparent displacement of the structure during 8 hours, calculated with a 3D algorithm. Light gray areas denote sublimated ice, dark areas signify deposited ice. The size of the slice is 2.12 *x* 2.95 mm^2.

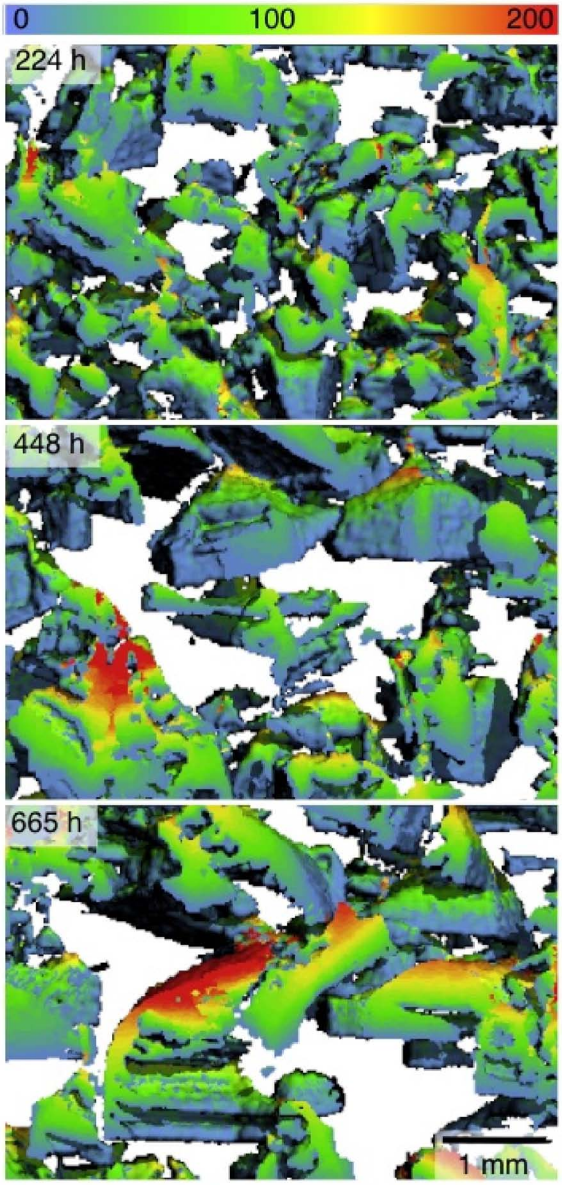

Figure 4. Visualization of the residence time at different stages of metamorphism. The young ice is found on the bottom where the crystals grow, while the “old” ice is found at the top where the crystals sublimate.

a clustering of voxels into largest inscribed spheres (Hildebrand and Ruegsegger, 1997). This results in a volume weighted distribution of local thicknesses. Note that this is typically different to the definition of grain size as the maximum extent of an ice grain.

Displacement field: Two subsequent CT images can be compared to calculate the virtual displacement of the structure due to vapour flux. A displacement vector is assigned to each voxel by locally comparing a neighbourhood of that voxel to a shifted neighbourhood of the subsequent image. Minimizing the deviation between the two windows (in 3D) gives a displacement vector.

Residence time: By keeping track of the appearing and disappearing voxels, a residence time (“age”) can be assigned to each voxel. After the first generation has passed, a steady state develops, describing the dynamics of mass relocation.

3 RESULTS

The structural evolution of the sample is shown in Fig. 1. Visually, it is obvious that the structure evolves towards a coarser pattern. A cup crystal, uniquely related to temperature gradient metamorphism, devolps during the final stages of the experiment. The size distribution of ice clearly shows a coarsening, although the changes are more pronounced for the pore space (Fig. 2).

According to the “hand-to-hand” transport mechanism proposed by Yosida (1955), water vapor is transported from one grain to another by sublimation and condensation. Comparing subsequent µCT images, the locations and the amount of transferred ice mass are revealed. Fig. 3 shows that the entire structure seems to move downwards (along the temperature gradient), which in reality is due to water vapor moving in the opposite direction. A well defined displacement vector field can be calculated for the apparently moving structure. The vector field in Fig. 3 is homogeneous, which indicates that all ice grains take part in the hand to hand transport, and not only particular “end-grains” (Gubler, 1985).

The fact that the entire structure is “displaced” is reflected in the short residence times of the ice voxels. Fig. 4 and Fig. 5 show the result of the residence time calculation. Note that the scalebar in Fig. 4 has a maximum of 200 h. Remarkably, very few voxels reach this age, even in the final stages after the experiment has

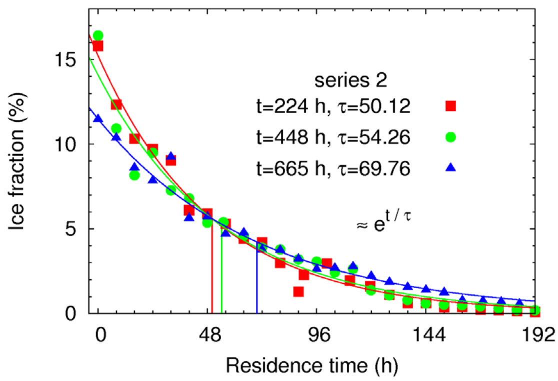

Figure 5. Histograms of the residence time at different stages of evolution, corresponding to the images in Fig. 4.

been run for 665 hours. The histogram in Fig. 5 can be fitted well by an exponential function, with an e-folding time of 2—3 days.

4 DISCUSSION

Although statistically the structure becomes coarser over time, the picture of single grains growing at the expense of other grains is wrong. With µCT, displacements and residence times as well as the thickness distributions of ice and pore phase can be unambiguously measured. The very short residence time on the order of 2 to 3 days shows that the entire structure is continuosly dissolved and rebuilt. Thus, most of the large crystals that we see in a snow profile where a temperature gradient had been acting for some time consist actually of fresh ice. The notion that larger grains become larger and smaller grains disappear has to be replaced by a statistical description. Large grains can shrink and small grains can grow, depending on the fluctuations of the temperature field surrounding them. The larger grains are more likely to survive a given fluctuation since it takes longer to dissolve them. The models that are based on local gradient enhancement (Colbeck 1983, Gubler 1985) have to be rethought.

5 OUTLOOK

The temporal evolution of the structure indicates that faceting does not play a role at the beginning of the experiment, although the growth rates are similar. To date, crystal habit is thought to be only a function of growth rate. With the full three-dimensional information at hand, these questions can be further investigated.

6 REFERENCES

Colbeck, S. C., 1983. Theory Of Metamorphism Of Dry Snow. J. Geophys. Res., 88 (NC9): 5475-5482

Colbeck, S. C., 1993. The Vapor Diffusion-Coefficient For Snow. Water Resour. Res., Amer Geophysical Union, 29 (1): 109-115

Gubler, H., 1985. Model For Dry Snow Metamorphism By Interparticle Vapor Flux. J. Geophys. Res., 90 (ND5): 8081-8092

Hildebrand, T. & Ruegsegger, P., 1997. A new method for the model-independent assessment of thickness in three-dimensional images. Journal of Microscopy, 185 (1): 67-75

Kerbrat, M.; Pinzer, B.; Huthwelker, T.; Gaggeler, H. W.; Ammann, M. & Schneebeli, M., 2008. Measuring the specific surface area of snow with X-ray tomography and gas adsorption: comparison and implications for surface smoothness. Atmos. Chem. Phys., 8 (5): 1261-1275

Schneebeli, M. & Sokratov, S. A., 2004. Tomography of temperature gradient metamorphism of snow and associated changes in heat conductivity. Hydrol. Process., 18 (18): 3655-3665

Sommerfeld, R. A., 1983. A Branch Grain Theory Of Temperature-Gradient Metamorphism In Snow. J. Geophys. Res., Amer Geophysical Union, 88 (NC2): 1484-1494

Sturm, M. & Benson, C. S., 1997. Vapor transport, grain growth and depth-hoar development in the subarctic snow. J. Glaciol., 43 (143): 42-59

Yosida, Z., 1955. Physical Studies on Deposited Snow. I. Thermal Properties. Low Temperature Science, 7: 19-74