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Temperature gradient metamorphism observed by computed micro-tomography

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ABSTRACT: Temporal changes in snow structure and in effective heat conductivity during temperature gradient metamorphism are reported. The structure was measured by computed X-ray micro-tomography, the heat conductivity determined by measuring heat fluxes and temperatures. The structural parameters analyzed are: the sizes of ice structures and of pore space, specific surface area, curvature, and anisotropy. The temporal changes in structure and heat conductivity are compared. The heat conductivity changed up to twice from its initial value, due to changes in structure and texture, but not in density. A plateau phase in the development of the heat conductivity was observed, indicating a quasi-steady state of the structural evolution with respect to thermophysical properties of snow.

Keywords: snow, X-ray tomography, effective heat conductivity, structure, texture

INTRODUCTION AND DESCRIPTION OF THE STUDY

Recrystallization of snow (snow metamorphism) takes place in form of phase transitions at the ice matrix surface. When a temperature gradient is present, these phase transitions are also responsible for the evolution of chemical and isotopic composition of snow. The present understanding of snow crystals growth is mainly based on empirical data on the ice crystals habits forms and growth rates in dependence on temperature and degree of supersaturation. However, in multielement systems, such as natural snow, the rules of recrystallization were found to be considerably different from the single crystals behavior, and they do not have a solid empirical dataset relating the growth rates and changes in shape to environmental conditions. Understanding the driving forces of snow metamorphism is of great importance for modeling the "effective" material properties of snow. The latter are required for modeling mechanical properties of snow in relation to avalanche danger, snow cover evolution as regulated by mass and energy fluxes through a snow cover, snow–firn–ice transition on glaciers for paleoclimate reconstructions, etc.

The effective heat conductivity of snow was chosen as an example of the snow bulk properties. A controlled temperature gradient was applied to a snow sample, and simultaneously during measuring heat fluxes and temperatures, the evolution of the internal snow structure was observed by X-ray computed tomography (i.e., in any way not disturbing the sample). The applied temperature gradient was from 25 to 100 K m^{-1}. Snow density range of samples varied from 150 to 500 kg m^{-3}. The structure was analyzed with respect to the size of ice and air structures, specific surface area, curvature, and anisotropy of the ice matrix. The temporal changes in structure and heat conductivity are compared.

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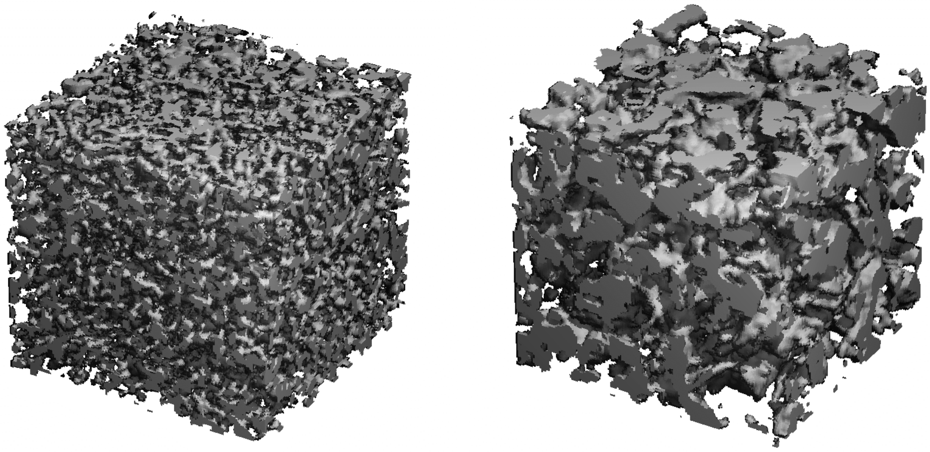


Example of structural evolution of snow under temperature gradient conditions:
Left-hand side-initial snow, right-hand side-after a week of applying a temperature gradient of 100 K m^{-1}.
Size of shown cube ≈5×5×5 mm, constant snow density of 268 kg m^{-3}.

RESULTS AND DISCUSSION

It was found that the snow density in the observed volume remained constant during the temperature gradient experiments (while without applying a temperature gradient density increases). This implies that chaining of snow, in our experiments observed as changing anisotropy, prevents compaction.

The observed mass exchange between ice matrix structures in the direction of heat flow was 2 orders of magnitude higher than the results of grain-to-grain water vapor flux estimations from an initial and a final (close to the end of a winter season) mean grain size in a selected snow layer of a natural snow cover (Sturm and Benson, 1997).

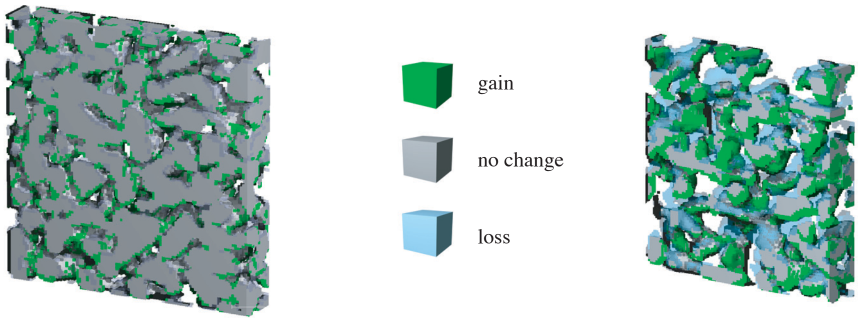
On one hand the mass exchange contributes to the effective heat conductivity value in essentially complicated form: In addition to conduction, the heat is not transported by water vapor, as is often cited, but is released and gained at the ice matrix surface during the process of recrystallization. The transport of this heat takes place through the ice matrix, from a position of deposition of the water vapor to a position of sublimation, affecting the gradient enhancement both in the ice matrix and in the pore space.

On the other hand the amount of mass passing through the sublimation/resublimation cycle corresponds to a life time of the whole ice matrix between the alternating phase transitions as not more than 1.5 days under a temperature gradient 40 K m^{-1} (i.e. corresponding to those often reported for a natural snow cover). The phase transitions should be accounted for at least the climate reconstructions based on isotopic composition of ground ice formed from seasonal snow (Konishchev et al., 2001).

The effective heat conductivity changed up to twice from its initial value, caused by changes in structure and texture, but not in density. This explains the wide scatter of previously reported empirical results, when for snow with similar density and even similar crystal shape the values differed up to several times (Sturm et al., 1997; 2002). The observed temporal trend, however, is not in agreement with the current understanding of the metamorphic process, where effective heat conductivity is expected to decrease with coarsening of snow due to the disappearance of bonds (Sturm et al., 1997). However, simultaneously with observing coarsening during our experiments, thickening of ice structures took place, thus increasing the effective heat conductivity.

Also, a plateau phase in the development of the effective heat conductivity was observed, which indicates a quasi-steady state of the structural evolution with respect to thermophysical properties of snow.

Altogether, the present descriptions of snow metamorphism available for models of snow cover evolution (Brun et al., 1992; Lehning et al., 2002), based on few empirical results on crystals' shape evolution (Delsol et al., 1978; Marbouty, 1980; Pahaut and Marbouty, 1981; Fierz and Baunach, 2000) and on the theoretical curvature difference between grains and necks (Brown and Edens, 1999), are incomplete and require revision of the accounted physical processes. Newly developed physical models for thermophysical and mechanical properties of snow, overcoming the traditional grain–neck paradigm, can be verified and validated with the real three-dimensional structure of snow provided by X-ray computed micro-tomography (Schneebeli, 2002; 2004; Kaempfer et al. 2004).



Example of estimated mass release/gain per day (by comparison of 3D images at the same position in the samples taken day apart): Left-hand side-shown volume 3.6×3.6×0.54 mm, constant snow density of 490 kg m^{-3}, temperature gradient 100 K m^{-1}; Right-hand side-shown volume 2.5×2.5×0.375 mm, constant snow density of 288 kg m^{-3}, temperature gradient 50 K m^{-1}

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