Temperature and Temperature Gradient Dependence of Snow Recrystallization in Depth Hoar Snow

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Abstract. Under extremely low temperatures (ranging from −65°C to −15°C), an experiment on temperature gradient metamorphism with 500 Km^{-1} was carried out for three days. Heat fluxes were produced in snow in either upward or downward directions. The effects of temperature, temperature gradient and its direction on crystal growth were investigated. The experiment showed that the growth rate was larger in layers where the average for the layer temperature was higher, even if the temperature gradient was small. The relationship of the calculated water-vapor flux and crystal growth to temperature was examined, and good correlation was found. It was concluded that crystal growth primarily depends on temperature, and secondarily on temperature gradient.

1 Introduction

Because of its significance as a cause for avalanche formation, dry snow metamorphism has recently been an intensive research topic in snow science. In Polar Regions, these processes are now also often included into the studies of the snow-cover interaction with the climate. It is also known that in cold environments the snow cover is characterized by highly developed depth-hoar layers. The purpose of the experimental work that we are going to present here is to investigate the growth of depth-hoar-crystals in cold dry snow. The results that are reported, are at variance with results presented by others.

It is known that snow metamorphism results from the processes of evaporation and condensation on the surfaces of the snow grains, giving rise to a water-vapor flux essentially from locations of evaporation to those of condensation [1–3].

It is an accepted understanding that under isothermal conditions the driving force for snow recrystallization is the difference of curvature between the crystals [4,5]. Likewise, it is widely believed though not uniformly accepted that when a temperature gradient is applied the main influencing activity of the snow recrystallization is this temperature gradient. Akitaya [2,3] reported that conditions for depth-hoar crystals to develop are, first, the magnitude of the temperature gradient and, second, the existence of a sufficient fraction of pore space. Fukuzawa and Akitaya [6,7] explicitly spoke out that the growth rate of the depth-hoar crystals is proportional to the magnitude of the temperature gradient. However, the temperature range of these studies was from -20°C to 0°C making it difficult to estimate the influence of the (mean) temperature on the process. In addition, there were very few experimental studies under extremely low temperatures. So the question remains open as to how the temperature itself affects the recrystallization processes in snow.

It was found that the depth-hoar-growth rate is also affected by the snow density. In fact experimental studies showed that depth hoar was not formed under high temperature gradients in snow samples with high density; however, they were formed under the same conditions in low density snow samples [8–10]. Generally, the larger the snow density was, the smaller the growth of depth hoar.

It is known that the shape of snow flakes is determined by the temperature and supersaturation of water vapor. This fact was constructively used by us to shape the depth hoar crystals accordingly; similar types of depth hoar crystals developed in the same temperature ranges as for the snow flakes [1,8].

In the present study, the crystal growth was observed under extremely low temperatures (ranging from −65°C to −15°C). The experiments were carried out with temperature gradients of about 500 Km^{-1} and lasted three days. Two samples, discussed here, were subjected to the same conditions except that the heat fluxes imposed on the snow were opposite in direction, upward and downward. Since we monitor both the (mean) temperature and the temperature gradient, the present study proposes a relationship for the growth rate of the depth-hoar crystals involving the temperature and temperature gradient.

2 Experimental Method

2.1 Snow sample

Lightly compacted snow (initially with density 290 kgm^{-3}) was used (Fig. 1 (**a**)), which was made in the Cryospheric Environment Simulator (CES) in Shinjo Branch, NIED and kept in a cold room (−15°C) for a month. Its average diameter is that of an equivalent circle of the grains' cross-sectional area which was calculated to be 2.56×10^{-4} m.

2.2 Apparatus

A scheme of the experimental apparatus is shown in Fig. 2. A thermo-insulated container (0.6 × 0.7 × 1.2 m) was installed in a cold room. The

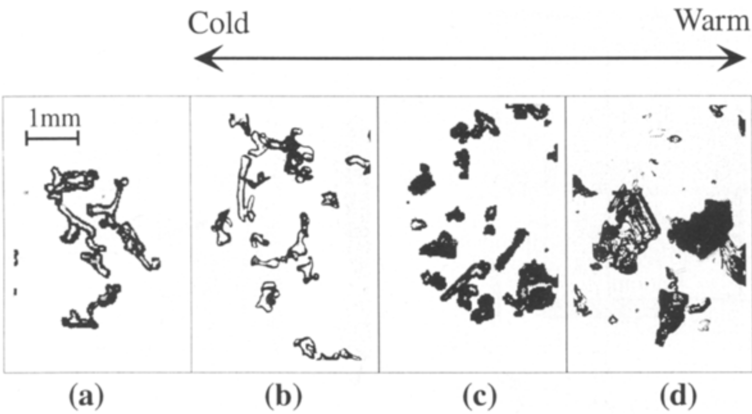

Fig. 1. Comparison of initial disaggregated grains with grains of each layer after experiments : (**a**) initial, (**b**) cold layer (about −65°C to −45°C), (**c**) middle (about −45°C to −25°C), (**d**) warm (about −25°C to −15°C)

inside temperature of the container was kept at −15°C by a heater and a fan that was automatically regulated. Snow was sifted into the sample box made with 0.1 m foam plastic walls, with the inside space for snow of 0.25 × 0.25 × 0.1 m. Those two sample boxes with snow were positioned in the thermo-insulated container as shown in Fig. 2. A cold plate of circulating thermostat was put between the samples. The opposite sides of the samples were in contact with iron plates. The temperature of the cold plate was kept to within an accuracy of ±0.05°C. The temperature of the iron plates was varied between ±0.2°C. In this way the samples ("**a**" – the "upper" one and "**b**" – the "lower" one) had temperature gradients with opposite directions. Six copper-constantan thermocouples were measuring the temperature in each sample every 1 minute, on the central axis parallel to the heat fluxes produced in the snow at intervals of about 0.02 m.

2.3 Method

Once a uniform temperature of −15°C was achieved throughout both samples, the temperature of the cold plate was changed to −65°C. So the samples were subjected to a strong temperature gradient of about 500 $\mathrm{Km^{-1}}$. The temperature distributions in the samples were measured continuously and soon achieved quasi–steady state conditions (i.e. there was no longer any temperature change according to the accuracy of the measurements). After three days of fixed thermal conditions each snow sample with thickness 0.1 m was divided into three layers: "Top" (0.067–0.097 m), "Middle" (0.034–0.067 m), and "Bottom" (0–0.033 m from the bottom face), as shown in Fig. 2.

Photographs of the disaggregated grains for each layer were taken using a microscope. The cross-sectional area of the digitized grains was determined

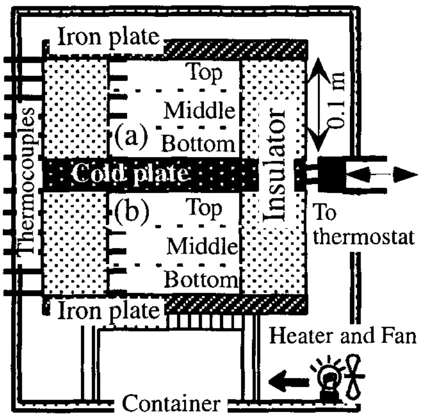

Fig. 2. Scheme of the experimental apparatus

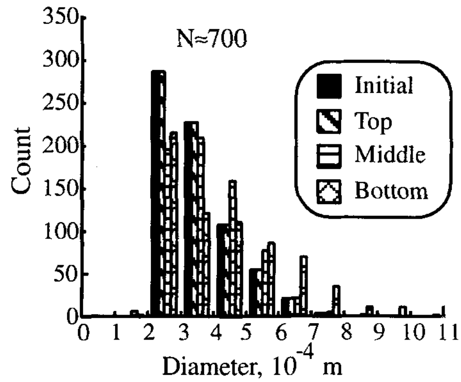

Fig. 3. Diameter distribution in each layer of the "lower" sample. N is the total number of crystals.

and the diameter of a circle with an equivalent area was computed. The diameter distribution of each layer after the experiment was compared with the initial diameters. This gave the relationships between the crystal growth rate and the temperatures, temperature gradients, and its direction.

3 Results

We found no difference in crystal shapes of the upper and the lower samples. Crystal shapes in the layers near the cold plate did not change from their initial state (Fig. 1**b**). As the average temperatures of the layers increased, crystals developed to solid type in the both "Middle" layers and to skeleton type depth hoar near the cold plate. Over the process the diameter of the crystal also increased (Fig. 1**c**, **d**).

Fig. 3 shows the diameter distribution of each layer for the "**b**"-sample in Fig. 2. We see that the initial distribution of the crystals (ranging between $1.1–6.8 \times 10^{-4}$ m) had a peak between 2 and 3×10^{-4} m.

The distribution in the "Top" layer (crystal size range $0.94–5.8 \times 10^{-4}$ m), being in contact with the cold plate, indicated little change from the initial one. The "Middle" (crystal size range $0.62–7.1 \times 10^{-4}$ m) and the "Bottom" ($0.36–9.3 \times 10^{-4}$ m) layers, whose temperatures increased in turn, showed smaller peaks than the initial reading and were widely distributed over a larger diameter. Small radii grains had to sacrifice as the large radii grains acquired mass from the smaller grains [4].

Fig. 4 shows quasi-steady state temperatures and calculated temperature gradients of each position. The temperature distributions were not linear

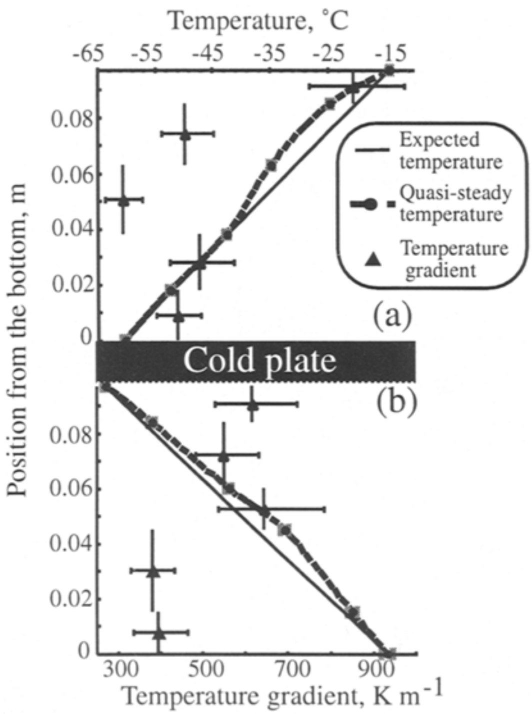

Fig. 4. Quasi-steady state temperature and calculated temperature gradients with vertical downward (**a**) and upward (**b**) heat fluxes.

in either of the samples and differed between the "upper" and the "lower" sample. A more detailed analysis of temperature distributions is given in [11].

Neither of the temperature gradients calculated from the observed temperature distributions were uniform in the two samples. Their change was within the accuracy of the measurements in those parts of the snow samples where temperatures were below −40°C. Above −40°C temperature gradients increased in the "upper" but decreased in the "lower" sample as the temperature increased.

Average crystal diameters in each layer with the mean temperatures and the mean temperature gradients are shown in Table 1. Akitaya [1] reported that the surface of the warmer snow grain evaporated sublimatically and then condensed sublimatically on the surface of the colder grain. However, our results showed in both samples that crystals of the warmest layer developed more than those in the other layers.

Fukuzawa et al. [6] reported that the growth rate of depth hoar was proportional to the magnitude of the temperature gradient. Contrary to this, crystals of the "Bottom" layer in the "lower" sample, whose temperature gradient was the smallest, had the highest growth rate of the sample.

Table 1. Average diameter of each layer with its temperatures and temperature gradients (Fig. 2)

Sample	Layer	Temperature °C	Temperature gradient ° m^{-1}	Crystal diameter $\times 10^{-4}$ m
"upper"	Top	-25	810	4.19
	Middle	-40	310	2.94
	Bottom	-53	460	2.86
"lower"	Top	-57	590	2.66
	Middle	-37	640	2.84
	Bottom	-23	400	3.33

4 Discussion and Conclusions

The results shown above contradict those previously reported. It is necessary for the development of the depth-hoar crystals to be supplied with water vapor. We assume that the water vapor in the porous space is saturated, and this depends on temperature. For example, the saturated water-vapor concentration in the porous space had to be 2.2×10^{-6} kgm^{-3} at -65°C, and 1.4×10^{-3} kgm^{-3} at -15°C, i.e. the water-vapor concentration at -15°C was about thousand times larger than at -65°C. The theoretically possible water-vapor flux in the porous space was calculated by multiplying the water-vapor-concentration gradient with the temperature dependent water-vapor-diffusion coefficient, both obtained from the temperature measurements.

Fig. 5 shows the relationship between this water-vapor flux and the crystal growth in each layer. In the "upper" sample the fluxes of the "Middle" and the "Bottom" layers were small, and that of the "Top" layer, whose temperature was high, increased abruptly. While in the "lower" sample the flux increased gradually from the "Top", the "Middle" to the "Bottom" layer. Thus, the flux did not show a symmetrical distribution.

The possible reason for such non-symmetry could be convection. In the "upper" sample the bottom plate was cold and the top plate was warm making this condition stable against convection. However, in the "lower" sample the bottom plate was warm and the top plate was cold making convection possible. It is generally accepted that the dimensionless Rayleigh number is used to estimate under what conditions convection will occur in snow [12–14]. This Rayleigh number (Ra) is

$$Ra = \frac{g\beta(\rho c)_f \Delta T h k_i}{\nu k_m}, \quad (1)$$

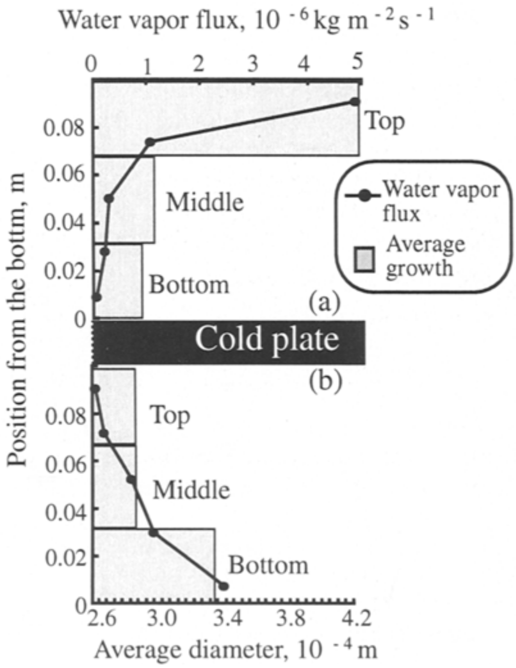

Fig. 5. Relationship between the water vapor flux and the crystal growth in each layer. Left end of diameter axis indicates average diameter of initial snow and then columns shows the growth of each layer.

where g is the acceleration due to gravity, β is the isobaric coefficient of thermal expansion, $(\rho c)_f$ is the volumetric heat capacity of the fluid (moist air), ΔT is the temperature difference across the sample, h is the thickness of the sample, k_i is the coefficient of air permeability, ν is the kinematic viscosity, and k_m is the thermal conductivity of the porous medium. We computed Ra roughly and compared it to a critical value (Ra_{cr}). It seems that convection will occur when $Ra > Ra_{cr}$. Ra_{cr} for snow is usually assumed to be between 18 and 40 [13,14]. In this experiment, Ra was 7.6. This value is lower than Ra_{cr}. However, Sturm et al. [14] observed convection at Rayleigh numbers as low as 4, and their temperature difference was smaller than in this experiment. This is why one can expect that convection could take place and influence the process of recrystallization under present conditions.

The diameters of the crystals increased with an increase in the magnitude of the flux. Crystals developed in the layers where the flux was large because of high temperature. The growth was small where the temperatures were low even if the temperature gradients were large, since the amount of water vapor was small.

Next, as an example of the effect of the temperature gradient, the "Top" layer of the "upper" with the "Bottom" layer of the "lower" sample can be compared. Both layers had similar temperatures but the temperature gradient in the "Top" layer was twice as large as in the "Bottom" layer. The growth in the "Top" layer was also twice as large as that in the "Bottom" layer.

We conclude that the temperature, which determines the water vapor amount in the porous space, is the most important factor for the depth hoar growth. The magnitude of the temperature gradient also affects the growth rate but not primarily, a fact that can be seen when temperatures are similar.

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