THE METAMORPHISM OF WET SNOW

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ABSTRACT

In order to study the metamorphism of wet snow, a block of snow was placed in a thermally insulated box and maintained at 0 °C for a long time. The microscopic changes occurring in the texture of snow were examined by the use of thin sections cut every other day from the block. Four series of experiments were carried out, using (1) dry snow, (2) snow wetted by adding a small amount of water, (3) snow immersed in water of 0 °C, (4) snow immersed in water of 0 °C and loaded with a weight. It was found that ice grains composing the snow grew rapidly in size in the case (3), while they grew slowly in the cases (1) and (2). In the case (4), snow was transformed into ice within a week.

RÉSUMÉ

Afin d'étudier le métamorphisme de la neige humide, une masse de neige a été placée dans une boîte isolée thermiquement et maintenue à 0 °C pendant longtemps. Les changements microscopiques intervenant dans la texture de la neige furent examinés en utilisant de minces coupes faites chaque jour dans la masse. Quatre séries d'expériences furent exécutées, utilisant : 1) la neige sèche, 2) la neige humidifiée en ajoutant une faible quantité d'eau, 3) la neige plongée dans de l'eau à 0 °C, 4) la neige immergée dans de l'eau à 0 °C et chargée d'un poids. Il a été trouvé que les grains composant la neige croissaient rapidement en dimension dans le cas (3), tandis qu'ils croissaient lentement dans les cas (1) et (2). Dans le cas (4), la neige se transformait en glace en une semaine.

I. INTRODUCTION

In the cold regions, snow crystals deposited on the ground become fine granular snow without being subjected to any melting. This metamorphism is very analogous to the sintering process in powder metallurgy, and further grain coarsening may be caused by recrystallization and plastic deformation. In the temperate regions, however, snow metamorphism proceeds very rapidly by the intervention of the melting process, creating various types of snow. The grain coarsening of snow may be caused by repeated melting and freezing processes. As these phenomena are usually observed at the surface layer of snow in the spring time, these mechanisms seem to be a reasonable cause of grain coarsening in snow. However, another mechanism of grain coarsening can often be observed within snow cover in the melting season. The melt water produced at the snow surface begins to permeate into snow cover, but its permeation is not always uniform, sometimes water penetrates deeply into the snow strata as if it drains along particularly permeable channels. If we investigate the penetration of melt water by digging into the snow, it is observed that preferential grain coarsening took place along such water channels, nevertheless hardly any grain coarsening can be observed in neighbouring wet snow strata. When whole snow layers are wetted and maintained at the melting point, no temperature gradient and no heat transfer exist throughout the strata. Therefore, the preferential grain coarsening created along water permeable channels within snow must be caused by the interaction between ice particles and melting water under quasi- or nearly equilibrium conditions. The main purpose of this paper is to study the metamorphism of wet snow under equilibrium conditions.

II. Two kinds of coarse-grained snow

In natural snow cover, four types of snow are found, namely: 1) newly-fallen snow, 2) fine-grained snow, 3) coarse-grained granular snow and 4) depth hoar. In midwinter in cold countries, the snow cover is commonly composed of fine-grained snow. In the melt season, however, coarse-grained granular snow becomes predominant.

It is believed that newly-fallen snow at the surface is changed into coarse-grained granular snow by repeated daytime melting and refreezing at night. Figure 2(a) shows a vertical thin section of newly-fallen snow which is melting. As seen in this picture, the superficial layer of snow, 1 cm thick, has changed into coarse grains, while below the snow survives as newly-fallen snow. The melt water coming down from the surface is held in the form of droplets in the surviving newly-fallen snow. These droplets will become frozen completely the following evening. This process of grain-coarsening is named "Grain coarsening by melting and refreezing". The coarse-grained granular snow produced by this process is, therefore, always found at the surface of a snow cover or firn field.

There is, however, another type of grain coarsening mechanism, which can be found in deep snow layers during the melt season. When melt water produced at the surface penetrates into deep snow, it becomes nutritious and causes grain coarsening. In spring, when the whole snow cover is wetted sufficiently by melt water permeating from the snow surface, grain coarsening is observed very often without any change of temperature. If fine-grained snow, $0.3 \sim 0.5$ mm in diameter, is covered with a thick film of melt water, the ice grains become bigger and bigger, and finally the snow texture becomes coarse with grains, $1 \sim 2$ mm in diameter. Figure 1 shows schematically a situation where a large amount of melt water held in the surface snow layer or impeded by strong water-holding layers beneath the surface has flowed down abruptly into the lower layers, making large "drains of melt water". Fine-grained snow encountered by a "drain of melt water" changes into coarse-grained granular snow without any heat exchange. A vertical thin section of coarse-grained granular snow cut from a "drain of melt water" is shown in figure 2(b). As no temperature

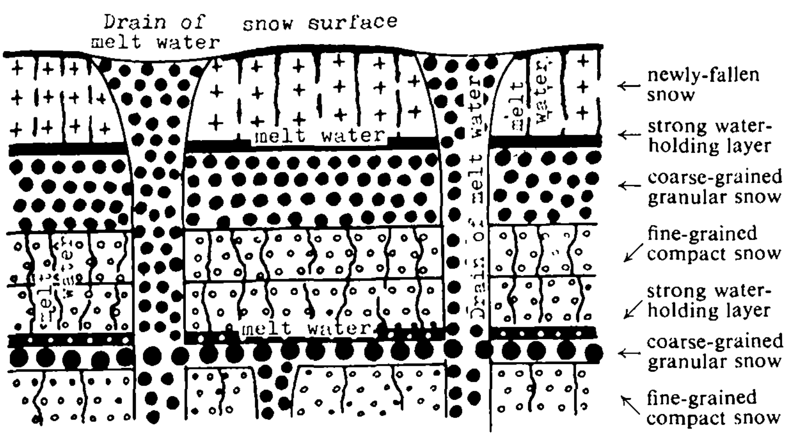

Fig. 1 — Schematic representation of the layered structure in a snow cover in the early melt season. Large "drains of melt water or water channel" are often found in the snow cover as shown in this figure.

gradient can be present within wet snow, this metamorphism from fine-grained snow to coarse-grained granular snow occurs without heat transfer. In order to study more carefully how fine-grained snow grows to large-grained snow under this equilibrium condition, a series of experiments on this metamorphism of wet snow was carried out in the cold laboratory.

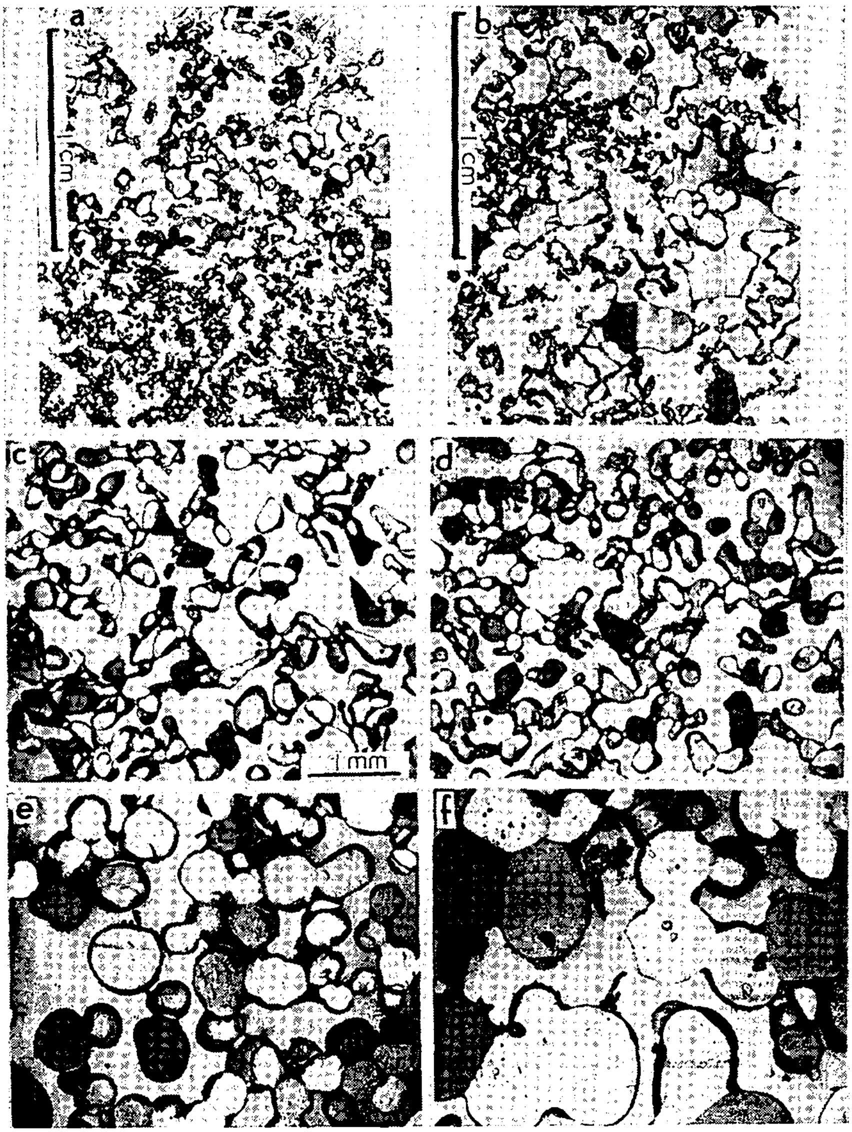

Fig. 2

III. Experiments

A cylindrical sample of fine-grained snow was put in a copper vessel surrounded by a ice-water jacket as shown in figure 3. In this figure, S is the snow sample, and, A, B and C are cylindrical copper vessels containing water and small blocks of ice. G is a wooden case, and dotted areas indicate foamed polystyrene used for thermal insulation. The whole set was placed in a room maintained at $+1 \sim +4\,°C$. The sample was thus kept at $0\,°C$ for many days.

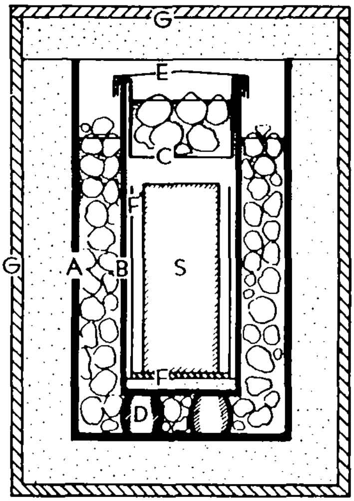

Fig. 3 — Schematic representation of the apparatus used in the experiments. S; sample of snow, A, B, C; cylindrical copper vessels, G; wooden case.

Every other day, thin sections were cut from the sample and grain size and thickness of ice bonds connecting the grains were measured microphotographically by the use of a particle size analyser.

IV. Results

The results obtained in these experiments may be summarized as follows.

(1) *Sample of dry snow* (initial density of the snow was 0.39 g/cm^3). In figure 2(c), the microscopic texture of the original fine-grained snow is shown. Figure 2(d) shows a thin section cut from the sample after it was maintained at $0\,°C$ for 5 days. The snow density never changed during the period of the experiment. It may be hard to distinguish visually any changes in texture between these two photographs (c) and (d), but precise measurement of the grain-size with a particle size analyser indicates that the mean volume of the grains increased by 30%. In figure 4, curves I, II and III show the grain size distributions observed in the initial stage, after 2 days and after 5 days, respectively. The ice bonds formed between the grains did not grow in thickness as shown by curves I and III in figure 5 which give the distributions of ice-bond thickness in the initial stage and after 5 days.

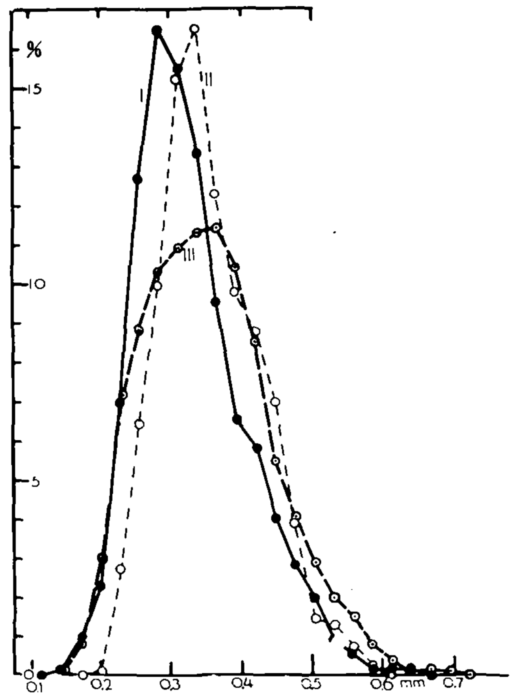

Fig. 4 — Size distributions of ice grains in the initial stage (curve I), after 2days(II), and after 5 days (III).

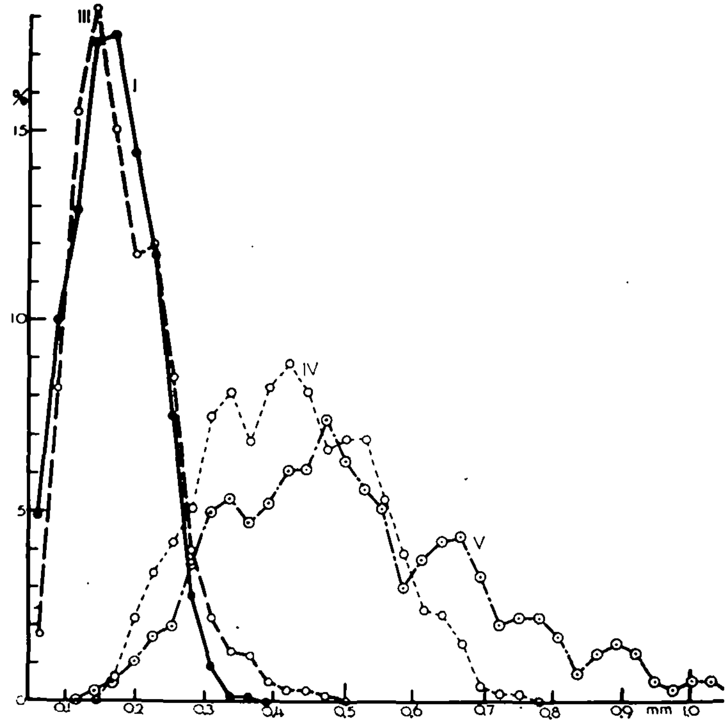

Fig. 5 — Distributions of ice bond thickness in the initial stage (curve I) and after 5 days (III) in experiment (1). Distributions of ice bond thickness in the initial stage (curve I), 3 days after the immersion (IV), and 6 days after immersion (V) in experiment (3).

(2) *Sample of snow wetted by adding water at* 0°C. A small amount of water (3 ~ 5% in weight percent) was sprayed on to the snow sample, and the sample was stored in the box for three days. No discernible change was found in the texture in three days as in the case of dry snow sample. The original volume of the sample was not changed by the addition of the water, and the apparent density of the snow did not change during the period of the experiment. The mean volume of the grains increased by approximately 40% during that time.

(3) *Sample of snow immersed completely in water at* 0°C. The sample was prepared from the same block of fine-grained snow as shown in figure 2(c). The apparent density of the snow (0.39 g/cm^3) did not change during the period of the experiment (one week), since the volume of the sample was not changed by the immersion. But, unlike the previous two cases, distinguishable changes occurred in the texture of snow. The ice grains grew rapidly in size and their shape became spherical. The ice bonds connecting the grains also increased in thickness. Figures 2(e) and (f) show respectively the microscopic texture of snow taken after three days and six days. The change in grain size distribution which occurred in this experiment is shown in figure 6. Curve I shows the initial distribution of grain size before the immersion. Curves IV and V show the changes of grain size distribution observed at 3 days and 6 days after the immersion into water. The mean volume of grains grew as large as 27 times within 6 days. The ice bonds between grains were thickened as shown by curves I (before immersion), IV (3 days after the immersion) and V (6 days after the immersion) of figure 5.

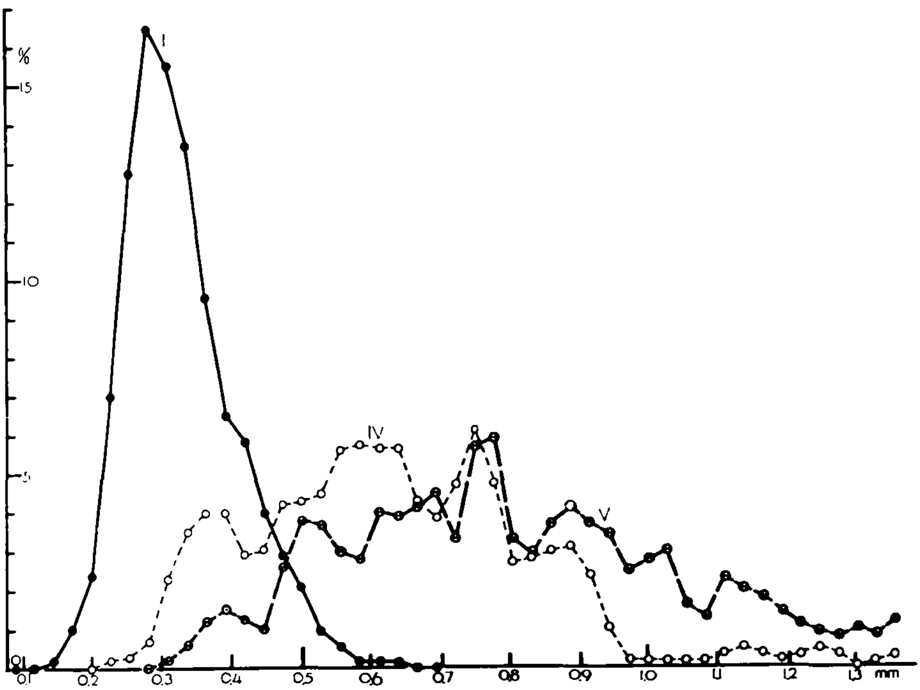

Fig. 6 — Grain-size distributions before (curve I), 3 days after (IV), and 6 days after (V) immersion into water (Experiment (3).

(4) *Sample of snow immersed in water and loaded with a weight.* A metal plate was placed on the top of the sample in order to produce a compressive stress of approximately 100 g-wt/cm^2. In three days, the grains of snow joined and united together, and turned into large grains as shown in figure 7(g). In this figure, the grain *P* consists of more than ten original grains. After one week, the compressed snow transformed into an ice block, and most of air bubbles were entrapped as seen in figure 7(h). Unlike the previous three cases, the apparent snow density increased gradually by plastic deformation due to the load, and finally it approached the density of ice. This type of the metamorphism must play a very important role in the densification mechanism of natural snow or ice formation in the accumulation area of temperate glaciers.

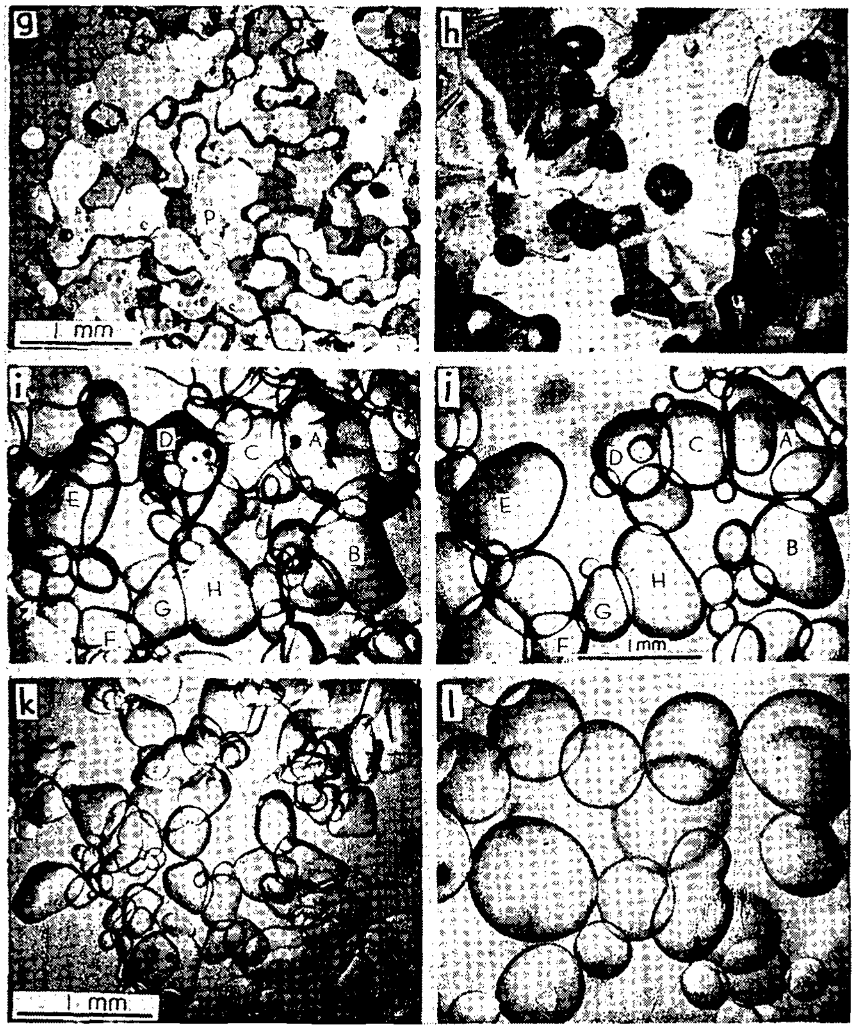

Fig. 7

V. Direct observations

In the experiments described above, the successive stages of the transformation occurring in a wet snow could not be seen directly. In order to observe directly the grain growth or coarsening in water under the microscope, a thin section *K* of fine-grained snow, sandwiched between two glass plates D and E, was soaked in a water-ice mixture in the glass vessel *B*, as shown schematically in figure 8. The whole apparatus was placed on the stage *S* of a polarizing microscope of which the objective lens is labelled *G* in the figure. The experiments were conducted in a room of +1 ~ +4 °C and the temperature of the water surrounding the specimen *K* was maintained at 0 °C by adding continuously pieces of ice to it. Figures 7(i) and (j) show the successive stages

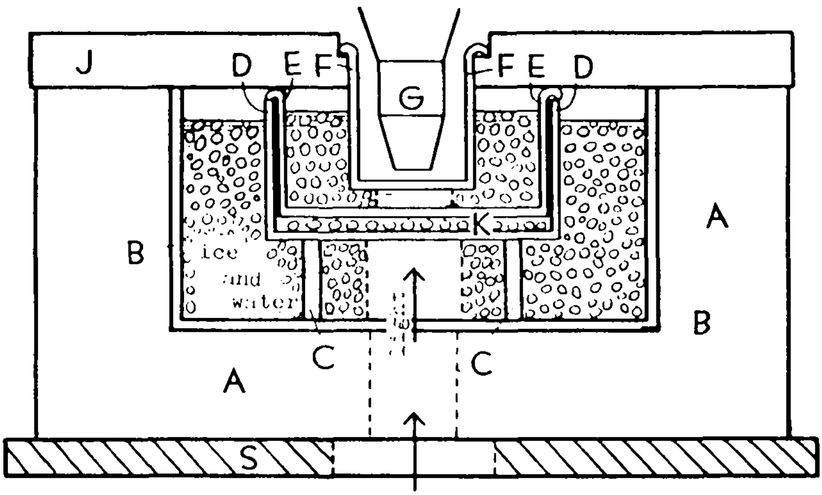

Fig. 8 — Schematic representation of the apparatus used for direct observations on metamorphism of snow immersed in water at 0 °C.

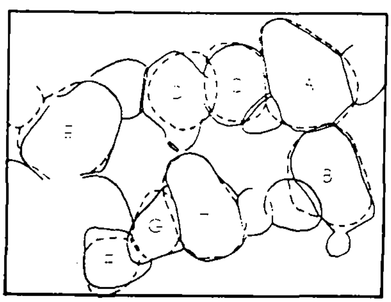

Fig. 9 — Superposition of two photographs (i) and (j) from figure 7. The solid lines indicate the initial ice grains, and the dotted lines indicate the grains 80 minutes after immersion in water at 0 °C.

approximately 80 minutes. Some of the small ice grains seen in (i) diminished in size or completely disappeared in (j). The comparatively large grains, on the other hand, grew in size and their shapes became more spherical. These transformation processes can be seen more clearly by superimposing of these two photographs. The peripheries of representative grains in both (i) and (j) are traced in figure 9. In this figure, the solid lines indicate the initial ice grains, and the dotted lines show the corresponding grains from (j). The last two photographs figures 7(k) and (l) show rapid grain coarsening of crushed snow in water at 0 °C taken 20 seconds and 12 hours respectively after immersion. Note how rapidly the ice grains change in shape and size.

VI. Discussion

On the basis of the experimental results described above, the mechanism of grain coarsening occurring in wet snow will be discussed briefly. As mentioned in Section II, "melting and re-freezing" is the predominant mechanism of producing coarse-grained granular snow at the surface of a snow cover during the melt season. In this process, heat exchange plays the most important role in the process of grain coarsening of wet snow. This process of grain coarsening never occurs in deep wet snow in a snow cover, because no temperature gradient can be present.

The free surface energy of ice grains is responsible for the grain coarsening in wet snow. Strictly speaking, the equilibrium temperature (the melting point) of each ice grain immersed in water is slightly different from 0 °C; the difference ΔT is given by Clausius-Clapeyron's formula: $\Delta T = -2\sigma T(\Delta v/JL).1/r$, where σ is the interfacial energy between ice and water, T the equilibrium temperature of plane ice and water, J the work equivalent of heat, L the latent heat of fusion, Δv the difference between the specific volumes of ice and water, and r the radius of curvature of ice grains.

TABLE I

Lowering of the melting point by the surface tension of the ice grains of diameter D

$D(=2r)$ mm	ΔT °C
0.1	-5.4×10^{-5}
0.6	-1.0×10^{-5}
1.0	-4.8×10^{-6}
2.0	-2.7×10^{-6}

The lowering (ΔT) of the melting point due to the surface tension of ice grains of different sizes are given in table 1, assuming that the ice grains are perfect spheres. The smaller the ice grain, the lower is the melting point. For instance, the melting point of the ice grain of 0.1 mm in diameter is lower than that of 0.6 mm in diameter by 4.4×10^{-5} °C. The difference in the equilibrium temperature of each grain is very small, but it may cause grain coarsening in water of 0 °C at the expense of smaller sized grains. Thus, the total free energy of the ice grains of wet snow in a unit volume is decreased to bring the system closer to the equilibrium state.

VII. Acknowledgements

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REFERENCE

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