The role of meltwater in densification processes of snow and firn

Gorow Wakahama

Abstract. It is well known that meltwater can weaken the mechanical strength of snow and the densification of snow may be accelerated by the existence of meltwater within the snow. Experimental studies on the densification processes and the metamorphism of wet snow containing free water of 0–30 per cent were made both in a snow field and in a cold laboratory. It was found that the rate of densification, density and hardness of snow vary with the lapse of time as the function of free water content of snow. The percolation rate of meltwater in a snow cover was also measured in connection with the free water content of snow.

Microscopic studies on the densification and metamorphism of wet snow were conducted, and 16 mm motion pictures were taken in an effort to clarify the mechanism of densification of snow. In the case of wet snow free from stress, snow grains turned into coarser rounded particles and ice bonds between the snow grains became smaller in number. This may result in the mechanical weakening of the snow. When wet snow was compressed, snow grains were brought closer as packing proceeded, whereby ice bonds between the snow grains grew thicker, until finally they turned into a coherent body of bubbly ice. This may be a predominant transformation process from firn to glacier ice in the accumulation area of a temperate glacier.

Résumé. Il est bien connu que l'eau à l'état liquide diminue la résistance mécanique de la neige de sorte que la densification de la neige peut être accélérée par la présence d'eau. Des études expérimentales des processus de densification et de transformation de la neige mouillée sont menées à la fois sur la terrain et en laboratoire. Il a été trouvé que la vitesse de densification, la densité et la dureté, varient avec le temps comme la teneur en eau libre dans la neige. La vitesse d'écoulement de l'eau de fonte dans un couvert de neige a été également mesurée en relation avec la teneur en eau libre dans la neige.

Des études microscopiques sur la densification et la transformation de la neige mouillée et des observations filmées en 16 mm ont été faites dans le but de vérifier le mécanisme de densification. Dans le cas de neige mouillée et libre de contrainte, les grains de neige se transforment en particules arrondies et le nombre des liaisons entre grains diminue. Il peut en résulter une diminution des caractéristiques mécaniques de la neige. Dans le cas où la neige mouillée est comprimée, les grains sont rapprochés, l'empilement devient plus compact et les liaisons entre grains deviennent plus efficaces: on obtient alors un solide cohérent de glace avec des bulles; cela pourrait être le processus dominant de transformation du firn en glace dans les zones d'accumulation *des glaciers tempérés*.

PERCOLATION OF MELTWATER INTO A SNOW COVER

A snow cover consists of a large number of layers of variously textured snow. Melting of snow begins in early spring at the surface of the snow cover, and meltwater percolates downwards into the whole body of the snow cover. Since the mechanical strength of snow may vary with the free water content of snow, it is important to study the permeation process, distribution and percolation rate of meltwater in snow.

In order to investigate the melting process of snow covers, the general stratigraphy, temperature, density, hardness, tensile strength, grain size and free water content of snow were measured in each layer of the snow covers in mountainous regions in Hokkaido since 1961 (Wakahama, 1963; Wakahama *et al.*, 1968). The free water content of snow was measured at a constant time interval from morning till late at night by the use of a 'combination calorimeter' (Yosida, 1960). Meteorological observations including air temperature, wind speed, solar radiation and net longwave radiation were also made during the period of investigations.

Distribution of free water content in a snow cover

Three diagrams in Fig. 1 illustrate changes in the distribution of free water content in snow covers on flat ground (Fig. 1(a)) and slopes (Fig. 1(b) and (c)). The ordinate gives the height above the ground and the abscissa the time. The free water content is shown by numbers in each contour in per cent.

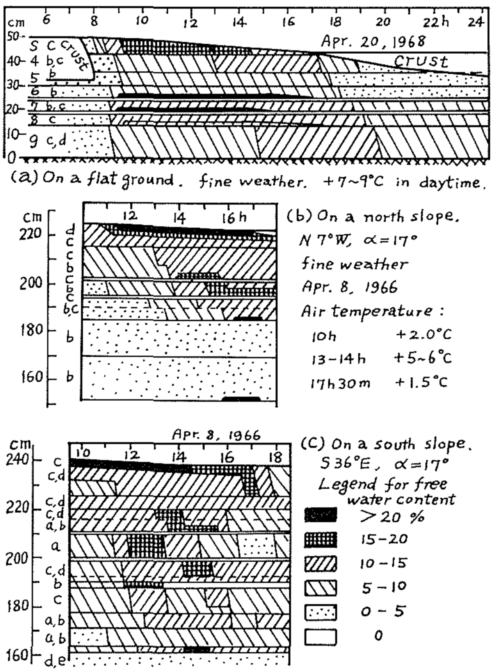

FIGURE 1. Percolation of meltwater into snow covers on flat ground (a), a north slope (b) and a south slope (c). Numbers on the ordinates indicate the height above the ground, and a, b, . . . , show the grain size of snow (Table 1).

Heavy melting took place at the surface in the daytime and meltwater percolated down to the lower layers with the lapse of time. The surface began to freeze at 4.00 p.m. in case of Fig. 1(a) due to the strong longwave radiation from the surface. Even at midnight the snow still contained 5—10 per cent of free water in the lower part of the snow cover.

As seen in Fig. 1(a), layers 6 and 7 held a large amount of free water up to 30 per cent at the bottom of each layer during the daytime. The meltwater was held there due to an abrupt change in the texture of snow. Microscopic observations show that the meltwater is arrested by such a boundary as marks an abrupt change located between fine-grained snow above and coarser-grained snow below. Only a very thin coarse-grained snow layer AB between fine-grained layers as shown in Fig. 2 is sufficient to hold plenty of water above the boundary AA of fine/coarse-grained snow.

Percolation rate of meltwater in snow

There are two modes of percolation of meltwater in snow: (i) 'channelled-water flow', in which meltwater flows down rapidly through snow as a continuous body of water, filling the voids among snow grains as shown in Fig. 3(a); (ii) 'water-film flow', in which meltwater flows down slowly covering ice grains of snow in the form of a thin film which is from several to about 20 microns in thickness as shown in Fig. 3(b).

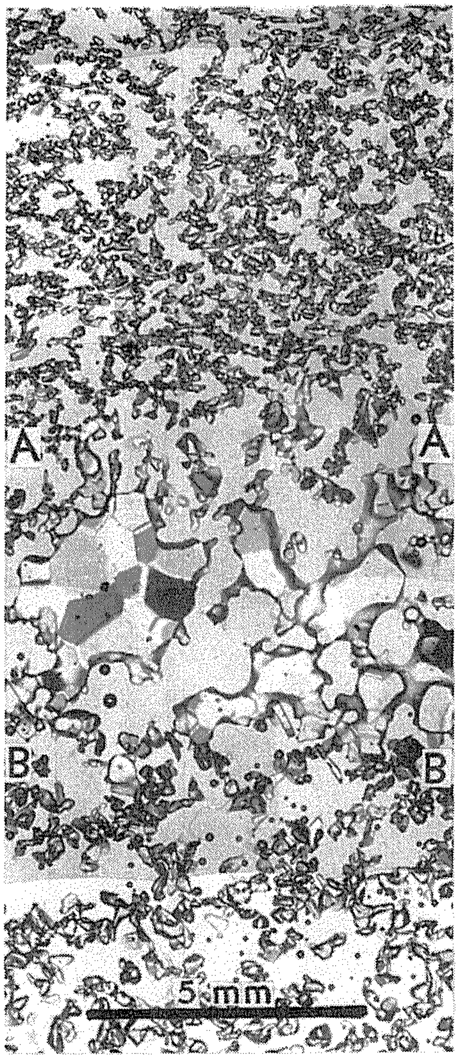

FIGURE 2. A vertical thin section of snow. A thin coarse-grained snow layer AB is sandwiched between fine-grained layers. The fine/coarse boundary AA can hold plenty of water above it.

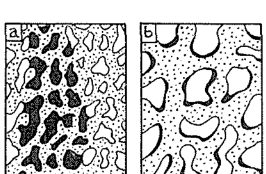

FIGURE 3. Schematic representation of channelled water flow (a), and water-film flow (b) in fine-grained snow. Dotted and dark portions respectively indicate snow grains and water.

Channelled-water flow

The percolation rate of channelled-water was directly measured in various types of snow. The observed values V were 1.2–1.3 cm/s for fine-grained snow and 2–3 cm/s for coarse-grained snow, which are listed in the fourth column of Table 1. Yosida (1965) described the percolation processes of meltwater in a snow cover for channelled-water flow. In a fine-grained snow layer of 0.2–0.5 g/cm^3 in density, he obtained a value in the order of 1 cm/s as the percolation rate of channelled-water flow, which agrees fairly well with the observed values obtained for the fine-grained snow by the present author.

TABLE 1. Percolation rate of meltwater within snow

Grain size*	Snow density (g/cm^3)	Free water content (per cent)	Channelled-water flow (cm/s)	Water-film flow (cm/min)		Author
			V	$\bar{u}$	u^*	
b	0.54	15	1.3	3.4	0.71	
b	0.48	15	1.2	3.2	0.56	
b	0.58	16	1.5	3.9	0.72	Wakahama
c	0.54	15	1.5	2.3	2.0	(1968)
c and b	0.51	13	1.6	2.4	0.8	
c and b	0.45	15	2.1	4.1	5.4	
d and c	0.53	15	2.6	2.9	7.5	
b	0.52	12 ~ 15		0.1 ~ 0.3		Fujino (1968,
c		15		0.5 ~ 1.8		1971)
b, c		16		0.4		
b, c	0.47	13		0.1		
		8.7		0.01		
		17		0.7		Kobayashi
c	0.47	14		0.1		(1973)
		9.5		0.003		
b, c	0.37	7.3		0.4		
b	0.44	6.8		0.3		

* a, <0.5 mm; b, 0.5–1 mm; c, 1–2 mm; d, 2–4 mm; e, >4 mm.

Water-film flow

The mean speed $\bar{u}$ of meltwater percolating in the form of a 'water film' covering ice grains of snow was measured *in situ*. The mass flux Q of the water film flowing down through a unit area of snow in a unit time can be expressed as $Q = (\pi/4)\,\rho(\bar{u}.\ S.\bar{\delta})$, where ρ, S and $\bar{\delta}$ are respectively the density of water, the specific surface of the snow and the mean thickness of the water film. $\bar{\delta}$ can be calculated from the formula $\bar{\delta} = (\rho_w . w)/(\rho . S)$, where ρ_w and w are respectively the wet density and free water content of snow. These two relations give $Q = \pi/4(\bar{u}.\rho_w . w)$. The mass flux Q, together with ρ_w and w, was measured *in situ* for various kinds of snow. The obtained values $\bar{u}$ were listed in the fifth column of Table 1. Yosida (1965) discussed the percolation rate, u^*, of water-film flow, and obtained a formula $u^* = \rho g \delta^2/3\mu$, where ρ, g and μ were respectively the density of water, the acceleration of gravity and the viscosity of water. Given in the last column of Table 1 are the values of u^* calculated from this formula. The observed and calculated values are in good agreement in the case of coarse-grained snow, while they disagree for fine-grained snow.

Fujino (1968, 1971) measured the electric conductivity of snow in which a dilute NaCl–water solution was flowing down as a water film and obtained $\bar{u}$. Recently, Kobayashi (1973) measured $\bar{u}$ in the laboratory by a similar method to the one mentioned in the foregoing paragraph. The results obtained by these authors are also tabulated in Table 1.

DENSIFICATION RATE AND MECHANICAL WEAKENING OF WET SNOW

The densification rate of wet snow layers was measured *in situ* and the compactive viscosity of snow defined by Kojima was obtained (Kojima, 1955, 1956). It was found that the densification rate of the upper snow layers in the daytime was more than two times larger than that at night. The daily variation in the densification rate might be attributed (1) to the decrease of overburden pressure at night due to a runoff of meltwater from the snow cover, and (2) to the mechanical weakening of snow in the daytime.

The decrease of overburden pressure at night due to the runoff was estimated as 10 per cent at most, which means this is not primarily important in the decrease of densification rate.

As a measure of the mechanical weakening of snow, Kinosita's hardness (Kinosita, 1960) of wet snow was measured with the lapse of time as the function of free water content of snow. The hardness at the surface layer remarkably decreased in the daytime: it was 1×10^4 g/cm^2 before melting in the morning, dropping down to 2×10^2 g/cm^2 around noon, when the free water content was 20–25 per cent. This is due to the breakdown of ice bonds between snow grains by the strong solar radiation. The hardness increased with the decrease of free water content in the afternoon by the refreezing of grain boundaries in ice bonds between snow grains. The same tendency was observed in snow layers down to 25 cm below the surface, though it was weaker in deeper layers.

Penetration of solar radiation into deeper snow layers such as at 20 cm in depth is very small. A rough estimation shows that the snow melted by the absorbed solar radiation is of the order of 2×10^{-4} g cm^{-3} day^{-1} at a depth of 20 cm and 1×10^{-7} g cm^{-3} day^{-1} at 50 cm in depth. However negligible these amounts may look they contribute greatly to the mechanical weakening of snow as explained below.

When the ice is kept at 0°C, a part of grain boundaries in the ice where more than two boundaries meet is melted and the greater part of the boundaries become so susceptible to any incoming energy that they start melting the instant even a very small amount of heat is supplied. This is because the free energy of the grain boundaries is slightly larger than that of the ice bodies (Nye and Mae, 1972). Only a small amount of solar radiation which has penetrated into deep wet snow layers may, therefore, cause the melting of grain boundaries in ice bonds between snow grains, which may result in the mechanical weakening of snow in the daytime. This was verified by the microscopic observations of snow samples immersed in water of 0°C: grain boundaries in ice bonds were easily melted and ice bonds were broken by only weak radiation from the light source of the microscope.

MICROSCOPIC OBSERVATIONS OF DENSIFICATION PROCESSES AND METAMORPHISM OF WET SNOW

Microscopic studies on the densification processes and the metamorphism of wet snow were conducted, and 16 mm motion pictures were taken to observe changes in the texture of snow in detail. This film was exhibited at the Symposium and showed the following phenomena: (1) when the snow was immersed in water of 0°C, relatively larger grains grew into coarser rounded ice particles at the expense of smaller ones which became smaller and smaller and finally disappeared; the total number of the snow grains thus decreased with the lapse of time, and the spherical ice particles of approximately 1 mm in diameter remained in water (Wakahama, 1967), (2) the average linear growth rate of snow grains was 0.02 mm/h just after the start of the experiment, which gradually decreased until 3 days after the start of the experiment, when the growth practically finished as shown by curve c in Fig. 4, (3) ice bonds between snow grains became smaller in number with the lapse of time, which may result in the mechanical weakening of snow as reported in the second section, (4) when wet snow was compressed, rounded snow grains relatively displaced each other gliding at the ice bonds and a closer packing of snow grains proceeded. No appreciable

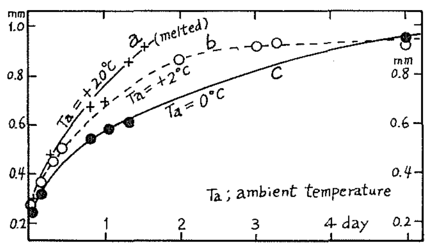

FIGURE 4. Grain growth of snow particles immersed in water of 0°C. The growth rate was larger when the ambient air temperature was higher (curves a and b), and the minimum growth rate was observed in the equilibrium condition (curve c).

deformation in snow grains was found during the packing process until the closest packing was completed. Then, heavy distortion took place in snow grains and ice bonds grew thicker. A whole body of wet snow finally turned into a coherent body of bubbly ice and grain coarsening took place as the result of recrystallization of ice. This may be a predominant transformation process from firn to glacier ice in the accumulation area of a temperate glacier.

It was found that grain growth took place even in the melting process of snow, and that the growth rate was larger than that obtained in the equilibrium condition: the growth rate in this case was approximately 50 per cent larger (curve a) than that obtained in the cold room of 0°C (curve c). The grain growth was observed just before the whole snow samples in the jar were completely melted away as shown by curve a in Fig. 4.

In order to clarify the effect of impurity on the metamorphism of wet snow, a small amount of NaCl was put in a snow–water mixture. The growth rate became smaller when NaCl concentration was larger than 0.1 g/l, whereas it became larger if the concentration was less than 0.1 g/l (Wakahama and Tusima, 1974).

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DISCUSSION

L. A. Lliboutry:
The idea that temperate firn turns into ice faster when water is abundant has been proved by measurements on the Vallée Blanche (Mt Blanc, French Alps) at 3550 m. The firn there is about 30 m thick, so its bottom is always at the melting point. The transformation of firn into about 3.5 m of ice each year happens almost entirely in summer, when an aquifer exists at the firn–ice interface. (See a paper by Vallon, Petit and Fabre submitted for publication to *J. Glaciol.*)

K. F. Voitkovsky:
I would like to know some details of the method of taking motion pictures of changes in the texture of snow.

G. Wakahama:
A small amount of crushed snow particles was sandwiched by two glass plates, which were immersed in water at 0°C. In order to keep the snow sample and water at 0°C during the experiment, they were placed in a vessel made of ice and an ice lid was placed on it. The ice box was placed in an acrylite vessel, which was put on the stage of a polarizing microscope. The whole system was placed in a cold room kept at 1 to 2°C, so that the ice box and ice lid were melting very slowly from outside, which allowed us to keep the snow sample at 0°C during the experiment. Sixteen millimetre motion pictures were taken at a constant time interval of 30 s or 1 min and sometimes 2 min by the use of an automatic timer attached to a cine-camera (Bolex). The lighting was synchronized at the time of exposure.