Studies on Heat Balance on Natural Snow Surfaces and Promotion of Melting of Snow

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Abstract

The heat which is required for snow melting may be separated into measured values of the net rediation S_o and the calculated quantity of transfer of atmospheric real and latent heat Q. The corelation of the above two items has been investigated for about half a month. The results of the investigation show that the theory of turbulent exchange on snow surfaces by Sverdrup is applicable in the field. The distribution of heat for melting snow is $S_o : Q = 36 : 64$.

The degree of promotion of snow melting M_p (mm) when black powder is scattered is given as the function of the solar radiation Rs (cal/cm²) in the following formula.

$$\sum M_p = m(\sum R_s)^n, \quad m = Ae^{-Bx}, \quad n = Cx^D$$

$$20 > x > 3 \text{ g/m}^2 .$$

Coefficients m and n are determined according to the quality and quantity x of the black powder to be scattered. Each of A, B, C and D is constant based on the quality of the black powder.

Introduction

Promotion of snow melting is an important technique for the stable cultivation of crops and increase of agricultural production in snowy districts in Japan. As a method of melting snow, black powder is scattered on the snow surface and is considered to be effective. Research on the actual atmospheric condition on the snow surface, and determination of the type and the amount of the powder to be scattered are the subjects which require close investigation for efficient promotion of snow melting. In this paper, the heat balance on the surface of melting natural snow is discussed first, and then the experimental results of research into the relation between the degree of snow melting and the type and quantity of powder are mentioned.

I. Heat Balance at the Natural Snow Surface

1. EXPERIMENTAL PROCEDURE

In order to investigate the heat balance on the natural snow surface, the quantity of net radiation S_o was measured during a period from March 1, 1965 to March 17, 1965 at Takada, Niigata Prefecture. The apparatuses for the measurements were windproof radiation meters consisting of two sets of thin poliethylene hemispheres which covers the element receiving radiation. Through this thin membrane a radiation of a wave length of 0.3−80 μ can penetrate. To prevent adhesion of falling snow, air is blown around the enclosure, and to prevent moisture and frost, silicagel is enclosed in the hemisphere. The temperatures of the upper and lower elements are measured and corrected by thermocouples.

The quantity of heat transfer in the atmosphere Q was calculated by the next formula every three hours. The temperature and the vapor pressure at a height of 1.5 m above the snow surface were observed in a shelter, and wind velocity was observed at 15 m above the snow surface.

$$Q = L + lE\,.$$

where

$$L = h(\theta_a - \theta_s) \qquad \text{cal/cm}^2\cdot 3\,\text{hr},$$
$$lE = k(e_a - e_s) \qquad \text{cal/cm}^2\cdot 3\,\text{hr},$$

θ_a, θ_s is air temperature (1.5 m above the snow surface) and snow surface temperature,
e_a, e_s vapor pressure in θ_a and saturated vapor pressure in θ_s,
h coefficient of transfer of real heat cal/cm²·3 hr·°C,

$$h_1 = 0.875\,U_a\,, \qquad \text{for} \quad U_a > 2.2\ \text{m/sec},$$
$$h_2 = 0.875\{1 + 2.03(2.2 - U_a)^3\}\,U_a, \qquad \text{for}\ 0.5 < U_a < 2.2\ \text{m/sec}\,,$$

k coefficient of transfer of latent heat cal/cm²·3 hr·°C,

$$k = 1.53\,h \qquad \text{for sublimation},$$
$$k = 1.74\,h \qquad \text{for condensation},$$

U_a wind velocity at anemometer-level.

The determination of h and k will be treated later.

The amount of permeation was measured by placing pans filled with sand on the ground and setting the orifice of permeation meters at 10 cm above the ground. The amount of permeation was used in comparing it with the corresponding amount of melted snow.

2. EXPERIMENTAL RESULTS

The value of S_o and Q. The net radiation of S_o was measured every twenty minutes and summed up for every three-hour-period. Compared with Q through all the periods, this is given in a curve in Fig. 1.

It was observed that S_o showed distinct daily variations according to the weather, and out-going radiation from the snow surface continued to be predominant through almost every night, indicating that the net radiation was zero or a negative value close to zero when snow was falling. Even in the daytime when snow was falling, S_o was near zero of sometimes negative because of a small amount of solar radiation and great albedo of snow.

lE, the quantity of transfer of latent heat containing heat transfer in the air, was found to be almost always negative, and this means that evaporation or sublimation was occuring from the snow surface. In the latter half of the experiment, condensation was sometimes recognized in the daytime.

From the results of the experiment the daily amount of S_o for each day is listed

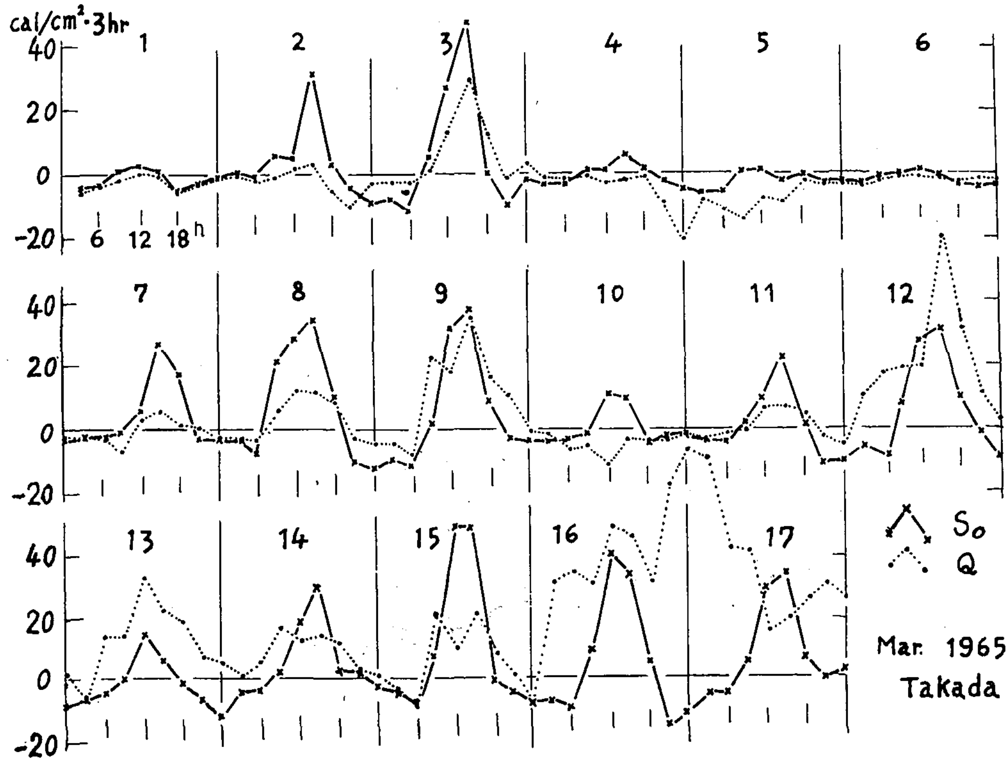

Fig. 1. Relation between observed net radiation S_a and calculated real and latent heat Q at the snow surface (every 3 hours)

in the left side of Table 1.
As seen at the bottom of the table, the rate of heat distribution for snow melting during this period is thus:

$$S_o \cdots\cdots 36\%, \qquad Q \cdots\cdots 64\%.$$

The experiment by Yoshida (1962) in 1958 at Tadami, which is in the same latitude as Takada, showed almost the same results:

$$S_o : Q = 35 : 65.$$

The amount of melted snow M. As the indirect indicator of M, the change in the amount of permeation for every three hours is given in Fig. 2. During the experiment the depth of snow cover measured up to 20–60 cm. Accordingly, when the snow was composed of zarame yuki (granular snow) the water which was produced by melting of snow easily flowed down to the ground and was measured as the permeation water. But when it was composed of new snow or settled snow which can retain much water, the water stayed in the snow and did not permeate.

From the quantity of incoming heat on the snow surface, the equivalent of melted snow was calculated and shown in the same figure, which indicates that the peaks of the amount of equivalent snow melt appear in a good correlation with those of permeating water, and that each of the latter usually follows the peak of the former with

Table 1. Observed data and estimated value of snow melt

Date* Mar.	Q cal/cm²	S_o cal/cm²	$Q+S_o$ cal/cm²	$(Q+S_o)/8$ mm	e mm	M' mm	P mm	R_w mm	R_m mm	E_m mm	M mm
1	−23.4	−13.3	−36.7	−4.6	−0.6	−5.2	3.3			−1.3	2.0
2	−18.9	+33.9	+15.0	+1.9	−1.0	+0.9	6.2			−1.3	4.9
3	+52.3	+52.2	+104.5	+13.0	−0.6	+12.4	18.1	−4.3	−0.2	−1.2	12.4
4	−40.3	−1.2	−41.5	−5.2	−0.7	−5.9	4.5	−1.6	0.0	−1.2	1.7
5	−58.0	−18.9	−76.9	−9.6	−1.1	−10.7	2.3			−1.2	1.1
6	−13.9	−13.2	−27.1	−3.4	−0.3	−3.7	2.2			−1.2	1.0
7	− 6.6	+38.1	+31.5	+3.9	−0.9	+3.0	2.0			−1.2	0.8
8	+22.9	+58.7	+81.6	+10.2	−0.4	+9.8	6.6			−1.1	5.5
9	+87.8	+55.5	+143.3	+17.9	−0.7	+17.2	20.0	−5.5	−0.9	−1.1	12.7
10	−35.7	+3.4	−32.3	−4.0	−0.5	−4.5	5.9	−0.9	−0.1	−1.1	3.8
11	+4.5	+11.3	+15.8	+2.0	−0.5	+1.5	4.6			−1.1	3.5
12	+169.9	+52.9	+222.8	+27.9	−0.3	+27.6	20.9	−4.6	−1.3	−1.1	13.9
13	+117.0	+8.3	+125.3	+15.7	−0.1	+15.6	18.6	−4.5	−1.1	−1.1	11.9
14	+74.5	+54.8	+129.3	+16.2	−0.3	+15.9	15.7			−1.0	14.7
15	+51.4	+101.3	+152.7	+19.1	−0.9	+18.2	16.9			−1.0	15.9
16	+362.9	+69.5	+432.4	+54.1	+0.4	+54.5	45.2			−1.0	44.2
17	+279.0	+95.6	+374.6	+46.8	−0.3	+46.5	41.0	−1.5	0.0	−1.0	38.5
Total	+1025.4	+588.9	+1614.3	+201.9	−8.8	+193.1	+234.2	−22.9	−3.6	−19.2	+188.5
Ratio	64	36	100%								

Q : Caluculated value of transfer of real and latent heat
S_0 : Observed net radiation
e : Evaporation or condensation
M' : Quantity of the equivalent of snow melt
P : Permeated water
R_w : Permeated water by rain
R_m : Snow melt by rain
E_m : Snow melt by heat transfer from the ground
M : Quantity of the snow melt at snow surface $=P-(R_w+R_m+E_m)$
* From 00 to 24 hr.

a short phase lag. In the quantity of permeating water, thaw water produced by rain and the heat conducted from the ground are contained. Examining the data of meteorological observation, it is known that the peaks, which do not correspond to the curve of incoming heat, are caused evidently by the permeating water by rain or sleet. And the reason why the quantity of the permeation water did not change on Mar. 7 in spite of a fairly large amount of incoming of heat is because, the water which was generated by melting of the snow surface was held within the thick new snow. On that day the new snow measured up to 37 cm in thickness and the water holding capacity of the snow was 20–40 mm. The equivalent snow melt by incoming heat on this day was 3.8 mm. So it is evident that the water did not penetrate down to the surface of the ground. It is also possible that the heat was consumed to raise the temperature of

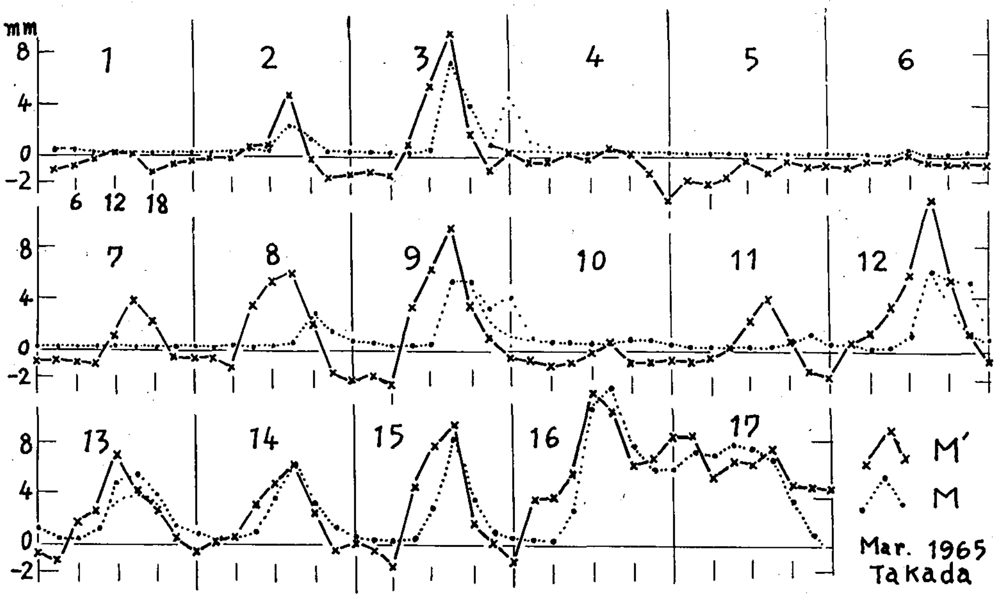

Fig. 2. Comparison of the quantity of the equivalent of snow melt M' and permeated water by snow melt M at snow surface (every 3 hours)

the snow to 0°C. But this may almost be insignificant because the heat for raising snow temperature 0.5 cal/g·°C is negligible when compared with the amount of heat consumption for melting snow at a rate of 80 cal/g. The same tendency was observable

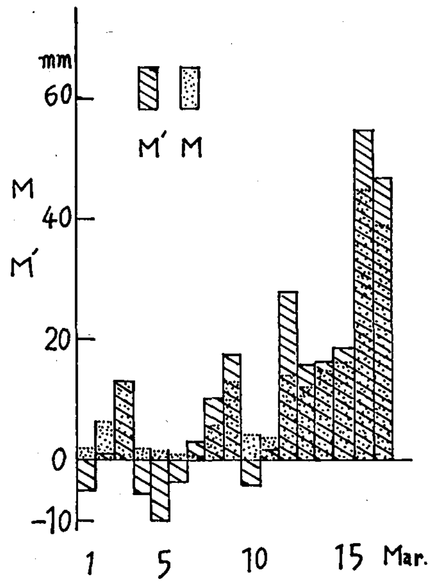

Fig. 3. Relation between the equivalent of snow melt M' and permeated water by snow melt M at snow surface

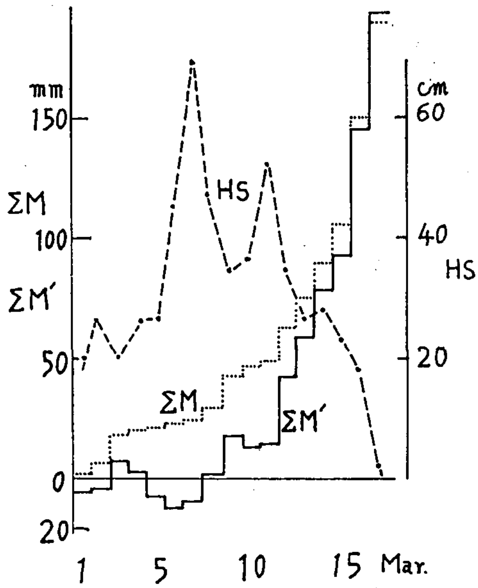

Fig. 4. Variation of $\sum M$, $\sum M'$, and snow depth HS with time

on Mar. 8 and Mar. 11. On Mar. 8, no new snow fell, but there was a layer of settled snow measuring up to 35 cm, and on Mar. 11, 21 cm thick new snow deposit existed.

Incoming of heat at snow surface and the amount of melted snow. The permeating water which was not produced by the melting of snow at the surface was separated and is listed in the right column of Table 1, and then the amount of actually melted snow at the surface was compared with the equivalent of melting calculated from the amount of incoming heat. Their daily amounts, given in Fig. 3, do not exactly coincide with each other. The first reason for this is that the water generated from snow melting at the surface is held in the snow and can not be measured as permeation water, but flowed down later the next day. The second reason is that negative quantity of heat balance cools down the upper snow layer and changes the water containing layer into a refrozen snow layer. To melt this frozen layer again, the corresponding amount of heat that was necessary for freezing is also required the following day.

Accordingly, the amount of the melted snow estimated by the total heat income throughout the 17 day period must coincide with the total amount of actually melted snow during the same period (*cf.* Fig. 4).

Determination of h and k. Many studies have been made on h and several different values have been presented according to their conditions. A theoretical study of the coefficient in transfer of heat (coefficient of turbulence exchange) was made by Sverdrup and the theory was applied in many reports.

$$h = C_p \frac{\rho K_0^2}{\ln \frac{a}{z_0} \ln \frac{b}{z_0}} U_a . \qquad (1)$$

C_p is specific heat of air at constant pressure $= 0.24$ cal/g,
ρ density of air $= 0.00129$ g/cm^3,
K_0 Karman's coefficient $= 0.38$,
U_a wind velocity at anemometer-level,
z_0 roughness parameter at snow surface $= 0.25$ cm,
a, b elevation of anemometer and hygrothermograph.

The values of h which have been reported by different investigators as different functions of U_a are listed in Table 2. The values of h' in Table 2 are the theoretical ones derived from eq. (1) for the cases when a and b are known or can be estimated.

In the case when a function h (U_a) consists of a term with U_a and another term without U_a, the value of the term of U_a is found to be approximately equal to h'. This is considered to mean that h can be obtained from the theoretical formula (1) when the wind velocity is not weak. The conditions required for eq. (1) are that the atmosphere is of normal state and the wind velocity is not weak. This sustains the conclusion mentioned above, so, in this experiment, h for a case when the wind velocity is greater than a certain value, can be obtained by the following formula, which is derived from eq. (1).

$$h = 0.81\, U_a \times 10^{-4}\ \text{cal/cm}^2\cdot\text{sec}\cdot{}^\circ\text{C} \qquad (a = 15\ \text{m},\ b = 1.5\ \text{m})$$
$$= 0.875\, U_a\ \text{cal/cm}^2\cdot 3\ \text{hr}\cdot{}^\circ\text{C} \qquad (\ ,,\ \ ,\ \ ,,\ ).$$

According to the diffusion of heat from quiet air to snow surface, Oguchi (1954)

Table 2. Coefficient of turbulent exchange of real heat transfer, h and h' in cal/cm²·sec·°C

No.	Author	Year	$h\times10^{-4}$	a	b	$h'\times10^{-4}$	Remarks
1	Angstorm, A.	1934	$1.12\ U_a$	320	190	$0.95\ U_a$	field
2	Sverdrup, H. U.	1935	$1.0\ U_a$	310	190	$0.95\ U_a$	field
3	Wilson, W. T.	1941	$0.36\ U_a$	—	—	—	
4	Yosida, Z.	1950	$1.11+3.78\ U_a$	15	5	$3.65\ U_a$	indoor
5	Oguchi, H.	1954	$1.78+7.22\ U_a$	—	—	—	
6	Shidei, T.	1955	$1+0.52\ U_a$	—	—	—	indoor
7	Ito, N.	1957	$0.94\ U_a$	350	250	$0.76\ U_a$	field
8	Namekawa, T.	1958	# $4.96\ U_a$	—	—	—	field
9	Marumoto, M.	1958	* $4.5+0.3\ U_a$	—	—	—	indoor
			** $5.0+0.6\ U_a$				
10	Ishii, S.	1959	$1.19\ U_a$	150	150	$1.09\ U_a$	field
11	Yoshida, S.	1962	† $0.85\ U_a$	700	120	$0.92\ U_a$	field
			‡ $0.85\{1+2.03(2-U_a)^3\}\ U_a$				
12	Nakagawa, M.	1964	# $4.3\ U_a$	—	—	—	field
13	Nakamura, S.	1964	$1+0.4\ U_a$	—	—	—	mean

U_a Wind velocity at anemometer level m/sec, # surmised value,
* for zarameyuki (granular snow),
** for shimariyuki (settled snow),
† $U_a>2.0$ m/sec, ‡ $0.5<U_a<2.0$ m/sec.

determined the constant term under a condition of $h=0.64$ cal/cm²·hr·°C. Yoshida (1962) made the following formula from the results of an open air experiment at Tadami.

$$h=0.85\{1+2.03(2-U_a)^3\}\,U_a\times10^{-4}\ \text{cal/cm}^2\cdot\text{sec}\cdot{}^\circ\text{C}$$
$$0.5<U_a<2.0\ \text{m/sec}\,.$$

In this experiment, Yoshida's method was adopted, because Yoshida's empirical formula was considered to fit more precisely in the case of a slight wind. In Yoshida's experiment the maximum wind velocity was 2.0 m/sec at the anemometer-level of 7 m above the ground. The wind velocity at the anemometer-level of 15 m may be 2.2 m/sec according to W. Paesechke's study on vertical distribution of wind on a snow field.

$$h=0.875\{1+2.03(2.2-U_a)^3\}\,U_a\ \text{cal/cm}^2\cdot3\ \text{hr}\cdot{}^\circ\text{C}$$
$$0.5<U_a<2.2\ \text{m/sec.}$$

Considering that the transfer of water vapor in the atmosphere occurs in the same way as heat transfer, the coefficient k of heat transfer caused by sublimation or condensation may be expressed, in relation to h, as follows:

$$k_s=1.53\,h\ \text{cal/cm}^2\cdot3\ \text{hr}\cdot{}^\circ\text{C} \qquad \text{for sublimation}$$

and

$$k_c=1.74\,h\ \text{cal/cm}^2\cdot3\ \text{hr}\cdot{}^\circ\text{C} \qquad \text{for condensation,}$$

using the mean atmospheric pressure at Takada 1 016 mb, the latent heat of sublimation of ice at 0°C, 677 cal/g, and the latent heat of water vapor for condensation at 0°C, 597 cal/g.

II. Promotion of Snow Melting

1. OBJECT OF THE EXPERIMENT

The amount of melted snow at natural snow surface (M mm) is represented in the following formula:

$$M=\{R_s(1-\alpha)-R_e+Q\}/8\,. \qquad (2)$$

R_s is solar radiation (short wave) cal/cm², α albedo of short wave,
R_e effective radiation (long wave) cal/cm², Q heat transfer in atmoshere cal/cm².

If black powder is scattered on a snow surface and the albedo is lowered to α_p, the amount of melted snow (M_p) promoted by the powder (the amount of the melted snow compared to natural melting of snow) is represented as:

$$M_p=\{R_s(\alpha_p-\alpha)+\beta\}\,/8\,, \qquad (3)$$

where β is the change in the amount of melted snow due to the variance of R_e and Q in the process of $\alpha\to\alpha_p$.

If the scattered powder is as fine as carbon black, and is not great in quantity (5–20 g/m²), the temperature of snow surface in such a case is considered to show no differnce from that of natural snow surface. Accordingly there will be no great variation in R_e. Small cavities are also observable around the powder in melting snow. For this reason the roughness changes, but not so greatly as to change to turbulent exchange and it will not increase the effective surface area. If the snow melting increases, there will be seen some changes in the atmospheric condition at the snow surface according to the variation of the amount of evaporation and condensation.

But considering the condition that the temperature at snow surface is 0°C, no great difference will be seen. Magono *et al.* (1954) obtained the results that when soil dust d l/m² was scattered, snow melting by the atmospheric temperature was $0.3\,d$ times less in amount than the amount of melted snow at natural snow surface. The theoretical reason of this is not clear, but in any event the amount of carbon black used by the author is 1/100 of that of the soil dust for Magono's experiment. Azuma *et al.* (1958) made an experiment investigating the change of meteorological conditions by scattering carbon black on a snow surface and making it black. But no revelation of systematic difference was seen. For this reason β in the formula (3) can be regarded omittable practically, and then the next formula (4) is obtained:

$$M_p=R_s(\alpha_p-\alpha)/8\,. \qquad (4)$$

The formula (4) represents the promotion of snow melting at a certain period. α on natural snow surface tends to lessen if there is no new snow or freezing of the surface.

On the other hand, as is often observable, the powder scattered shows a tendency of grouping, and the rate of covering snow changes, and α_p tends to decrease as the time passes. So $\sum M_p$ few days after the scattering can not easily be formularized, because no clear theory concerning the variation of α and α_p is available. Their relationship was investigated in this experiment.

2. EXPERIMENTAL PROCEDURE AND SPECIMEN

The powder scattered on the snow surface in this experiment consisted of nine kinds of carbonaceous powder as shown in Table 3. The amount of scattering is divided

Table 3. Characteristics of powder

Powder symbol	Bulk density	Angle of repose	Reduction by drying %	Settlings to water %	Carbon content %	Mixture	Percentage of grain size (mesh)				
							<32	32< <55	55< <120	120< <250	250<
C 1	0.28	50°	3	0	100			1	8	46	45
C 2	0.44	45	3	75	50	Clay		1	14	60	25
C 3	0.45	50	4	30	52	Bentnite		1	5	52	42
C 4	0.45	45	2	40	46	Slaked lime		1	12	20	67
S 1	1.09	35	2	30	24	?			2	14	85
S 2	0.94	40	1	35	24	?			3	46	51
T	0.66	40	6	80	100		2	27	45	13	13
CD	0.15	40	4	0	100		1	10	50	16	23
CS	0.43	40	4	95	100		4	13	42	18	23

into six grades (1, 3, 5, 7, 10 and 20 g/cm²) respectively, and 54 sections of 1 m² were made.

The degree of subsidence at snow surface caused by snow melting and the surface density of snow were observed at nine o'clock every day, and from these the daily amount of melted snow was calculated. M_p was obtained by subtracting the daily amount of melted snow on natural snow surface from that on the snow surface with black powder.

3. EXPERIMENTAL RESULTS AND CONSIDERATION

M_p was regarded as the function of R_s according to eq. (4) and their relation (*cf.* Fig. 5. was given in the following formula:

$$\sum M_p = m(\sum R_s)^n , \tag{5}$$

where m and n are coefficients affected by the amount of the scattered powder (x). A coefficient m shows the character of promotion of snow melting in the early stage, and n shows the character of the changes in the promotion with the increase of $\sum R_s$, that is to say with the days elapsed. This n is considered to show the durability of efficiency in promotion of snow melting.

The relations between m, n and the amount of scattered powder (x g/m²) are given in Fig. 6. The coefficient m becomes maximum when x is about 2 or 3, and then it decreases according to the increase of x, taking the form of $m=Ae^{-Bx}$. The other constant n is found to be related to x by $n=Cx^D$.

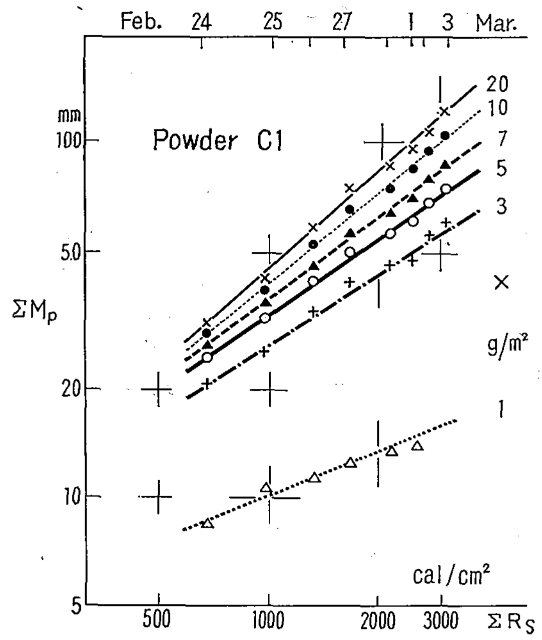

Fig. 5. The relationship between the promoted snow melt M_p and solar radiation R_s. x: Amount of scattered powder (parameter)

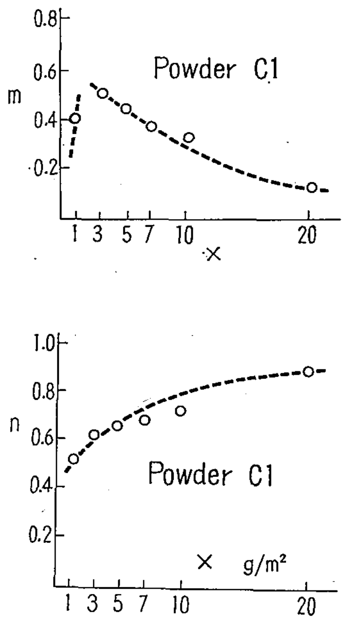

Fig. 6. m and n as a function of the amount of scattering powder x

The variation of m and n with x will be explained as follows. If the powder warmed by the sun melts the snow around it only by heat conduction, m may increase along with x. But in the present experiment m shows a tendency of becoming rather smaller. The reason for this fact may be explained as follows. If a large amount of powder is scattered within the range of influence of long wave radiation from a black particle (such cases are seen, for instance, in the hollows around the trees caused by snow melting), the radiant heat will be consumed by warming the powder instead of the melting snow. In such a case the heat of the warmed powder is radiated upward and transfered to the atmosphere, which means a loss of heat for snow melting. And so the above mentioned radiant heat surpasses the conduction heat from the powder to snow. If x is especially small, it means that the powder is thin at the snow surface, and as its influence cannot cover the whole area of the snow surface of the test site, m decreases.

The increase of n along with x will result from the fact that the more the amount of scattered powder is, the greater the number of cohered powder lumps becomes. It also will result from the fact that if the powder is scattered thickly, it cannot easily flow down into the snow layer, much of it being kept on the snow surface.

4. JUDGEMENT OF EFFICIENCY IN PROMOTION OF SNOW MELTING

The usual way of judging the efficiency in snow melting up to this time has been to scatter a certain amount of powder on snow surface and then examine the degree of subsidence after a short period. But according to the results of the above observation, the durability of the efficiency must be taken into consideration.

When both m and n are great, there will be a greater effect. But when merely the efficiency of snow melting is expected we should choose a powder with greater m and when the durability of the effect is needed, it would be better to use a powder with a greater n. Generally speaking, the powder with a great n is more effective in the promotion of snow melting even if m is rather small.

In order to know the concrete comparative merits, the number of days which was required for reducing the efficiency of snow melt ($\sum M_p/\sum R_s$) to a half of its initial value was also obtained by this experiment (Ônuma *et al.*, 1964).

Acknowledgments

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