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Studies of Snow Transport in Low-Level Drifting Snow*

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Abstract

The snow-drift observations were performed as regards snow-drift by noting the surface drift which contributed significantly to the total amount of snow-drift and to the drift formation. The following results are obtained:

(1) Drifting snow near the snow surface is transported mainly by saltation motion at the wind speeds lower than 10 m/s (1 m level).

(2) The mean length of saltation paths of snow particles ranges from 5～14 cm (wind speed: 5 m/s) to 11～30 cm (10 m/s) and the rebound mass of drifting snow on the snow surface ranges from about 10^{-3} g/cm^2·s (5 m/s) to 4×10^{-3}～2×10^{-2} g/cm^2·s (10 m/s).

(3) The maximum snow-drift rate is represented by the simple equation $Q=0.03\,V^3$ $(5<V<12$ m/s), where Q is the snow-drift rate in g/m·s and V is the wind speed in m/s.

(4) The snow-drift is developed to the 90% of the saturated value of the drift rate in a length of 30 to 60 m.

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北海道大学審査学位論文

I. Introduction

In snow storms most of snow particles are carried along near the snow surface even when appreciable concentrations of snow particles are observed above the levels of eyes. For example, when the wind speed is 10 m/s at a 1 m level, it is estimated that 80% to 90% of drifting snow streams along near the snow surface in a layer about 10 cm thick atop the surface (OURA and KOBAYASHI 1966, BUDD, DINGLE and RADOK 1966). This drifting snow which confines itself to a thin layer atop the snow surface actually contacts the surface, and playing a major role in the formation of depositional or erosion features of the surface. Therefore, it is very important to observe this stream heavily concentrated with snow particles but small in thickness. The difficulties of observing snow drifting in close proximity to the surface have, however, prevented longtime many investigators from gaining exact data on snow storms. Most investigators, having measured drift fluxes at levels higher than a few centimeters above the snow surface, have estimated the total amount of snow-drift and have supposed that the dominant mechanism for snow transport is suspension of snow particles in the atmosphere.

The purpose of this work is to directly observe low-level snow streams and to clarify the mechanism of snow drifting when the wind speed is lower than 10 m/s at a 1 m level. Chapter II provides the photographs of saltation motion of drifting snow particles which bear evidence of saltation motion obtained for the first time in the world. Some examples of vertical distribution of drifting snow particles are also given by some of the photographs. Chapter II suggests that the mechanism of snow transport and of drift formation should be reexamined in consideration of saltation motion, that is, it is necessary to recognize that snow particles actually rebound on the snow surface and sometimes eject other snow particles from the surface as a result of hitting the surface. Chapter III gives the quantitative data on the behaviour of saltation motion, such as mean lengths of saltation paths of snow particles and the mass of snow-drift rebounding on a unit area in a unit time. Chapter IV shows the maximum snow-drift rate determined by a trench method. A wide trench was used for the direct measurement of the total amount of snow-drift. This method covers thoroughly the surface drift which has an important significance for the total amount of snow-drift. Chapter V describes growth length of snow-drift development. Helpful for clarifying the mechanism of drifting snow, the data of growth lengths are also useful for selecting the efficient location of a snow fence.

II. Trajectories of snow particles and transportation mechanism

To investigate the mechanism of snow transportation within a thin layer of space located in close proximity to the snow cover, where the most amount of drifting snow is concentrated, the author planned to begin studies from photographing trajectories of drifting snow particles. First attempts were to take photographs in the field in daylight. A black plate was placed vertically as a backdrop but no clear photograph was obtained, because the light reflected from moving snow particles was weaker than the light from the black plate. Thus the plan to take a photographs in daylight was abandoned after two winters were wasted in unsuccessful attempts to take photographs of drifting snow particles.

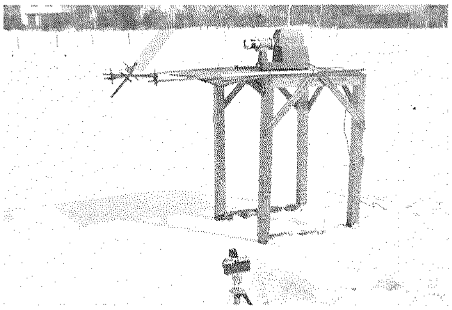


Fig. 1. Illumination device for photographing drifting snow particles

Then a new method was developed by using an artificial illumination at night for this study. The device for photographing is shown in Fig. 1. As a method of illumination,

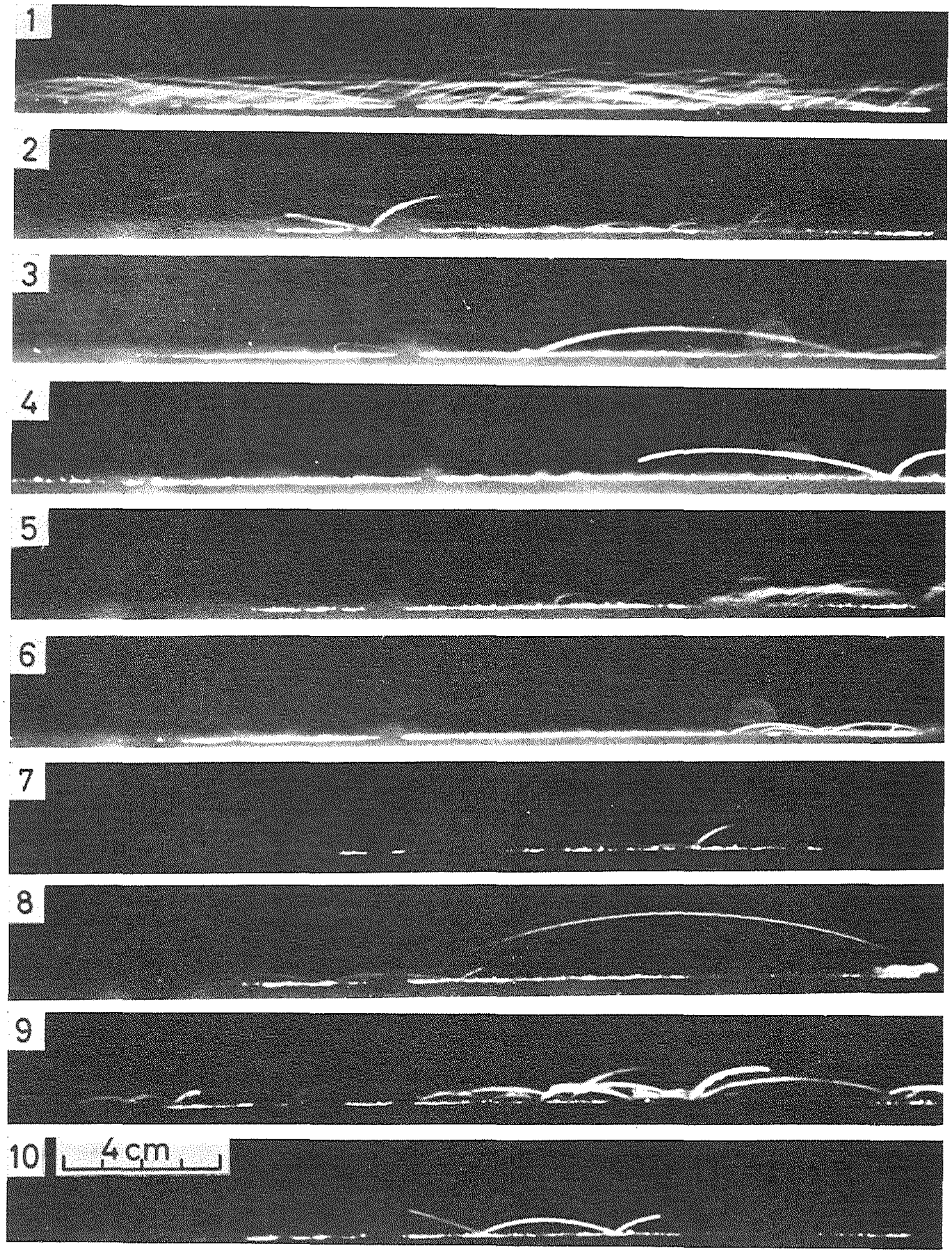


Fig. 2a. Examples of saltation at very low wind speeds during a light snowfall

Row No.	1	2	3	4	5	6	7	8	9	10
1 m wind speed (m/s)	3.8	3.4	3.4	3.2	3.0	2.9	2.8	2.5	2.4	1.9

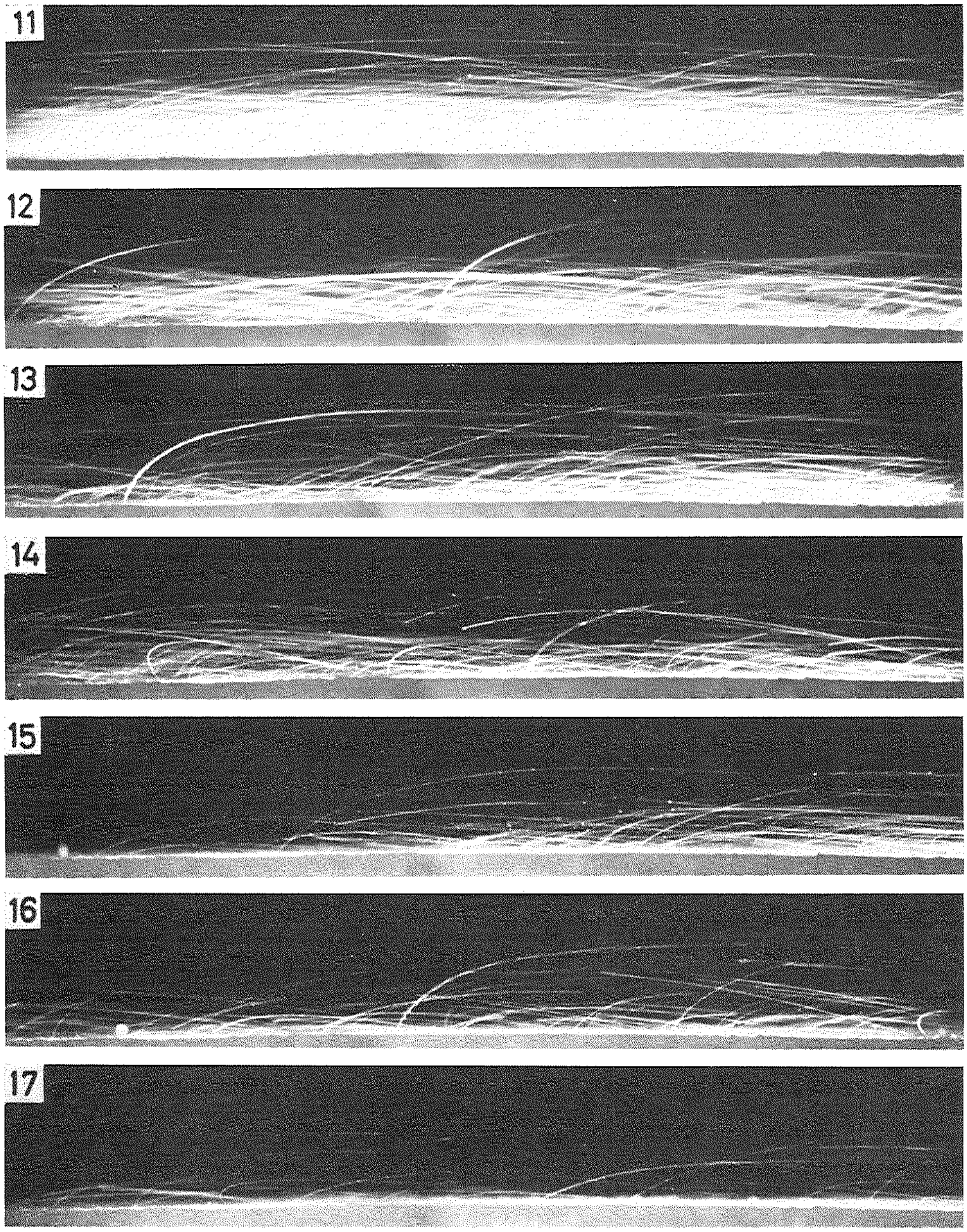


Fig. 2 b. Examples of saltation of typical shallow drift in absence of snowfall

Row No.	11	12	13	14	15	16	17
1 m wind speed (m/s)	4.6	5.0	4.8	3.9	4.4	3.8	3.9

a slide projector was placed on the table, 1 m in height, a vertical slit was inserted into a slide holder. The light passing through the slit was reflected by a mirror placed at the top of the table so as to illuminate a vertical thin space which was 2~3 cm thick and 30 cm long. The orientation of illumination was adjusted to be in a direction parallel to the wind direction by rotating the slit in the slide-holder around the optical axis of the projector.

Using this simple illumination apparatus, the bouncing of snow particles, so called "saltation" on the surface of a snow cover, was successfully captured in films. Hitherto the existence of the phenomenon of saltation has not been fully believed, and the magnitude of the saltation's contribution to the total amount of snow-drift has not been well appraised accodingly.

The saltation process of snow particles is, however, well illustlated by Figs. 2a and 2b. Figure 2a shows some examples of saltation at low wind speeds (2~4 m/s at a 1 m level) during a very light snowfall. The temperature of the snow surface was −8°C and the photographic exposure time was 1/8 sec. The width of the illumination on the snow surface was 2 cm in the case of Fig. 2a. Figure 2b shows the photographs of a typical case of a low-level drift at a wind speed of 4~5 m/s at a 1 m level in absence of any snowfall. The temperature of the snow surface was −11°C and it had not been snowing since about 3 hours before the photographs were

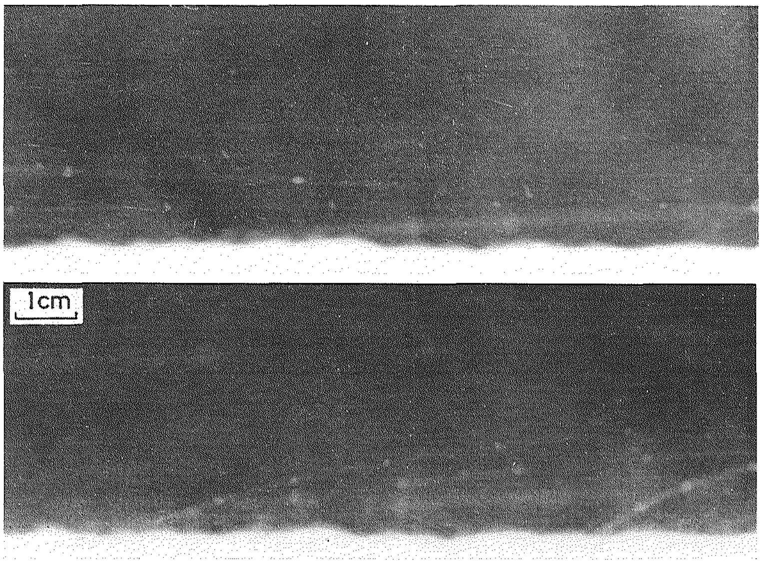


Fig. 3. Trajectories of snow particles in a wind tunnel. Series of spots are made by strobolight flashing every 5 ms

taken. From this series of photographs it was confirmed that the saltation accounts for the main transport mechanism of drifting snow in a thin layer of space atop the snow surface.

A similar experiment was carried out in a wind tunnel to study the movement of drifting snow particles. Figure 3 shows the trajectories of snow particles in the wind tunnel. The series of spots were made by strobolight flashing every 5 ms. The cross section of the wind tunnel is 30 × 30 cm. The wind speed in the center was 15 m/s and the 1 cm level wind speed was 9 m/s.

The author took some cinefilms in the field using a high speed 16 mm cinecamera with a frame rate of 200～280 pictures per second. The temperature of the snow surface was $-8°C$ and the wind speed was 5 m/s at a 1 m level. This cinefilm shows many examples of snow particles rebounding and sometimes ejecting other snow particles from the snow surface. Figure 4 shows an example of the movement of snow particles in the photographs which were obtained by compounding a number of frames of the cinefilm.

However, it would be difficult to determine how practical the significance of saltation may be for snow transport. To confirm the role of saltation, the author made a simple experiment digging a small trench of about 5 cm in width in the surface layer of snow perpendicular to the wind direction, whereby he observed the variation of snow transport while the

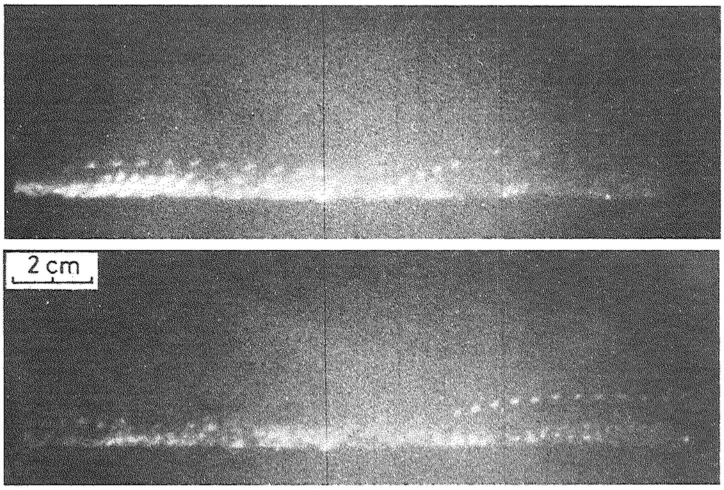


Fig. 4. An example of snow particle motion reproduced by compounding 21 frames of a cinefilm. The time interval of spots is 4.8×10^{-3} sec; the 1 m wind speed is 5 m/s

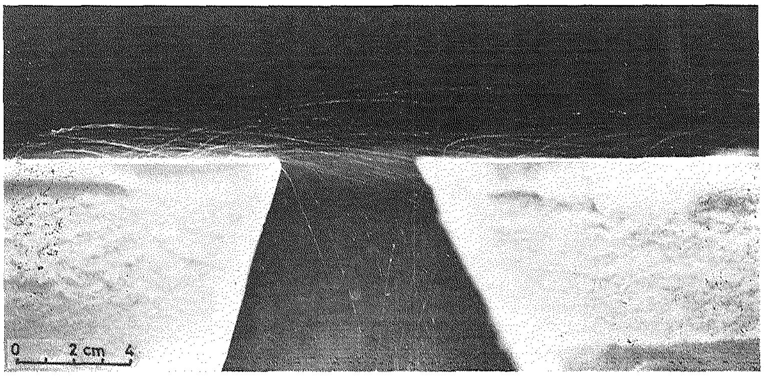


Fig. 5. Movement of saltating snow particles passing a small trench. The 1 m wind speed is 5 m/s

drift was passing the trench. It is clear from Fig. 5 that most of the saltating snow particles were caught in the small trench and there were only few particles reaching beyond this trench leeward. This photograph illustrates that saltation motion is the dominant mechanism for snow transport. The temperature of the snow surface was -15°C and the 1 m wind speed was 5 m/s. The width of illumination was 3 cm, and the shutter speed was 1/8 sec.

It is said that density of snow-drift increases exponentially as the height lowers down, but no data has been reported concerning the drift density below a 3 cm level, since it was difficult to observe snow-drift at such a low level. Figure 6 shows the vertical distribution of drifting snow particles. The photographs were taken under the strobolight which flashes for 20 μs every 0.1 s and the photographic exposure time of the camera was 1 s. The width of illumination was 3.3 cm. The 1 m wind speed was about 5~6 m/s and the temperature of the snow surface was -10°C. As is shown in the photographs the number of snow particles extremely increases as the level lowers down to the snow surface.

This phenomenon is also illustrated more clearly by Fig. 7, which shows the vertical distribution of the number of snow particles counted on a cinefilm. Counts were made in 2 mm vertical intervals on 41 cinefilm frames in every 50th picture. The number of snow particles increases exponentially as the level lowers down to the snow surface.

Figure 8 is the pictures of the so called sastrugi and the shape of a sastrugi suggests such a vertical distribution of drifting particles, that is, especially the foot of a sastrugi is eroded by drifting snow particles.

From the simple analysis of the cinefilms and photographs, it turned

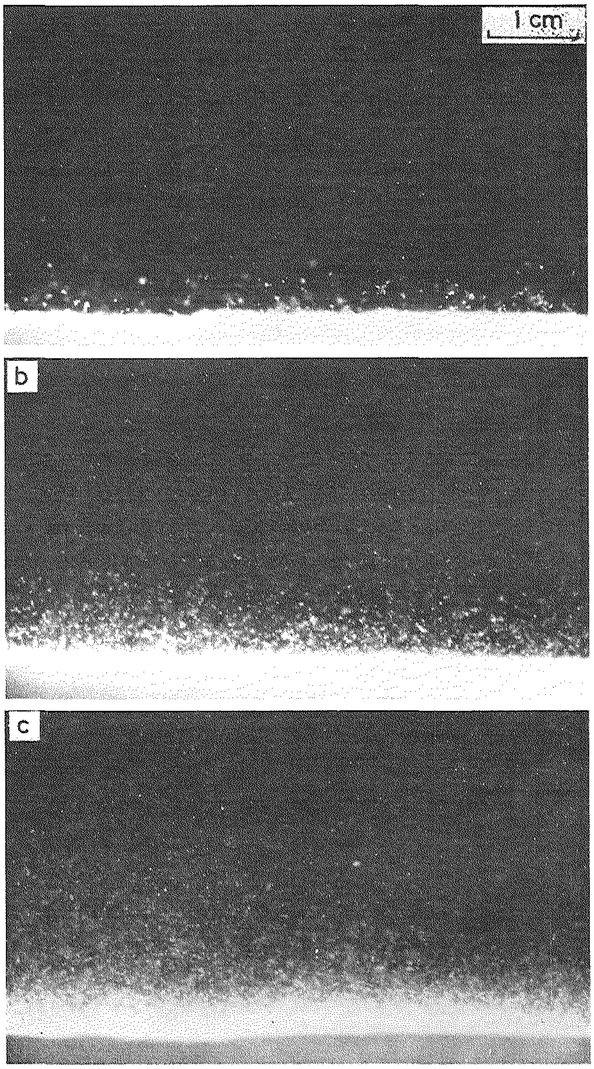


Fig. 6. Vertical distributions of drifting snow particles

	a	b	c
1 m wind speed (m/s)	4.5	4.5	6.4
number of times of strobolight flashing for each exposure	1	10	10

out that a saltating snow particle moved in such a curved path that its smoothness was in little likelihood of getting affected by a small turbulence of air. The trajectories of drifting snow particles are shown in Fig. 9 and an example of a result of analysis of the motion is shown in Fig. 10. The

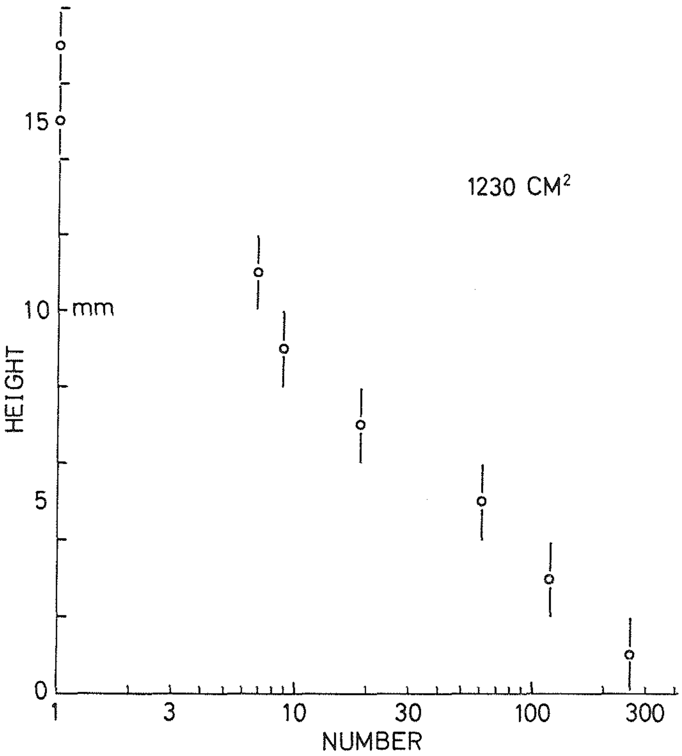


Fig. 7. Vertical distribution of numbers of snow particles on an area of $1230\,cm^2$. Counts were made in 2 mm vertical intervals on 41 cinefilm frames

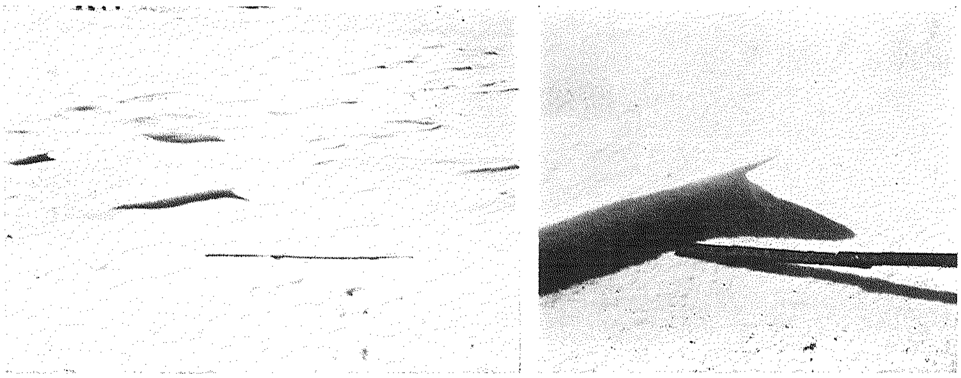
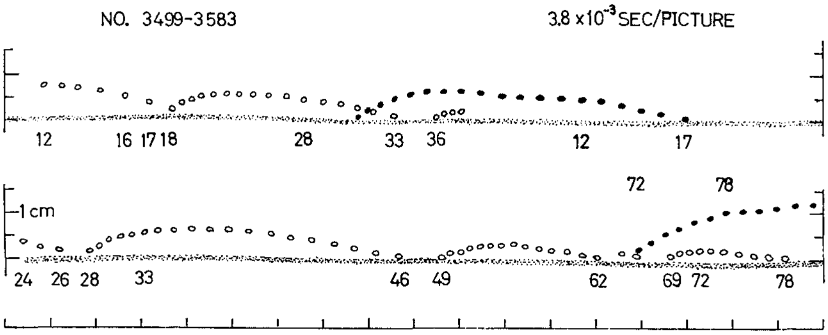


Fig. 8. Sastrugi undercut by saltating snow particles



Fsg. 9. Examples of snow particle motion observed by high speed cinecamera. The frame number is shown under snow particles

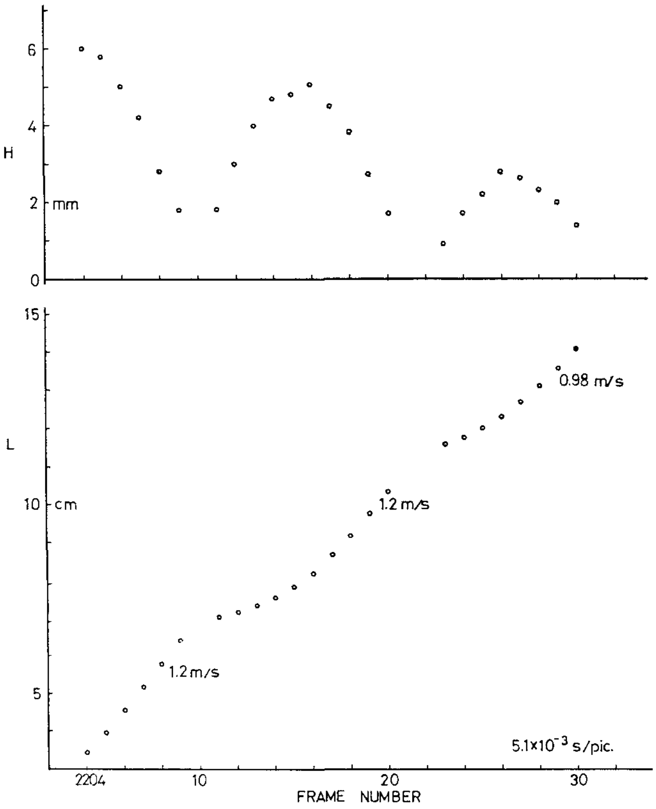


Fig 10. An example of horizontal and vertical motion of a snow particle.
H: height of a snow particle from the snow surface
L : Horizontal distance

vertical motion is shown in the upper part of Fig. 10, in which the height of a snow particle is plotted against a time scale counted by the frame number; the horizontal motion is shown in the lower part of Fig. 10, in which a traveled horizontal distance of a snow particle is plotted against the same time scale. Figure 10 shows that a snow particle rises from the surface with a relatively small forward velocity and it attains a higher velocity during subsequent flights and a vertical motion resembles that of a projectile which has a parabolic trajectory.

III. Mechanism of "saltation"

III. 1. *Box-type drift gauge*

The photographs and cinefilms gave us plenty of qualitative information on the mechansim of snow particle motions, but only a small amount of quantitative information thereof.

To investigate saltation phenomena in more detail, a series of measurements were carried out for determining the mean length of saltation paths by the following method. A collector of drifting snow was made of thin sheet metal, which comprised 6 or 8 boxes aligned lengthways with an open top. Each box measures 10 × 20 cm in width and 5 cm in depth. This collector was laid with its lengthwise side along the wind direction in the center of a shallow pit dug in the surface layer of a snow cover, the size of which is 40 cm in width, 60 or 80 cm in length and just 5 cm in depth (Fig. 11).

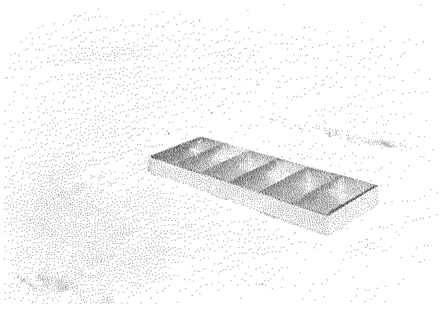


Fig. 11. Box-type drift gauge. Size of each box is 10×20 cm and 5 cm deep.

During a run of drifting snow, saltating snow particles are collected separately in each box. After a period from 1 to 4 minutes, the mass of deposited snow in each box is weighed, varying the period according to the strengh of snow-drift. From the distribution of deposited amount, the lengths of paths of saltation and the mass of snow particles rebounding on a unit area in a unit time are graphically calculated as explained below. Further, the amount of snow-drift is also estimated from the summation of the weight of deposits in all boxes and from the distribution of the mass of drifted snow caught in each box.

The method of calculation is as follows after KAWAMURA (1951). Let the co-ordinate measuring the position of a point on the snow surface along the wind direction be x. And let the mass of drifting snow which falls on a unit area in a unit time at x be $F(x)$. The origin of the x co-ordinate is taken at the windward end of the collector and the leeward is made positive. A snow particle falling on the snow surface at the x co-ordinate, $x<0$, rebounds or ejects another particle, but for $x>0$ a snow particle only falls on the surface to be caught by the collector boxes. Let the path length of a saltation be l and the distribution function of the length be $g(l)$.

Then let $F(x)$ for $x<0$ be G when snow drifting is stationary. For $x>0$, $F(x)$ is expressed as

$$F(x) = G\left\{\int_0^\infty g(l)\,\mathrm{d}l - \int_0^x g(l)\,\mathrm{d}l\right\},$$

where

$$\int_0^\infty g(l)\,\mathrm{d}l = 1\,. \qquad \text{(III. 1)}$$

Differentiation of eq. (III. 1) with respect to x gives $g(x)$

$$g(x) = -\left(\frac{\mathrm{d}F(x)}{\mathrm{d}x}\right)\Big/G\,. \qquad \text{(III. 2)}$$

Let Q be the mass of snow-drift which passes through a unit length perpendicular to the wind direction in a unit time, which is called snow-drift rate, and the mean length of paths of saltation be denoted by $\bar{L}$. If all particles with the length $\bar{L}$ saltate, then

$$Q = \bar{L}\cdot G\,. \qquad \text{(III. 3)}$$

And

$$Q = \int_0^\infty F(x)\,\mathrm{d}x\,, \qquad \text{(III. 4)}$$

$$G = \lim_{x\to 0} F(x)\,. \qquad \text{(III. 5)}$$

Thus from the observation of $F(x)$ by use of a simple collector, much useful information such as Q, G, $g(l)$ and $\bar{L}$ can be obtained, concerning snow drifting by the saltation process.

Observations of saltation were carried out both on the flat plain and on the slope with an incline of 16° to 28° at a mountainous district (see Fig. 12). The author aimed to know how much the length of the saltation path is shortened on the slope and to what extent the length of the path affects the drift amount.

Tables 1 and 2 show the conditions and data observed as regards snow-drift. The conditions under which the observation was made are:

Table 1. General information and data on measurements

Date 1971	Hours	Run No.	Wind Speed (Mean) m/sec	Air Temp. °C		Mass of Deposited Snow in Each Box (Box No.)							
						1	2	3	4	5	6	7	8
1/7	1137	11	7.4	−3.5	D g	48.1	8.8	3.0	1.3	0.8	0.5		
					$F(x)$g/m²·s	24	4.4	1.5	0.65	0.4	0.25		
1/7	1605	12	5.7	−5.5	D	23.3	4.3	2.0	1.1	0.5	0.6		
					F	9.2	1.7	0.79	0.044	0.02	0.02		
1/7	1659	13	6.7	−5.2	D	27.3	14.7	4.2	2.2	1.0	0.6		
					F	18	9.8	2.8	1.4	0.66	0.04		
1/8	1053	21	5.2	−6.0	D	24.3	8.3	2.0	0.8	0.4	0.3		
					F	6.9	2.4	0.57	0.23	0.11	0.085		
1/8	1134	22	5.5	−4	D	43.4	22.1	9.2	4.5	2.6	1.7		
					F	8.8	4.5	1.9	0.91	0.52	0.35		
1/8	1223	23	6.7	−3.5	D	95.2	33.0	9.3	6.3	4.0	2.4		
					F	16.4	5.7	1.6	1.1	0.69	0.41		
1/8	1841	24	4.4	−6.5	D	4.1	0.7	0.1	0	0.2	0		
					F	1.2	0.2	0.03	0	0.06	0		
1/12	1045	31	6.5	−2.5	D	52.5	11.8	5.7	2.8	1.7	1.2	1.0	
					F	10.2	2.34	1.1	0.55	0.33	0.23	0.20	
1/12	1151	32	7.5	−3	D	64.1	38.5	22.8	15.9	11.5	7.3	5.1	
					F	12.3	7.4	4.4	3.1	2.2	1.4	0.98	
1/12	1411	33	7.2		D	108.5	47.7	21.1	11.3	6.5	4.2	4.0	
					F	22.6	9.9	4.4	2.4	1.4	0.88	0.83	
1/14	1202	41	10.3	−3.5	D	245.8	88.4	44.4	23.1	15.9	10.9	9.2	7.4
					F	99.1	35.6	18.0	9.3	6.4	4.4	3.7	3.0
1/14	1403	42	9.1	−4	D	150.8	111.0	69.2	46.5	27.3	20.2	14.9	10.4
					F	38.9	28.6	17.8	12.8	7.03	5.21	3.84	2.68
1/14	1730	43	7.6	−5.5	D	114.5	71.1	40.0	26.2	17.8	14.3	11.4	8.4
					F	12.4	7.7	4.3	2.8	1.9	1.6	1.2	0.91

of snow transport by saltation in a flat plain

Total Amount of Snow Drift g	Duration sec	Drift Rate Q g/m·s	Rebound Mass G 10g/m^2·s	Saltation Length L cm	Snowfall g/m^2·s	Snow Density g/cm^3	Surface Hardness g/cm^2	Drift Particle Size*	State of Snow Surface
64	60	5.3	7.0	7.6	0	0.14	7.5	M	
33	126	1.3	1.8	7.2	1.4	0.056	3	L	
51	75	3.4	2.9	12	0.65			L, M	
37	176	1.1	1.15	9.6	0.17		<1	M	• soft new snow
90	246	1.8	1.3	14	0		<1	S	• soft
158	290	2.7	2.8	9.8	≃0	0.051	<1	M, S	• soft smooth weak crust
5.1	172	0.14	0.29	4.8	0.44	0.058	1.5	L, M	
86	252	1.7	1.95	8.8	0			M, S	• soft drifted snow layer (1.5 cm thick) overlying glanular snow cover
172	260	3.31	1.62	20.4	0			S	• slightly melted small ripple
222	240	4.63	3.33	13.9	0	0.11 (1911	3.5 Hours)		
490	124	19.8	16.8	11.8	0	0.20	60	M, S	• depositional • wavy snow patch
497	194	12.8	4.9	26.1	0	0.24	60		• erosional
347	460	3.77	1.7	22	0	0.20	75	M, S	• slightly erosional

Table 1. (*Continued*)

Date 1971	Hours	Run No.	Wind Speed (Mean) m/sec	Air Temp. °C		Mass of Deposited Snow in Each Box (Box No.) 1	2	3	4	5	6	7	8
2/24	1105	51	11.2	−4.0	*D*	160.5	83.4	67.3	27.6	20.1	13.0	10.0	10.5
					F	73.0	37.9	30.6	12.5	9.14	5.90	4.55	4.77
2/24	1410	52	7.9	−5.5	*D*	101.9	45.9	23.2	15.3	7.2	5.9	3.7	2.9
					F	15.0	6.75	3.41	2.25	1.1	0.87	0.54	0.43
2/24	1645	53	8.4	−8.5	*D*	208.5	45.6	22.8	11.6	7.5	6.1	5.8	3.9
					F	54.9	12.0	6.00	3.05	2.0	1.6	1.5	1.0
2/24	2008	54	6.6	−9.0	*D*	85.5	16.6	7.0	2.2	0.9	0.0	0.7	0
					F	19.6	3.81	1.6	0.50	0.2	0.0	0.16	0
2/25	1216	61	8.3	−7.5	*D*	157.1	116.2	49.5	50.0	41.7	29.8	18.4	15.5
					F	20.5	15.1	6.45	6.51	5.43	3.88	2.40	2.02
2/25	1530	62	7.2	−7.5	*D*	74.3	42.4	21.7	11.0	9.2	4.0		
					F	22.4	12.8	6.54	3.31	2.8	1.2		
2/25	1538	63	7.3	−7.5	*D*	81.6	43.5	28.2	14.8	7.5	4.3		
					F	26.5	14.1	9.16	4.81	2.4	1.4		
2/25	1603	64	7.4	−8.0	*D*	207.0	122.8	58.0	23.5	16.4	10.5	9.3	4.8
					F	30.4	18.1	8.53	3.46	2.41	1.54	1.4	0.71
3/2	1122	71	8.8	−5.5	*D*	62.5	27.5	16.9	12.2	8.1	6.5	5.2	3.5
					F	30.6	13.5	8.28	5.98	4.0	3.2	2.6	1.7
3/2	1130	72	9.9	−5.5	*D*	74.2	35.3	33.9	20.5	16.6	12.8		
					F	34.4	16.3	15.7	9.49	7.69	5.93		
3/2	1232	73	10.2	−5.0	*D*	80.9	43.8	33.7	21.3	17.0	13.8		
					F	29.7	16.1	12.4	9.86	7.87	6.39		

Total Amount of Snow Drift g	Duration sec	Drift Rate Q $g/m \cdot s$	Rebound Mass G $10 g/m^2 \cdot s$	Saltation Length $\bar{L}$ cm	Snowfall $g/m^2 \cdot s$	Snow-Density g/cm^3	Surface Hardness g/cm^2	Drift Particle Size*	State of Snow Surface
459	110	20.9	10.2	20.0	1.4	0.27 (granular snow layer)	200	M, S	• patch of thin soft snow layer
218	340	3.21	2.1	15	0	0.12	9	S	• slightly erosional • packed snow
335	190	8.82	10.2	8.6	0	0.12	12	S	• depositional • packed snow (4 cm thick)
113.5	218	2.60	3.4	7.6	0.57	0.15	12	M, S	• depositional • soft crust (3 mm thick)
527	384	6.86	2.6	26.4	0	0.15	7.5	S	• wind crust
179	166	5.40	3.0	18	0	0.13 (1603 hours)	12	S	• very small ripple
190	154	6.2	3.7	17	0	0.13 (1603 hours)	12	S	"
479	340	7.04	3.95	18	$\simeq 0$	0.13	12	S	"
168	102	8.25	4.3	19	$\simeq 0$	0.11	13	S	• erosional • packed snow (5 cm thick)
(277)	108	12.8	4.7	27	0	0.11	13		"
(320)	136	12	3.9	30	$\simeq 0$	0.11	13		"

* L : about 1 mm mixed with graupel
M : about 0.5 mm
S : about 0.2 mm

Table 2. General information and data on measurements

Date 1971	Hours	Run No.	Wind Speed (Mean) m/sec	Air Temp. °C		Mass of Deposited Snow in Each Box (Box No.)							
						1	2	3	4	5	6	7	8
1/21	2207	81	8.5	−8	*D* g	71.4	27.1	11.7	7.0	6.3	3.6		
					F g/m²·s	54.9	20.8	9.0	5.4	4.8	2.8		
1/21	2317	82	6.8	−8	*D*	49.4	16.1	7.3	4.3	3.1	2.4		
					F	35.3	11.5	5.2	3.1	2.2	1.7		
1/25	1235	91	7.5	−6	*D*	38.0	17.5	5.0	2.7	1.4	0.9		
					F	24	11	3.1	1.7	0.88	0.56		
1/31	0745	101	7.8	−7	*D*	14.0	5.1	1.7	0.6	0.1	0		
					F	12	4.3	1.4	0.5	0.08	0		
1/31	0845	102	5.9	(−7)	*D*	6.2	1.9	0.4	0.15	0.05	0		
					F	2.1	0.63	0.13	0.05	0.017	0		
2/1	1447	111	5.6	−6.0	*D*	34.5	5.6	1.5	0.7	0.4	0.2		
					F	9.58	1.6	0.41	0.2	0.1	0.06		
2/1	1525	112	8.5	−6.5	*D*	67.6	31.2	15.4	8.6	4.7	3.0		
					F	22.5	10.4	5.1	2.9	1.6	1.0		
2/1	1610	113	7.6	−6.2	*D*	71.5	22.2	8.9	4.6	2.5	1.6		
					F	19.9	6.17	2.5	1.3	0.69	0.44		
2/1	1645	114	8.8	(−6.5)	*D*	60.4	24.4	12.3	7.6	4.2	2.6		
					F	33.6	13.5	6.8	4.2	2.3	1.4		
2/1	1835	115	7.4	−6.8	*D*	46.0	27.9	11.8	6.3	3.6	3.4		
					F	19.2	11.6	4.92	2.6	1.5	1.0		
2/1	1914	116	12.8	(−7)	*D*	66.0	39.1	23.5	16.6	10.5	7.2		
					F	55.0	32.6	19.5	13.8	8.8	6.0		
2/1	2125	117	8.3	−7	*D*	61.9	39.0	20.3	11.3	6.0	3.8		
					F	25.8	16.3	8.46	4.71	2.5	1.6		
2/1	2200	118	7.7	−7	*D*	63.4	30.1	16.1	9.3	5.6	3.7		
					F	26.4	12.5	6.71	3.9	2.3	1.5		

of snow transport by saltation on a mountain slope

Total Amount of Snow Drift g	Duration sec	Drift Rate Q g/m·s	Rebound Mass G ×10g/m²·s	Saltation Length $\bar{L}$ cm	Dip of Slope deg.	Snowfall g/m²·s	Snow Density g/cm²	Surface Hardness g/cm	Drift Particle Size	State of Snow Surface
>127	65	9.8	9.7	10	16	≃0	0.16	7.5	S, M	
>83	70	5.9	6.2	9.5	18	≃0	0.13	7	S, L (graupel)	· erosional · small ripple
>66	80	4.1	3.7	11	28	0.4	0.069	too soft	L, M	· depositional · new snow
22	60	1.8	2.0	9.0	17	0.7	0.16	5	L	· crust (5 mm thick) · hoarfrost
8.7	150	0.29	0.34	8.5	18	0	0.11	3	L, M	· crust (2 mm thick) · hoarfrost
43	180	1.2	1.8	6.6	16.5	0.14	0.07	2	S, M	· soft crust (2 mm thick)
135	150	4.5	3.3	14	18.5	0.13			S	
115	180	3.2	3.4	9.4	17.5	0.14	0.072	3	S	· crust (3 mm thick)
115	90	6.4	5.0	13	18	0.2	0.13	4	S	· erosional · pitted pattern · crust (7 mm thick)
103	120	4.3	2.6	16	22	0.2	0.080	6	S (M)	
175	60	14.5	7.1	20.4	22	≃0	0.071	7	S (M)	
147	120	6.14	3.3	19	24.5	≃0	0.15	11	S (M)	· erosional · slightly rippled
135	120	5.6	4.0	14	25.5	≃0	0.15	11	S	”

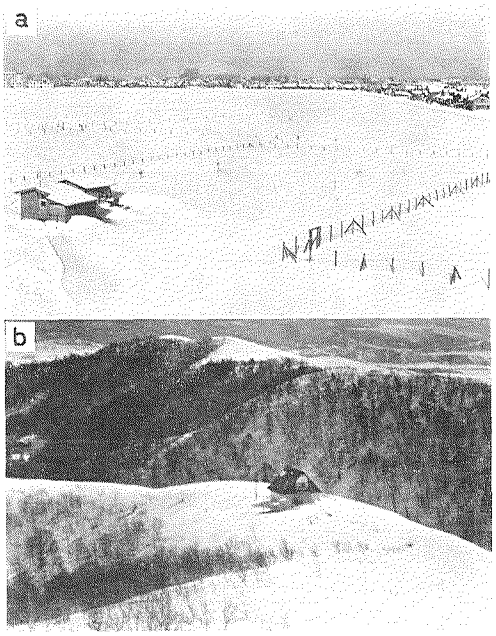


Fig. 12. General views of the observed field.
a: flat plain (Experimental Farm of Hokkaido University, Sapporo)
b: mountain slope (Experimental Forest of Hokkaido University, Teshio)

the air temperature, the surface temperature of the snow cover, the wind speed at a 1 m level, the amount of snowfall, the density and the hardness of the surface layer of the snow cover, and the shapes and sizes of drifted snow particles (see also Figs. 17 and 18). The wind speed was measured with a Biram's vane anemometer and an aerovane type anemometer for low wind speeds ; a Canadian type hardness gauge was used for measuring the hardness of the snow cover.

To measure the amount of snowfall during snow-drift is extremely difficult. This time the amount of snowfall is estimated using the distribution of snow deposits in the row of boxes used as snow-drift collector. The amount of drifted deposits caught in the boxes decreases exponentially as it goes down leeward in the case of a drift without snowfall. But when it snows during snow-drift, the amount of drifted deposits is distributed in a different way from that for deposits without snowfall, i. e., the deposits in the boxes do not decrease exponentially especially at the leeward end of the row of boxes.

III. 2. *The distribution functions, $F(x)$ and $g(l)$*

The examples of $F(x)$ and $g(l)$ are shown by histograms in Figs. 13 and 14. In Fig. 13, the deposit distribution $F(x)$ is approximately represented by a smoothed curve, and the rebound mass G is determined as the value of $F(0)$. Using the gradient of the curve of $F(x)$ in Fig. 13, the value of $g(l)$ is graphically calculated and is shown in Fig. 14 (cf. eq. III. 2).

The distribution $g(l)$ almost exponentially decreases as the saltation length l increases as shown in Fig. 14 and the same tendency is also seen

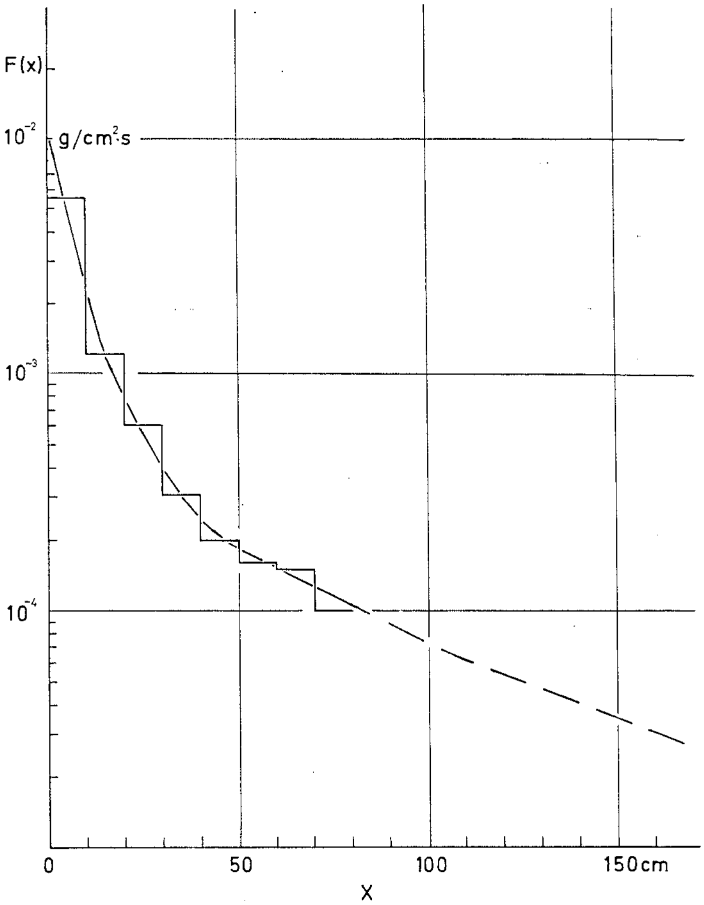


Fig. 13. An example of deposit distribution in the box type drift gauge (Run No. 53)
$F(x)$: mass of deposited snow in g/cm²·s
x: distance from the windward end of the drift gauge

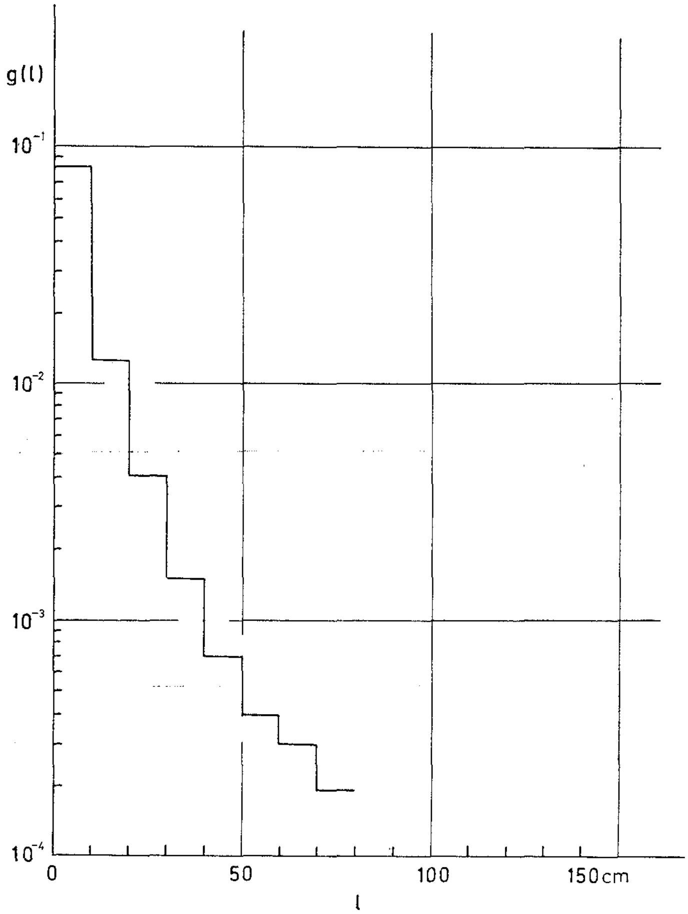


Fig. 14. An example of the distribution function $g(l)$ of saltation length (l) (Run No. 53)

in other examples. This means that the distribution function of the height of the saltation path also has extremely high values for the low values of the height of the saltation. But from these distribution functions $F(x)$ and $g(l)$, it is impossible to know the precise vertical distribution of the mass fluxes of blowing snow.

The actual amount of snow-drift may be a little more than the total amount of the drift caught in the row of boxes. The amount of the drift was corrected by adding the amount of snow-drift which passed over the collector boxes. This was estimated graphically by using the dotted part of the curve in Fig. 13.

III. 3. *The relation between the drift rate Q and wind speed*

The relation between the snow-drift rate Q g/m·s which is observed by the collector boxes and the wind speed at a 1 m level is shown in Fig. 15. The data in the flat plain are represented by the circles o and the data on the mountain slope with an incline of about 16°~28° are represented by the crosses +.

The drift rate in this chapter is different from the drift rate for the same wind speed which is measured by using wide drift capturing trenches in a relatively long period of time from 30 to 150 min. The details on the

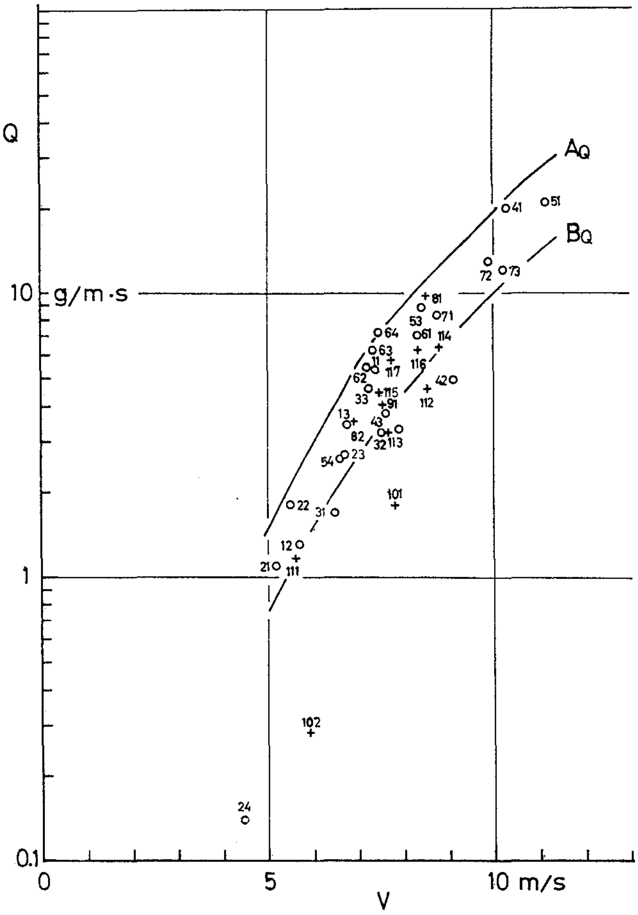


Fig. 15. Snow-drift rate Q measured by box-type drift gauge as a function of 1 m wind speed V.
o : data in the flat plain + : data on the slope (16°~20°)

trench method and on the difference of drift rates will be described later in Chapter IV, where the relation between the drift rate and the wind speed is discussed.

In Fig. 15, Line A_Q shows the upper limit of the domain of the plots of observed drift rates; the drift rates given by Line A_Q for a wind speed must be nearly equal to the maximum snow transport ability of the wind. A saturation drift rate can not be determined theoretically but the author considers that the drift rate represented by Line A_Q may be in a saturated state.

Line A_Q in Fig. 15 is given by the empirical formula:

$$Q = 0.03\,(V-1.3)^3 \qquad (Q:\ \mathrm{g/m\cdot s},\quad V:\ \mathrm{m/s}), \qquad (\mathrm{III}.\,6)$$

where Q is the total amount of snow-drift passing a fixed point in a lane of 1 m in width in a second and V is the mean wind speed at a 1 m level. The plots of Q show a considerable degree of scatter because of variations in snow surface conditions, but observed conditions of the snow surface such as snow temperature, density and hardness do not always determine the value of Q.

Generally speaking, the magnitude of Q decreases as the hardness of the snow surface increases with the lapse of time even when the wind speed does not change in a run of snow-drift. After snow-drift ceases for more than half an hour, the hardening of the snow surface due to the sintering of snow particles increases extremely threshold wind speeds for beginning snow-drift and any drift does not occur again except when it begins snowing or wind speeds extremely increases. So there should be no minimum boundary of the domain of Q except $Q=0$, if all kinds of surface conditions of snow are included in the observations. Line B_Q in Fig. 15 only means the unsaturated state which is nearly the lower limit of the domain of the observed values of Q and this line B_Q is never the minimum boundary of the domain of the drift rate Q as mentioned above. Line B_Q is related with Lines B_G in Fig. 16 and B_L in Fig. 19 by eq. (III. 3), which are explained later.

It is seen in Fig. 15 that the values of Q observed on a mountain slope are about 70% of those observed in a flat plain. But, as shown later in the next section, there is little difference between the values of G on a mountain slope and in a flat plain, therefore eq. (III. 3) suggests that the decrease of Q on the mountain slope may depend on the shortening of saltation paths as is seen in Fig. 19.

III. 4. *The relation between the rebound mass of drift G and wind speed*

The relation between the rebound mass G of snow drift on an area of 1 m^2 in a second and the wind speed is shown in Fig. 16. The values of G are obtained by extrapolating the curve of distribution $F(x)$ of deposition to $x=0$ (Fig. 13). Figure 16 indicates that the values of G increase as the wind speed increases and scatter to a greater extent as compared with those of Q for a wind speed which are shown in Fig. 15. The magnitude of G is about $1.2\times 10\,\text{g/m}^2\cdot\text{s}$ at a wind speed of 5 m/s and they vary from $3.4\times 10\,\text{g/m}^2\cdot\text{s}$ to $1.8\times 10^2\,\text{g/m}^2\cdot\text{s}$ at a wind speed of 10 m/s.

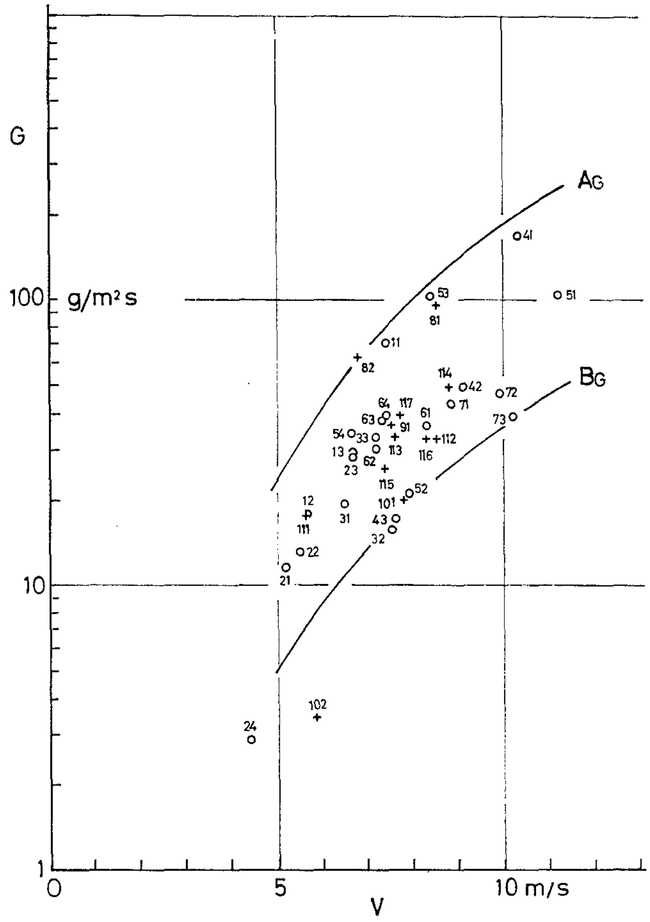


Fig. 16. Relation between rebound mass G of snow-drift and 1 m wind speed V.

The upper limit envelope of the plots in Fig. 16 is drawn and named Line A_G. Line A_G is given by the formula:

$$G = 3.0\,(V-2.1)^2 \qquad (G:\ \mathrm{g/m^2\cdot s},\quad V:\ \mathrm{m/s}). \qquad (\text{III}.7)$$

Plotted points Nos. 41, 53 and 11 which are located near Line A_G are also located near Line A_Q in Fig. 15. This means that drifting snow with a value of Q close to the saturation value also has a value of G close to the saturation value provided the wind speed is more than 7 m/s. The values of G observed on the mountain slope are found to be nearly equal to those in the flat level plain. Plots of the former case are indicated by the mark + and that of the latter by the mark o in Fig. 16.

Line B_G is drawn so as to envelope nearly the lower limit of the observed values of G. Points Nos. 72, 73, 43 and 32 which are located around Line B_G in Fig. 16 are also located near Line B_Q in Fig. 15, though Line B_G has not a clear physical meaning except that Line B_G is far from the saturation values of G as mentioned in the previous section.

The number of snow particles falling on a unit area in a unit time is tentatively estimated by assuming the mean weight of a snow particle to be 10^{-6} g. Using the observed saturation value of G, $6\times10^{-3}\,\mathrm{g/cm^2\cdot s}$, at a wind speed of 7 m/s, the number of snow particles rebounding on an area of 1 $\mathrm{cm^2}$ in a second in the saturated state is estimated to total about 6,000 for this wind speed.

The shapes and sizes of drifted snow particles caught in the drift gauge boxes are observed by the close-up photography. The rough mean size of snow particles are summarized on Tables 1 and 2. And a series of photographs of snow particles are shown in Figs. 17 and 18. These photographs show that in most cases newly fallen snow crystals are drifted and shattered to fragments, but they undergo little metamorphosis and their shapes are irregular.

III. 5. *The mean length of saltation paths*

· The mean length $\bar{L}$ of saltation paths for various wind speeds are summarized in Tables 1 and 2 and Fig. 19. The lengths $\bar{L}$ are calculated out by using the relation between Q, G and $\bar{L}$ represented by the eq. (III. 3). Figure 19 shows that the plots $\bar{L}$ against the wind speed seems to increase as the wind speeds increase, but they are scattered as broad as the plots of G against the wind speeds in Fig. 16. The values of $\bar{L}$ vary from 6 cm to 12 cm at a wind speed of 5 m/s, and from 11 cm to 30 cm at a wind speed of 10 m/s in Fig. 19.

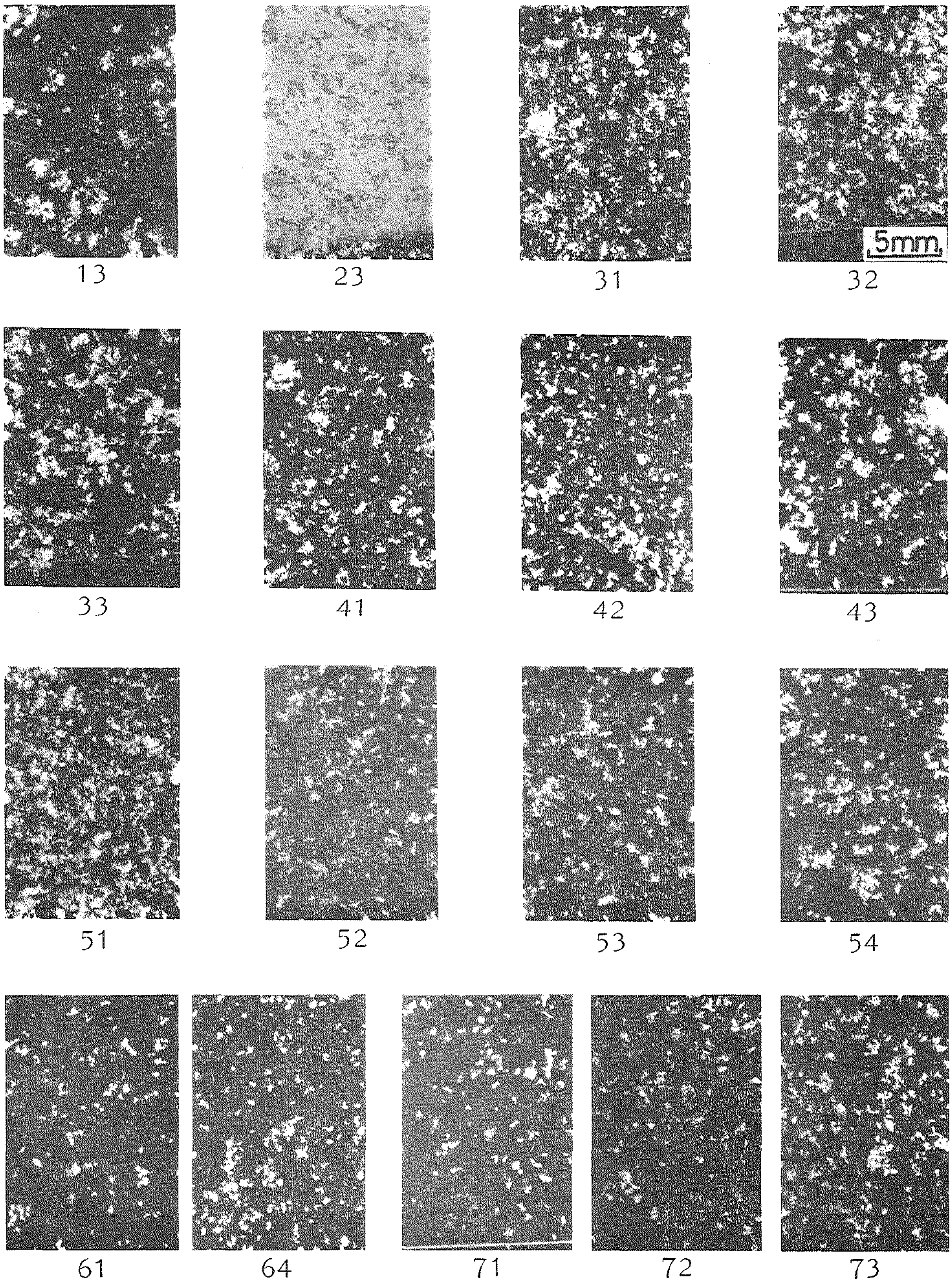


Fig. 17. Drifted snow particles in the flat plain.
Photographs numbered as in Table 1

The lower limit of the plots of $\bar{L}$ is enveloped with Line A_L, which is given by

$$\bar{L} = 0.011\,V \qquad (\bar{L}: \text{m}, \quad V: \text{m/s}). \qquad (\text{III}.8)$$

Equations (III. 8), (III. 6) and (III. 7) satisfy eq. (III. 3) which relates the values of $\bar{L}$ with the values of Q and G. Plotted points Nos. 41, 53 and 11 are comparatively near the line marked A in each figure of relations $Q\sim V$, $G\sim V$ and $\bar{L}\sim V$. These lines marked A give an interpretation that, when drifting snow is in the state of saturation, the values of G are maximum

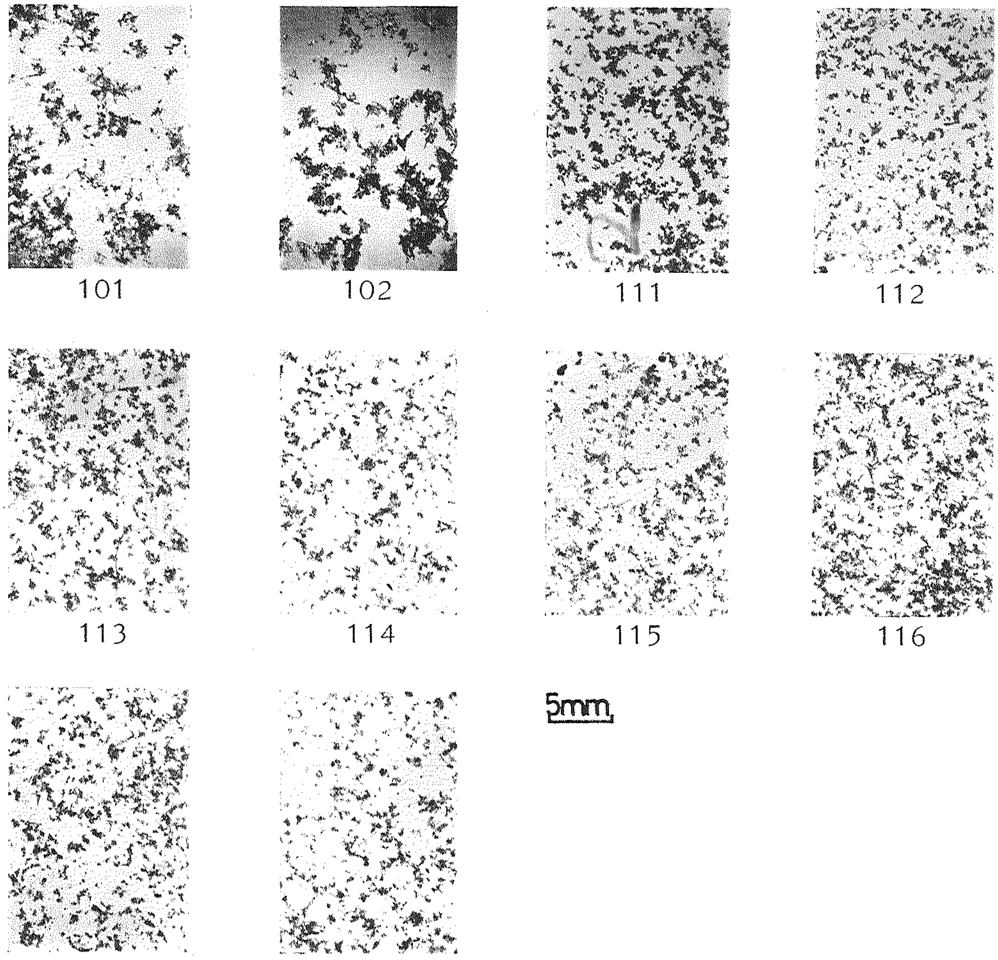


Fig. 18. Drifted snow particles on the mountain slope (16°~20°). Photograph numbered as in Table 2

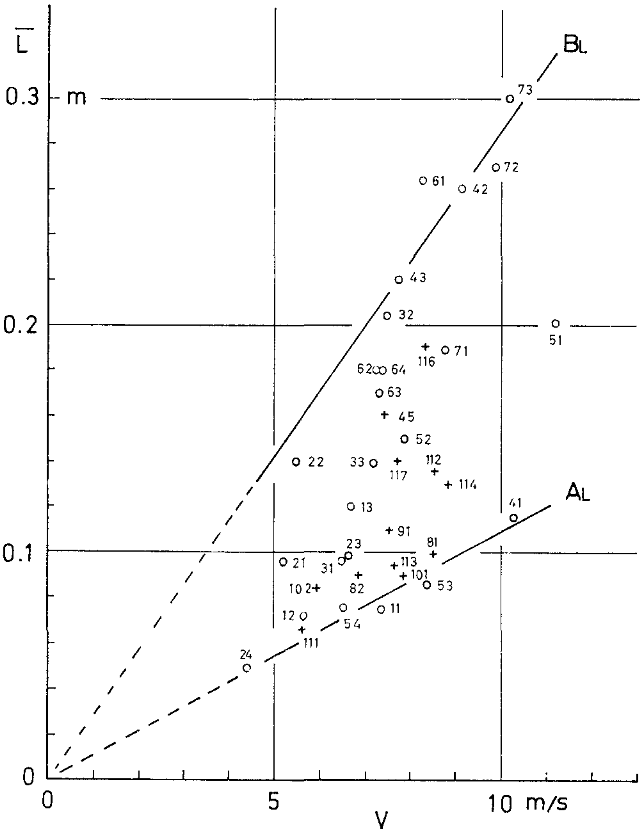


Fig. 19. Relation between mean length of saltation path ($\bar{L}$) and 1 m wind speed (V)

and the lengths $\bar{L}$ of the saltating paths of snow particles are minimum.

On the other hand, Line B_L in Fig. 19 is drawn nearly along the upper limit of the domain of the plots of $\bar{L}$ against the wind speeds. Using Line B_L in Fig. 19 and Line B_G in Fig. 16, Line B_Q is drawn as they also satisfy eq. (III. 3) in Fig. 15. Line B_L does not also have a clear physical meaning but the saltation lengths of drifting snow particles in the unsaturated state are fairly longer than those in the saturated state. For example, plots Nos. 73, 72, 42, 43 and 32, are near Lines B_L, B_G and B_Q. The details on factors for elongation of saltation paths will be described later.

The author observed drift deposits in two parallel ruts of a tractor on a snow-covered road (OURA and KOBAYASHI 1966, OURA and others 1967). A photograph is shown in Fig. 20. The windward rut was buried under drifted snow, while the leeward rut was free from drifting snow. The

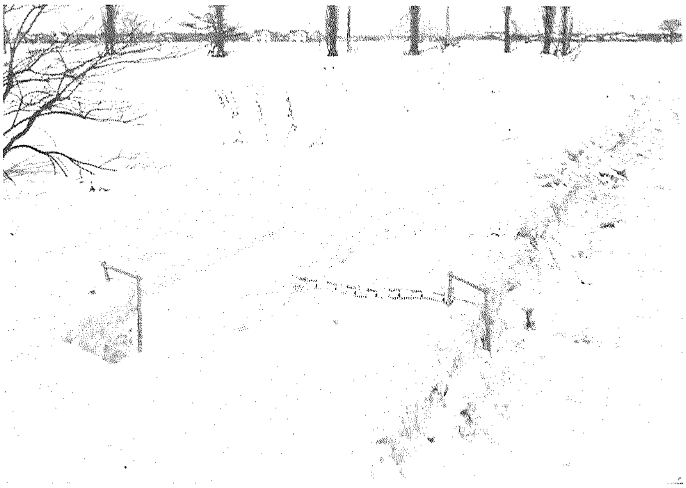


Fig. 20. Vertical section of ruts; only left side is buried under drifted snow

maximum wind speed was 6 m/s during the time after the ruts were made until the photograph was taken. This photograph interprets that the saltating snow particles of drifting snow could not cross the width of wheels which was about 50 cm. This phenomenon is reasonably understandable by the observed data shown in Fig. 19, in which the values of $\bar{L}$ range only from 7 cm to 15 cm at a wind speed of 6 m/s. And even at a wind speed of 10 m/s the lengths of $\bar{L}$ are not over 30 cm, that is, the trench of only 30 cm in width can catch at least the half amount of snow-drift at a wind speed of 10 m/s.

The hardness of snow at the surface layer ranged from 3 g/cm^2 to 150 g/cm^2 as shown in Table 1. The author could not find a clear correlation between snow hardness and lengths of saltation $\bar{L}$. There was a close correlation between the degree of saturation of drifting snow and the saltation length; the influence of snow hardness upon saltation lengths could not be distinguished from the effect of drift density.

The values of $\bar{L}$ observed on the mountain slope with an incline of 16° to 28° are found to be shorter by about 20～30% than those in the flat plain as seen in Fig. 19, where the values on the slope are marked as +. This fact affected the quantity of Q on the slope, which also decreased by 20～30%. But the quantity of G for the wind speed V in the flat plain is almost equal to that on the mountain slope.

III. 6. *The relation between the degree of saturation of snow-drift and the mean length of saltation paths of snow particles in connection with erosion and deposition*

In the previous sections, where the drift rate Q, the rebound mass G and the mean saltation length $\bar{L}$ were discussed, it was confirmed that Lines A_Q, A_G and $A_{\bar{L}}$ are closely interrelated by eq. (III. 3) and Lines B_Q, B_G and $B_{\bar{L}}$ are also interrelated but in a less strict degree. This was briefly explained by the conception of the degree of saturation of snow-drift.

Here the author intends to discuss this problem in connection with deposition or erosion, the vertical distribution of wind speeds and the shear stress at the snow surface. In a snow field with a sufficient space for a development of drifting snow, snow-drift which is generated at a point develops into the drift in a state of saturation as regards the capacity of transporting snow particles by the wind. In such a case, the author calls the state of snow drift stationary. The magnitude of a drift, however, oscillates along the wind direction after the snow-drift is fully developed (Fig. 21). Дюнин (1963) observed the oscillation of the quasi-static pressure and the concentration of snow particles in the wind tunnel ; he was of the opinion that this oscillation might explain the origin of the relief seen atop the snow cover which appears often under drifting conditions.

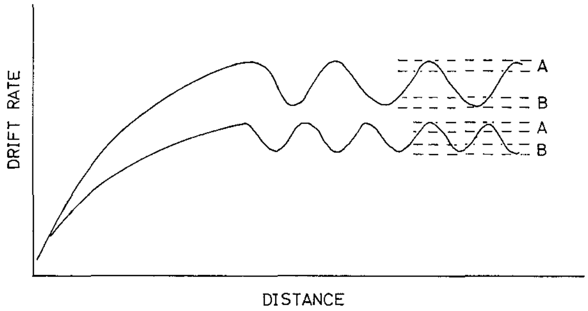


Fig. 21. Schematic curves of a development stage of drifting snow and oscillation of drift rate after the full development of snow-drift

In the flat plain, depositional surface and erosion surface appear one after another while a snow-drift is running. The observation of saltation was, however, restricted to such a snow surface that was not so rough, because a rough surface tends to disturb regular saltation paths of drifting snow particles. The example of the observed surface is shown in Fig. 22a. Figure 22b shows a typical surface undergoing erosion in its early stage ;

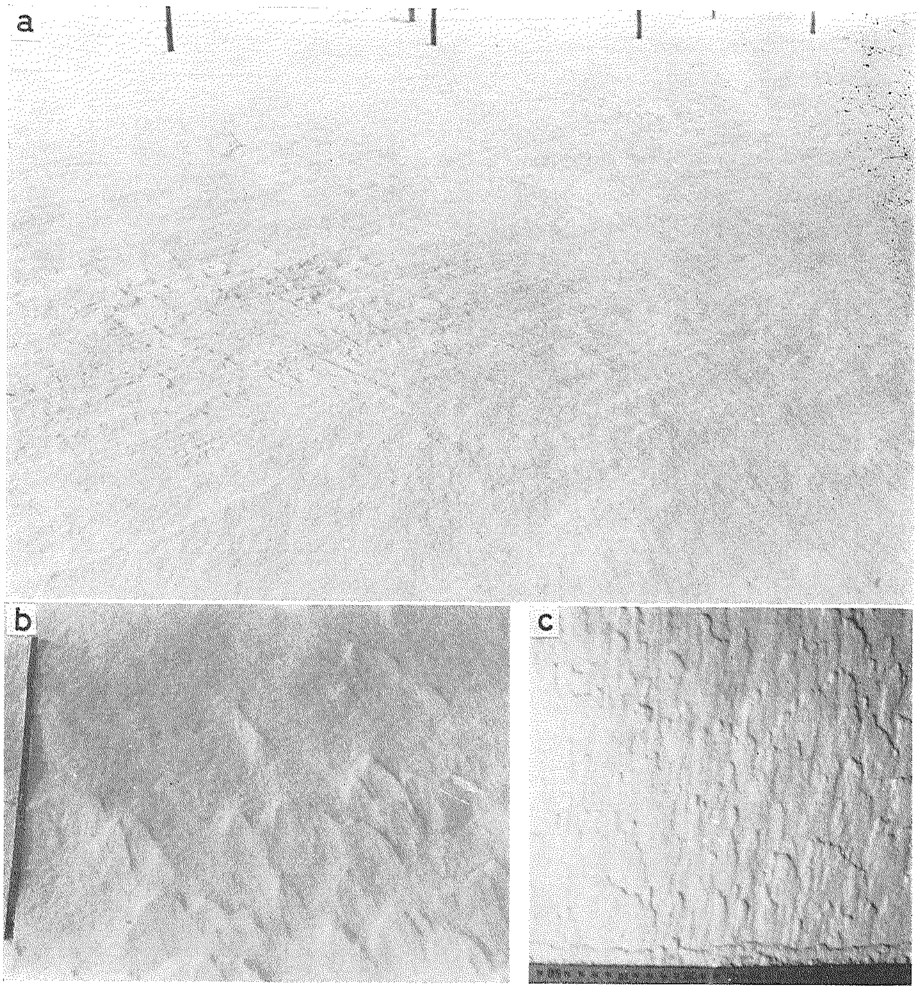


Fig. 22. **a :** A typical example of observed snow surface.
b : Erosion surface with tiny sastrugi.
c : Depositional surface with a scale like pattern

its pattern is of tiny sastrugi. Figure 22c shows a typical depositional surface; a scalelike pattern is seen. It was confirmed that this scalelike pattern was formed when drifted snow was actually deposited.

In most data observed on the depositional surface, the lengths of saltation paths $\bar{L}$ are short and Line A_L in Fig. 19 represents the saltation path length under the depositional conditions. On the other hand, Fig. 16 shows that the plotted points of the rebound mass G on the depositional surface are at a higher part which are represented by Line A_G in Fig. 16. And it is also seen in Fig. 15 that the drift rate Q is relatively greater on the depositional surface than on the erosion surface, though the difference is not so remarkable as to G in Fig. 16 and as to $\bar{L}$ in Fig. 19. These states in which drift rates are high may correspond to the states shown in the neighbourhood of the crests of the semi-stationary waves representing snow-drift rates (cf. Fig. 21). It is not confirmed theoretically that the drift rate at the crests of the drift rate waves corresponds to the saturated drift rate of the snow transport capacity of the wind, but it was observationally confirmed that the states represented by Lines A in Figs. 15, 16 and 19 are of depositional.

On the contrary, the lengths of saltation paths observed on the erosion surface are long as represented by the points near Line B_L in Fig. 19. And the plotted points of the rebound mass G are located at the lower part represented by Line B_G. The plotted points of the drift rate Q on the erosion surface are also located at a relatively lower part and they are roughly represented by Line Q_B. These erosion states are probably equivalent to the states shown in the neighbourhood of the troughs of the drift rate waves (cf. Fig. 21). These erosion states are unsaturated states of drift rates and are represented by Lines B for the sake of convenience, but these states have quantitatively wide ranges of Q, G and $\bar{L}$.

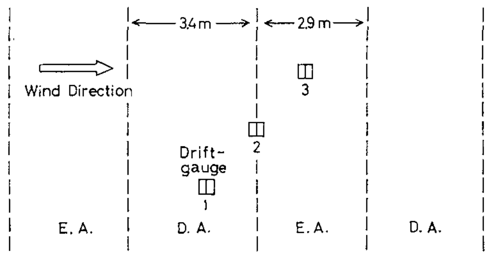


Fig. 23: Sketch of locations of box-type drift gauges.
D. A.: depositional area.
E. A.: erosion area.

An additional simple experiment was attempted to confirm the above explanation on the saltation length and the drift rate wave. Three couples of box-type drift gauges were spaced for a simultaneous measurement on the snow surface as shown in Fig. 23 (Gauge No. 1—in the area of deposition, No. 2—at the boundary, No. 3—in the area of erosion). The 1 m wind speed was 9.3 m/s and there was no snowfall during the drift observation. The mass of snow deposited in the boxes during 60 sec and the estimated values of the rebound mass G were as follows:

gauge No.	1	2	3
deposited snow in the first box (g)	54.2	45.6	40.8
in the second box (g)	30.7	23.9	33.7
G (g/m^2·s)	6.0×10	5.0×10	3.8×10

The value of G in the depositional surface is clearly larger than that in the erosion surface. The distribution of deposited mass of snow suggests that the saltation length in the depositional area is shorter than that in the erosion area and that the drift rate in the former may be larger than that in the latter.

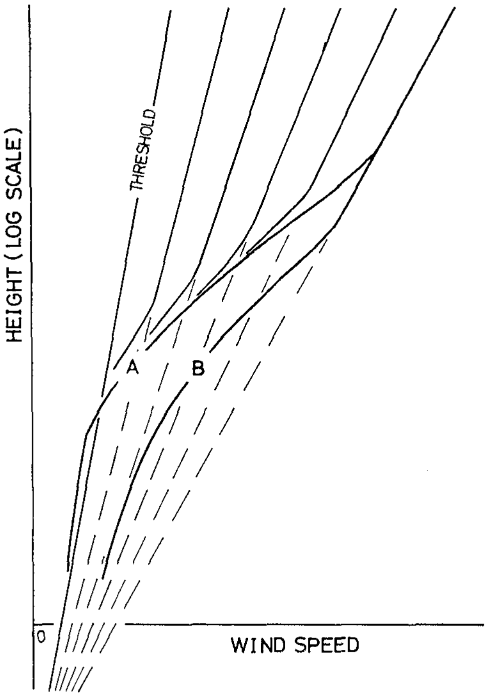


Fig. 24. Schematic wind profiles assumed to be modified by drifting snow

To illustrate more physically the difference between the depositional and erosion states, the author shows a schematic representation of the distribution of wind speeds against heights in Fig. 24. When snow-drift is absent, it is said that there is a logarithmic relationship between the wind speed and the height, i.e., the wind speed and the log-height have a straight-line relationship. This logarithmic relationship is shown in Fig. 24 with a bundle of straight lines which focus on a height called roughness parameter.

When snow-drift takes place, the movement of snow particles will modify the state of wind at a low level in which snow particles are concentrated. These phenomena were confirmed in the case of sand storms by Bagnold (1954) and by Kawamura (1951) but in the case of snow storms the deviation of wind profile was observed only by Дюнин. The author has not yet measured the wind profile at a very low level below $2\sim3$ centimeters, but from the observation of the mechanisms of saltation the deviation from the logarithmic profile like in Fig. 24 may be assumed to exist. It is estimated from the results both in Figs. 6 and 7 that a wind deviation layer has a thickness of only 1 or 2 cm and this thickness increases as the wind speed increases. The threshold wind speed profile is assumed to be a straight line as shown in Fig. 24. The deviated wind profile cannot exist at the left side of the threshold line of Fig. 24, that is, a snow-drift does not occur in the range of the wind profile lower than that line of the threshold wind speed.

In the case of heavy snow storm in the saturated state the deviation is large and the wind profile comes near the threshold line or slightly exceeds that line to the lower speed domain at a lower level as represented by Line A. On the contrary, in the case of light snow-drift, i. e., in the unsaturated state, the deviation is not so large as Line A and the deviated wind profile may be like Line B. And these deviations of wind profiles will oscillate between LINES A and B according to the oscillation of drift rates as shown in Fig. 21. And in the case of Line A snow particles will deposit on the snow surface and in the case of the Line B the snow surface will be eroded.

The frictional force exerted on a unit area of snow surface, denoted by τ_0, is divided into two drags, τ_w and τ_s, then

$$\tau_0 = \tau_w + \tau_s , \qquad \text{(III. 9)}$$

where the drag τ_w is caused by the wind friction and the drag τ_s is caused by the rebound of snow particles on the snow surface. If the snow particles strike the snow surface with the mean horizontal velocity $\bar{u}_1$, and rebound from the surface with the mean horizontal velocity $\bar{u}_2$, the momentum loss due to the impact of snow particles on a unit area within a second will be

$$G \cdot (\bar{u}_1 - \bar{u}_2),$$

where G is the mass of particles rebounded on a unit area within a second. And this momentum loss is equal to τ_s, then

$$\begin{aligned} \tau_s &= G \cdot (\bar{u}_1 - \bar{u}_2) \\ &= G\bar{u}_1 \left(1 - \frac{\bar{u}_2}{\bar{u}_1} \right). \end{aligned}$$

Assuming that the ratio $\bar{u}_2/\bar{u}_1$ is constant as one of the horizontal restitution coefficients,

$$\tau_s \propto G \cdot \bar{u}_1 , \qquad \text{(III. 10)}$$

The snow particle velocity $\bar{u}_1$ will be proportional to v which is the wind speed at a low level with a height of 2~3 mm above the snow surface. This fact was ascertained by the observation with a high-speed cine-camera at a low wind speed of about 5 m/s. From the field data on the saltation length of snow particles in Fig. 19, it may be estimated that the mean length $\bar{L}$ is directly proportional to the wind speed. Consequently the drag τ_s is estimated to be proportional to the drift rate Q, so that eq. (III. 10) leads to

$$\begin{aligned}\tau_s &\propto G\cdot\bar{u}_1\\ &\propto G\cdot v\\ &\propto G\cdot\bar{L}\\ \tau_s &\propto Q\,. \qquad \text{(III. 11)}\end{aligned}$$

The conditions of erosion of snow particles from the snow surface are as follows. The first condition is that impulsive force of a falling snow particle is great enough to break snow particles free from the snow surface. The second condition is that the wind has the remainder of transport ability which is large enough to remove snow particles from the snow surface.

If the wind speed is constant, the total drag τ_0 is the same in the two states A and B shown in Fig. 24. Therefore, eq. (III. 9) leads to the relation

$$\tau_{sA}+\tau_{wA}=\tau_{sB}+\tau_{wB}\,, \qquad \text{(III. 12)}$$

where the subscripts A and B denote the states A and B in Fig. 24 respectively. The drift rate Q_B is smaller than the drift rate Q_A at the same wind speed, so τ_{sB} is smaller than τ_{sA} by eq. (III. 9). Consequently τ_{wB} is larger than τ_{wA} by eq. (III. 12) and in the state B the wind has the remaining transport ability nearly equal to the drag difference $(\tau_{wB}-\tau_{wt})$, where τ_{wt} is the wind drag of the threshold wind profile. Comparing the state A with the state B the drag τ_{wB} is relatively large, so the wind speed at the low level in the state B must be so large as to impel the drifting snow particles to have enough impulsive force to break snow particles free from the snow surface. This ejecting force may be also assumed to be proportional to the wind shear force $(\tau_{wB}-\tau_{wt})$. Thus the shear force $(\tau_{wB}-\tau_{wt})$ may be called erosion force. This mechanism of erosion is not strictly confirmed, but, as described before, the author observed the fact that in the case of erosion the drift rate was small and the saltation length was long compared with those in the case of deposition.

As a special case of the state of erosion, observations made in the initial state of generation and development of a snow-drift disclosed that the snow surface was being violently eroded over a wide area. Since the drift rate Q is very small in that initial state, the drag τ_w may be large and the length of saltation must be very long.

The conditions of deposition are contrary to those of erosion. The first condition of deposition is that the snow transporting ability of the wind is saturated or supersaturated. The second condition is that the wind becomes too weak for a saltation motion to occur successively or for a saltating snow particle to eject another snow particle on the surface. The drift conditions in the state A are considered to satisfy these conditions. The drift rate Q in this state is large and consequently the drag τ_{sA} is so large as to make the drag τ_{wA} smaller than the threshold drag τ_{wt}. So unable to drive snow particles away, the wind abandons the overloaded part of drifting snow and deposition occurs on the snow surface. The field data show that, in most cases of saturated drift rates, surface patterns are depositional and the lengths of saturation paths are comparatively short.

III. 7. *The restitution coefficient of small ice spheres on a thick ice plate*

In the previous section, the saltation motion was treated simply without considering snow conditions such as snow surface hardness or snow temperature. As far as the author observed, these snow conditions did not have a clear effect on the snow-drift rate or on the behaviour of saltation motion. However, snow particles in the drift continue their saltation motion by getting kinetic energy from the wind and losing a part of their energy while hitting the snow surface. The behaviour of the motion on the snow surface must be influenced by snow conditions. It is a fact that the threshold wind speed for snow-drift increases as the air temperature increases from $-7°C$ to $0°C$ (OURA *et al*, 1967).

A simple laboratory experiment of the impact motion was carried out in an effort to find out the coefficient of restitution of small ice spheres on a thick ice plate. Ice spheres were made by plunging water droplets into liquid nitrogen. The size of each ice sphere was 2.5 mm in diameter. They

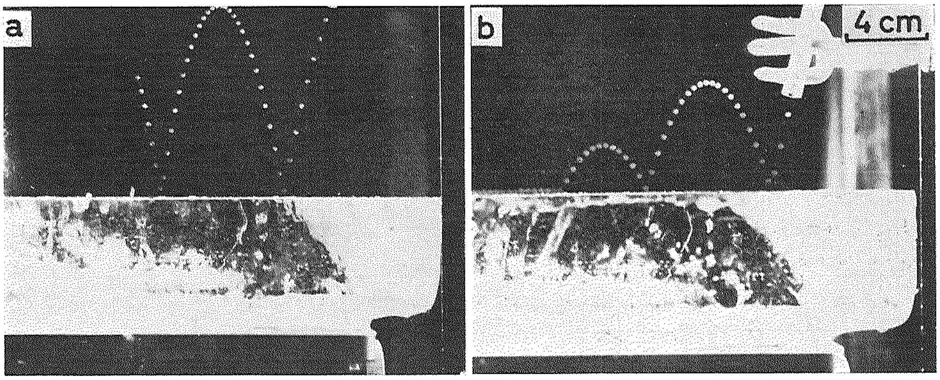


Fig. 25. Examples of bouncing ice spheres on a thick ice plate. Series of spots were made by strobolight flashing every 10 ms.
Temperature **a**: $-21°C$, **b**: $-1.5°C$

were dropped on the thick ice plate at various temperatures and the behavior of their bouncing motion was photographed with the aid of strobo-light illumination.

Two examples of the bouncing ice spheres are shown in Figs. 25a and 25b. The left side photograph (Fig. 25a) was taken at a temperature of −21°C and the right one (Fig. 25b) at −1.5°C. The results of the experiment of bouncing are shown in Fig. 26, where the coefficients of restitution are plotted against the room temperature. The restitution coefficient is determind by the ratio of the velocity components of an ice sphere, normal to the ice plate surface, at the instants immediately after and immediatly before the impact. As is shown in Fig. 26, the restitution coefficient decreases as the temperature increases. This means that the loss of kinetic energy at the instant of impact becomes larger as the temperature increases.

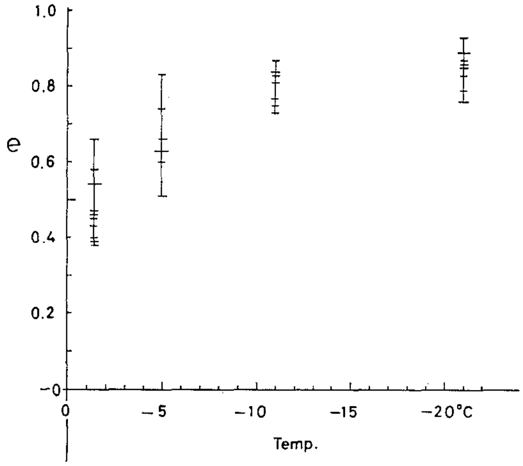


Fig. 26. Temperature dependence of restitution coefficient e of small ice spheres on a thick ice plate

The height of rebound was observed to be almost proportional to the square of the coefficient of restitution for the same velocity of collision. As is shown in the photographs in Figs. 25a and 25b, the differences in the heights of rebound among different temperatures are remarkable. It is a well-known fact that the wind speeds in the flat plain increase exponentially with the increase in height. So the height of rebound of a snow particle is an important factor for maintaining snow drifting by the transfer of kinetic energy from the air to snow particles. Consequently at high temperatures snow-drift is of rare occurrence. A similarity is suggested between the experiment, which was done with ice spheres and an ice plate, and the case of snow particles against the snow cover as regards the results of the experiment.

IV. Direct measurement of the total drift amount by a trench method

IV. 1. *The method of the drift measurement and the observational condition*

One of the main objectives of studies on drifting snow has been to estimate the snow-drift rate for various wind speeds, as is shown by a fact that many investigators have been mainly concerned with the measurements of the snow-drift rate. The majority of these investigators gauged drift fluxes at several levels, using so-called snow drift traps. And the total drift rate was computed by integrating each drift flux with respect to height. However, conventional drift gauges are found inaccurate to measure drift fiuxes in the layer closest to the snow surface in spite of the fact that this layer contains the maximum mass flux. This fact includes the danger of miscomputing the drift rate using extrapolated values for the layer closest to the snow surface.

OURA and D. KOBAYASHI (1966) tried to trap most of the amount of snow-drift directly by using wide trenches, 1.8 m in width, perpendicular to the wind direction. Their main purpose was to observe the occurrence of snow-drift from the snowfield lying between the trenches.

After this trial the author succeeded in taking photographs of the trajectories of saltating snow particles as described in Chapter II in this paper. Then it was learned that the main mechanism of snow transport was saltation and that few snow particles could pass across a trench of 1.8 m in width.

The author intended to make a direct measurement of the amount of snow-drift using trenches in an effort to determine drift rates for various wind speeds. He also tried to find out the threshold wind speed for snow-drift to be generated, using the results of the measurements of drift rates.

Measurements were made on the Experimental Farm of Hokkaido University in Sapporo, Japan (Fig. 12). The windward space was about 700 m in length and 500 m in width; the leeward space was about 100 m in length and 500 m in width. A pair of parallel trenches were dug to the direction perpendicular to the wind 7 times from January to February in 1969; the dimension of a trench was 1.6~1.8 m in width, 0.6~0.8 m in depth and 10 m in length. The distance between the two parallel trenches was 3 m in most cases. The leeward trench was dug as an auxiliary trench to capture the drifting snow which passed over the windward trench. The results of observations disclosed that this leeward trench was not necessary except the occasion when the wind speed was over 10 m/s.

During a snow-drift, coloured water was sprayed from the windward into the trenches as time markers at an interval of 30 to 60 minutes, which was adjusted according to the intensity of snow-drift.

After the snow-drift measurements were made of the amount of the drifted snow, which was trapped during each time interval. The method of measurement of drifted snow is as follows. Firstly vertical pit walls of snow along the wind direction are made at two points in each trench. Secondly, by fitting a transparent sheet of vinyl resin on this wall, boundary lines coloured with the spray as are shown in Fig. 27 are traced so that the drift during each interval can be sketched. Thirdly, the density of snow deposited in each interval is measured. Finally, the mass of drifted snow is calculated by multiplying the snow density by the cross sectional area of the drift snow deposited in each time interval. A cross sectional area is measured much more accurately by this method than by using a photograph, because the latter does not necessarily reduce an actual area in uniform proportion. Direct snowfalls into the trenches were eliminated by comparing the amount of drifts in the windward trench with that in the leeward trench. The collection efficiency of trenches was nearly 100% for wind speeds lower than 6~7 m/sec and more than 90% for a wind speed of 10 m/sec. But no correction was made in this regard in this study.

As a wind-speed instrument a cup anemometer was used at a 1 m height and the wind speed was determined by the distance traveled by the wind for each interval during a drift. The amount of drift is mainly

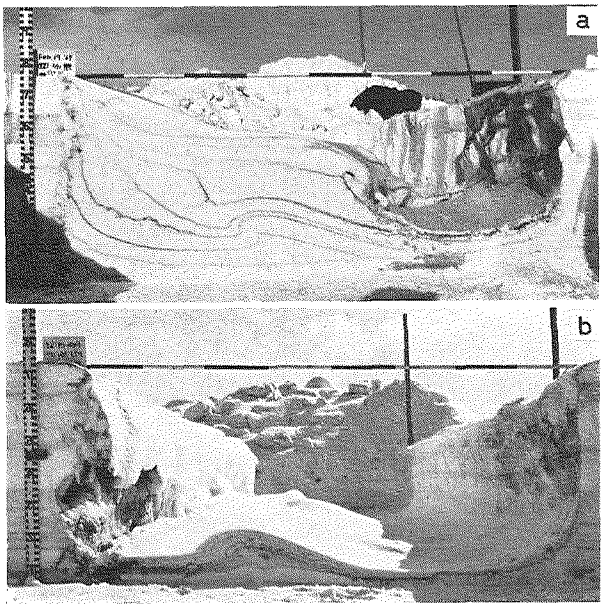


Fig. 27. Vertical sections of trenches.
a: windward trench
b: leeward trench
The wind direction is from left to right

dependent on the wind speed, but, at the same time, it is influenced by snow surface conditions. Therefore the conditions of the snow surface such as snow temperature, density and hardness (by KINOSITA's method) were observed. The projective diameters of drifting snow particles were also measured on the replicas of the particles. The replicas were made by catching drifting snow particles on a glass plate which was covered with a 1% solution of Formvar in ethylene dichloride. The size distribution of drifting snow particles which are usually observed in the same snow field in Sapporo where this investigation was conducted were reported by KOJIMA (1969).

IV. 2. *Determination of the maximum snow-drift rate*

Table 3 shows the general information and data on measurements of snow-drift rate with a trench method. They are the wind speed, the range of variation of wind speed with time, the wind direction, the total amount of snow-drift, the duration of a drift, the drift rate, the temperature of snow surface, the qualitative intensity of snowfall, the density and the hardness of snow surface layer, and the sizes of drifting snow particles. The snow-drift rate is the total snow transport quantity which passes through over the snow surface of 1 m in width perpendicular to the wind direction within a second.

Figure 28 shows the snow-drift rate plotted on a logarithmic scale against the wind speed. The run number in Table 3 accompanies each plot in Fig. 28. A snow-drift in absence of a snowfall is distinguished by intersecting on each plot by a bar (-●-) from a snow-drift with a snowfall (●). It may, however, be seen in Fig. 28 that the snowfall does not influence so much the snow-drift rate. This phenomenon may be explained by the following observational data. The amount of snow deposited on the snow surface by snow-drift is 20 times as much as that by a direct snowfall even when the wind speed is as weak as 7 m/s, as is shown in Tables 1 and 2 in Chapter III. This suggests that the snowfall may be a trigger for the generation of snow-drift but after the occurrence of snow-drift falling snow does not play a major role in the amount of drift.

Since the density and hardness of the snow surface were small enough for occurrence of snow-drift except those of Feb. 7th, a correlation between the snow-drift rate and surface snow conditions was not clear. The snow temperatures ranged from -0.2°C to -7.3°C, but they also seemed not to influence remarkably the snow-drift rate.

However, the plots of snow-drift rate versus the wind speed scatter

Table 3. General information and data on measurements of snow-drift rate with a trench method

Date 1969	Hours	Run No.	Wind Spped (Mean) m/sec	Wind Speed (Variation) m/sec	Wind Direction	Amount of Snow Drift g/cm	Duration min	Drift Rate g/m·sec	Snow Temp. °C	Snowfall*	Snow Density g/cm³	Surface Hardness g/cm³	Drift Particle Size mm
1/23	2100												0.2–0.5
		11	4.9	4.4–6.1		60	75	1.3		M			
	2215												
		12	5.1	4.8–5.7		57	60	1.6		M	0.059	9.6	
	2315												
		13	4.7	4.2–5.3	WNW	47	55	1.4	−6.0	M			
1/24	0020												
		14	4.3	3.1–4.7	WNW	15	20	1.3		O			
	0100												
		15	4.8	1.4–5.7		33	40	1.4		L	0.087	14.	
	0305												
1/28	1605												0.5
		21	4.9	3.7–5.9	NW	32	55	0.97	−6.2	M			
	1710												
		22	4.7	3.0–4.9	NW	15	45	0.56	−6.8	S	0.083	11.	
	1845												
		23	4.7	3.2–5.5	NW	30	55	0.91	−7.2	L			
	2000												
2/5	1555												
		31	11.5	9.6–12.0	NW	923	35	44.		S	0.15 (14 h 30 m)	5.2 (14 h 30 m)	
	1630												
		32	13.3	12.0–14.3	NW	1198	30	67.	−0.2	S			
	1700												
2/6	2310												0.1–0.5
		41	9.6	9.3–9.9	NW	287	30	16.	−7.0	M			
	2340												
		42	8.9	7.5–9.8	NW	379	40	16.		H			
2/7	0020												
		43	6.9	6.6–7.1	NW	110	25	7.3		M			
	0045												
		44	6.2	5.6–6.6	NW	(112)	35	5.3	−7.3	S			
	0120												
		45	6.1	4.8–7.4	NW	(115)	80	2.4		O			
	0240												

2/7	1250												
	1410	51	5.7	5.1- 6.0	WNW	100	80	0.21		O	0.20	135.	
	1520	52	6.5	5.8- 7.7	WNW	94	60	0.26	−6.0	O	0.29	300.	
2/15	1145												0.2-0.5
	1320	61	6.9	6.7- 7.4	(NW)	302	95	5.3		O			
	1420	62	7.1	6.6- 7.6	(NW)	300	60	8.3		O			
	1700	63	5.6	4.9- 7.0	(NW)	90	70	2.1		O	0.12	26.	
2/20	1132												0.1-0.3
	1155	71	7.8	7.7- 8.0	NW	150	23	11.		O			
	1224	72	7.8	7.4- 8.5	NW	170	29	9.8	−4.7	O			
	1258	73	6.4	5.9- 7.0	NW	140	34	6.9	−4.0	O			
	1334	74	6.4	5.9- 7.4	NW	135	36	6.3		M, L			
	1435	75	5.1	4.7- 5.2	NW	130	61	3.5	−4.5	S			
	1600	76	4.6	3.6- 5.0	NW	90	65	2.3	−6.0	S			

* H : Heavy snowfall
M : Moderate snowfall
L : Light snowfall
S : Slight snowfall
O : No snowfall

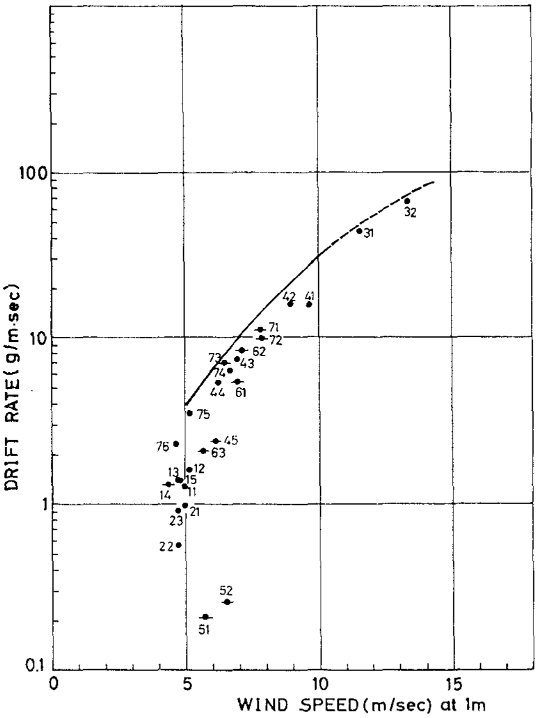


Fig. 28. Snow-drift rate as a function of 1 m wind speed.
-●- : without snowfall
● : with snowfall

widely in particular at low wind speeds even when there is a minor difference in snow conditions. So the threshold wind speed for the occurrence of snow-drift is not distinctly found, but it ranges from 4 m/s to 6 m/s at a 1 m level.

Since the snow surface was soft enough for the occurrence of snow-drift, the observed snow-drift rates should be nearly the saturation values. Such a line may be reasonably drawn as passes the upper limit of the domain of the plots in Fig. 28 of the observed drift rates. It may be assumed that this line shows the ability of the wind to transport snow for various wind speeds. This line is represented by the simple equaton:

$$Q = 0.03\,V^3, \tag{IV. 1}$$

where Q is the snow-drift rate in g/m·s and V is the wind speed in m/s at a 1 m level. This equation may be suitable for the wind speeds which range from 5 to 12 m/s.

The equation of the snow-drift rate which is obtained in Section III-3 by using the snow-drift boxes

$$Q = 0.03\,(V-1.3)^3 \qquad \text{(III. 6)}$$

is different from eq. (IV. 1). The snow-drift rate Q in eq. (IV. 1) gives a greater value than that in eq. (III. 6) against the same wind speed. This difference mainly depends on the length of observational time. The reason is as follows. The drift rate Q is, of course, a nonlinear function of the wind speed which fluctuates always in the flat plain. However, in most cases, the simple arithmetic mean wind speed for observational time is used for the sake of convenience. Consequently, the expression of a snow-drift rate function will be different even for the same mean wind speed according to the variance of wind speeds provided the arithmetic mean of wind speed is used.

For example, let the drift rate be expressed by

$$Q = a(V-b)^3, \qquad \text{(IV. 2)}$$

where a and b are constants. Let V_i be the wind speed for a short period and $\bar{V}$ be the arithmetic mean of V_i for a relatively long period T. Then the following inequation will generally hold:

$$\frac{1}{T}\sum a\,(V_i-b)^3 \geq a\,(\bar{V}-b)^3.$$

The longer the period is, that is, the larger the variance of wind speeds is, the larger the difference between both sides of the inequation is. So if one wants to express the drift rate Q by eq. (IV. 2) using an arithmetic mean wind speed $\bar{V}$, he must change a or b according to the length of observational time. And generally the longer the period is, the larger the drift rate is for the same arithmetic mean wind speed. Equation (III. 6) is based on observations during 1 to 3 minutes and eq. (IV. 1) is based on those during 30 to 90 minutes.

IV. 3. *The results by other investigators*

There have been many reports on the relation between the snow-drift rate and the wind speed. But the method and the instrument of the measurement of the wind speed and the treatment of the data are naturally different, depending on individual investigator. It is presumable that the reported contributions of the wind speed to the drift rate are not the same, because the observational periods are different. Consequently it is difficult to compare the results by different investigators and a careful comparison is called for.

The typical equations of drift rates reported by different investigators are summarized in the following table, where added to equations (A) and (B) are equations (C)~(F) which were shown in Дюнин's report (1954):

D. KOBAYASHI (1969)	$Q = 0.03\, V^3$	(A)
BUDD, DINGLE & RADOK (1965)	$\log Q = 1.15 + 0.115\, V$	(B)
Мельник (1952)	$Q = 0.092\, V^3$	(C)
Дюнин (1954)	$Q = 0.0334\left(1 - \frac{4}{V}\right) V^3$	(D)
Дюнин (1954)	$Q = 0.0234\,(1.062\, V - 4)^3$	(E)
Иванов (1951)	$Q = 0.0295\, V^3$	(F)

In these equations Q is the snow-drift rate in g/m·s and V is the wind speed at a 1 m level in m/s. These equations are represented by the curves in Fig. 29, each of which accompanies the same symbol as the foregoing capitals.

Иванов's equation is accidentally almost the same as the author's. But the observational time and the snow conditions for his equation are not given by Дюнин.

Дюнин reported many other observational data and many other equations of drift rates in relation to wind speeds but the values of Q given by those equations are included in the range of Q by the two equations (D) and (E). Дюнин's observational time ranged from 1 to 3 hours and the air temperature during a snow storm was in the range from -20°C to -30°C, while the duration of the author's observation was from 30 to 90 minutes. Дюнин's equation (E) gives almost the same values of Q as the author's data plotted in Fig. 28.

Мельник's equation shows relatively higher values of the snow-drift transport rate. Дюнин pointed out that Мельник's equation was most applicable for the total amount of snow-drift for a long period such as an entire winter. SHIOTANI (1958) measured the accumulation of snow around a snow storm prevention forest during a winter and reported that Мельник's equation is satisfactory for estimating the total amount of snowdrift in a winter from the records of wind speeds through the winter. The author also considers that Мельник's equation may be reasonable for the long period estimation of the amount of snow-drift according to what was pointed out in the previous section.

BUDD, DINGLE and RADOK (1966) pursued a detailed study of drifting

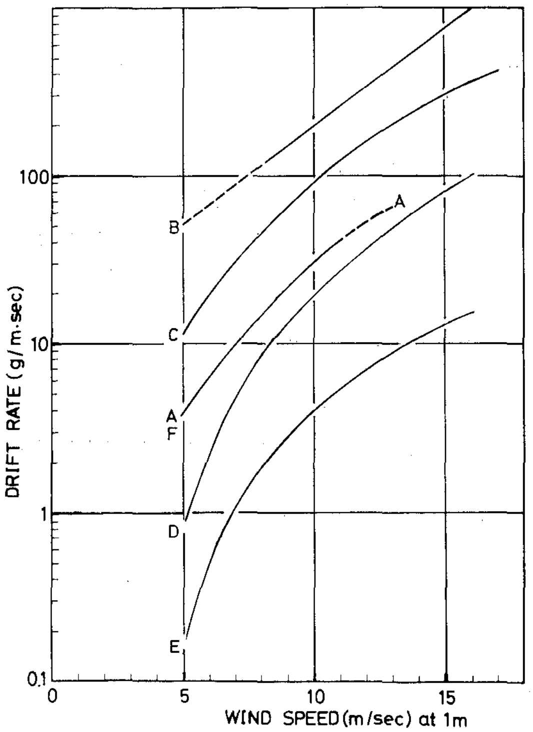


Fig. 29. Comparison of different investigators'data on snow-drift rate. A: KOBAYASHI, D., B: BUDD, W., C: Мельник, D. M. (after Дюнин), D and E: Дюнин, A. K., F: Иванов, B. V. (after Дюнин)

snow at Byrd station during 1962~1963 using Mellor drift traps; they reported eq. (B), which gives, however, the highest drift rate as shown in Fig. 29. They calculated drift-snow rates in the layer from 1 mm to 300 m above the snow surface using an extrapolation on the basis of their measurements of drift fluxes at 8 levels between 400 and 3.125 cm above the snow surface and derived eq. (B). Their typical exposure periods of drift gauges are in a range of 10 to 60 minutes, which are nearly the same as the observation periods of the author and Дюнин. It may be said that the estimation of Budd and others gives too large values at least for wind speeds lower than 10 m/s at a 1 m level.

V. Generation and development of drifting snow

V. 1. *Growth lengh of drifting snow*

In a snow field which has a sufficient space for the development of drifting snow, the drift transporting capacity of the wind may be approximately saturated with drifting snow and the snow-drift rate may be roughly uniform everywhere. Of course, as pointed out in Section III–6 (Fig. 21) the snow-drift rate may fluctuate but the amplitude is not so large and the wave is not standing, so the time averages of drift rates will be approximately the same everywhere after the full development of the snow-drift. Such a state may be called a stationary state of drifting snow. The snow-drift rate treated in the previous chapter is the drift value in a stationary state.

This chapter describes the generation of drifting snow and the process of its development, mainly the growth length required for a fully developed state or a stationary state to be formed. This development process is schematically shown in Fig. 21 by the curves indicating an increasing stage of the drift rate. The knowledge of the growth length of drifting snow is helpful for clarifying the mechanism of drifting snow and is useful for abating the nuisance of drifting snow, especially for selecting the efficient location of a snow fence or of a snow storm prevention forest.

OURA and D. KOBAYASHI began the study of the growth length from January in 1965 by the wide trench method as mentioned in Section IV–1. They estimated in January in 1966 that the growth length was from 20 m to 30 m when the wind speed was about 5 m/s. Thereafter the author observed the growth length more than 10 times and concluded that the growth length, required for the snow-drift rate quantity to develop to 90% of that in a stationary state, is from 30 m to 60 m.

Мельник studied this problem in 1952, observing the drifting snow before and after a valley at a point 200 m distant leeward from the valley, and found that the drift value at the leeward was 1/15 to 1/19 times as small as that at the windward of the valley (**Дюнин** 1963). **Дюнин** (1963) studied in detail the growth length both in a wind tunnel and in the field; he reported that the growth length in the field varied from 200 m to more than 500 m according to snow conditions. But **Дюнин** did not give a clear conclusion as to the result in the field.

V. 2. *The method of measurements of growth length*

To investigate the process of development of snow drift the following method was adopted. At first, a long trench of 10～35 m in length, perpendicular to the main wind direction, was dug in a snow field; for the sake of convenience, this is named trench *A*. Next, some shorter trenches 6～10 m in lengths were made at various distances leeward from trench

A and each of them is called trench *B* (Fig. 30). The sizes of the trenches are 1.6 to 1.8 m in width and 0.7~0.9 m in depth. Trench *A* has a sufficiently spaced windward field and catches almost thoroughly the amount of snow-drift which may be in a stationary state. Starting from the leeward edge of trench *A*, a snow-drift newly generates and increases its quantity mainly by saltation bombardment of snow particles onto the snow surface as it goes leeward. Trench *B* catches the amount of snow-drift generated in the snow field between trenches *A* and *B*. The way in which the drift rate increases with the distance indicates the process of snow-drift development; this can be made known by observing the drift amount deposited in each leeward trench *B*. The method of the measurement of the drifted snow in the trenches is similar to the method described in Section IV–2. To compare a development process of a run of snow-drift with that of another, the author normalized the drift amount and/or rate by taking the ratio of the drift amount and/or rate at leeward trench *B* to that at windward trench. *A*.

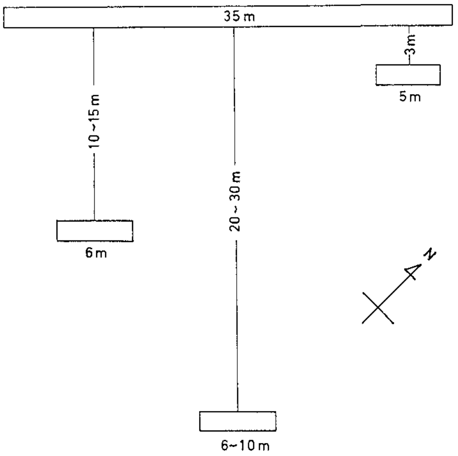


Fig. 30. Locations of trenches for measurements of growth length of snow drift

The snow drift development was observed by the trench method 12 times from January to February both in 1969 and in 1970 on the Experimental Farm of Hokkaido University in Sapporo. The author and OURA studied this problem previously by the following method different from the trench method. They spaced 6 rocket-type snow-drift gauges at 20 m intervals along the wind direction on the flat snow field in the leeward of the Ishikari River, which is 250 m wide. The foremost windward gauge was situated at a distance of 10 m from the leeward bank of the river. There was no ice cover in the Ishikari River at that time, namely on March 17th, 1968. Since all the snow-drift from the windward of the river was, therefore, plunged into the river, the snow-drift was newly generated from the place near the leeward bank. The bank was not higher than the surface level of the snow field. The entrance of the rocket type drift gauge was 2.3 cm in diameter and the center of the entrance was set at the level

Table 4. General information and data on measurements of growth length of snow drift

Date	Hours	Run No.	Wind Speed m/sec	Wind Direction	Air Temp. °C	Snow-fall*	Amount of Snow-Drift (Windward Trench) q_A g/cm	Duration min	Drift Rate g/m·s	Distance between Trenches m	Amount of Snow-Drift (Leeward Trench) q_B g/cm	Ratio Q_B/Q_A $(=q_B/q_A)$
1966. 1. 30	(0000) 0200	1	(4.5)	(WNW)	−6.5	O	697	—	—	11	375	0.54
1968. 3. 17	1635 1705	2	(11)	NW	−2.0	M	(9.1)	30	—	30	(6.7)	0.75
1969. 1. 23	2100 2215	3-1	4.9	WNW	−6	M	67	75	1.5	19.5	49	0.73
1. 24	0020	3-2	4.9			M	117	115	1.7	19.5	87	0.75
	0100 0305	3-3	4.8			L	33	40	1.4	19.5	24	0.72
1969. 1. 28	1605 1710	4-1	4.9	NW	−6.2	M	41	55	1.2	18.5	26	0.63
	2000	4-2	4.7	»	−7.0	L	59	100	1.0	18.5	39	0.66
1970. 2. 2	1120 1300	5-1	10.2	NW	0	M	431	100	7.2	30	361	0.84
	〃	5-2	〃	»	〃	»	〃	〃	〃	15	272	0.63
1970. 2. 10	(0350) 0530	6-1	9.0	NNW,NW	(−5.0)	O	1387	100	23.1	31	956	0.69
	〃	6-2	〃	»	〃	»	〃	〃	〃	15	949	0.68

1970. 2. 21	2350 0120	7-1	5.0	WNW	−4.7	M	270	70	6.4	16	157	0.58
	〃	7-2	〃	»	〃	»	〃	〃	〃	16	155	0.57
1969. 2. 5	1555 1630 1700	8-1	11.5	NW	(0)	L	763	35	36	3	160	0.21
		8-2	13.3	NW	−0.2	»	954	30	53	3	244	0.26
1969. 2. 6	2310 2340	9-1	9.6	NW	−6.5	H	200	30	11	3	47	0.23
1969. 2. 7	1250 1410	10-1	5.7	WNW	(−5)	O	100	80	2.1	3.1	≃0	≃0
1969. 2. 15	1145 1320	11-1	6.9	—	(−5)	O	240	95	4.2	3	62	0.26
1969. 2. 20	1132 1224 1258 1600	12-1	7.8	NNNWW	−5.6	O	280	52	9.0	3.05	46	0.16
		12-2	6.4	»	−4.0	O	131	34	6.4	3.05	10	0.08
		12-3	5.2	NW	−6	L	323	162	3.3	3.05	39	0.12

* H : Heavy snowfall
M : Moderate snowfall
L : Light snowfall
O : No snowfall

5 cm above the snow surface. The snow drift gauge was set only at one level at each point, so the total amount of snow-drift was not obtainable. Then it was assumed that the mass of snow caught in the drift gauge was directly proportional to the total amount of snow-drift and the process of snow-drift development was estimated by comparing the mass of snow caught in each drift gauge.

V. 3. *Growth length for 90% saturated drift rate*

The results are summarized in Table 4, where the data obtained at the bank of the Ishikari River are shown in the second line (run No. 2) and the data obtained by the trench method are shown in the rest of the table. Most of the items including date, hours and run No. are almost common with those in Table 3 in Section IV–2 except the last two columns. The distances between windward and leeward trenches A and B are measured along the wind direction and the maximum distance was 31 m. The last column of Table 4 shows the ratio q_B/q_A, where q_A is the drift amount in trench A and q_B is that in trench B; this ratio q_B/q_A is equal to the ratio Q_B/Q_A, where Q_A is the drift rate at trench A and Q_B is that at trench B.

The observation of run No. 2 was performed on the shore of the Ishikari River by using rocket-type drift gauges (Section V–2). The mass of snow-drift caught in the gauge during 30 minutes is as follows: 6.7 g (at a point 30 m from the bank), 9.2 g (70 m), 8.5 g (90 m), 9.5 g (110 m). Although gauging was not successful both at 10 m and 50 m points, it can be estimated, from the above data, that the snow-drift was developed to the stationary state before the 70 m point. So the author adopted the mean mass of snow caught in the gauge at the 70 m, 90 m and 110 m points as the representative value of the mass for the stationary state; this mean value is shown with parentheses in the column of the amount of snow-drift q_A. The mass of snow caught in the 30 m point gauge is shown in the column q_B. From these two values the ratio of the amount of snow-drift was calculated.

Figure 31 shows the process of snow drift development. Plots of the drift ratio Q_B/Q_A $(=q_B/q_A)$ against the distance x from windward trench A show a gradual increase but the plots scatter. The numbers attached to the plotted points are the run numbers of Table 4. It is difficult to explain systematically the reason for the scattering of the plots of Q_B/Q_A.

In the process of snow-drift growth, drifting snow particles repeat successive saltation on the snow surface and occasionally eject other particles

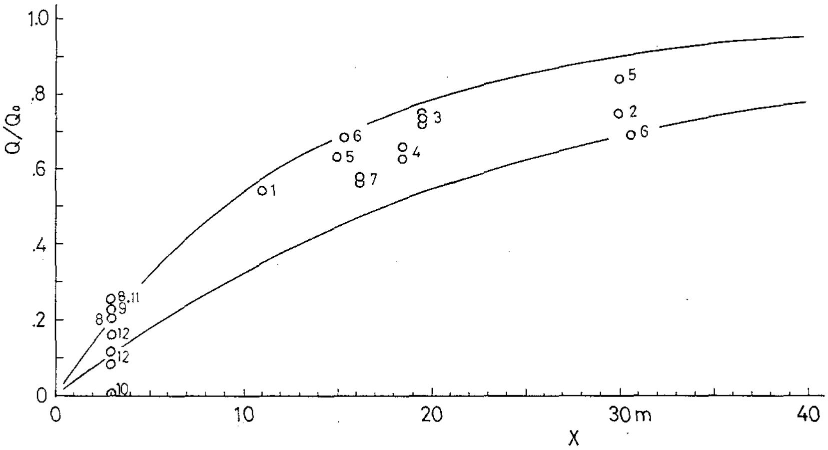


Fig. 31. Increase of drift ratio (Q/Q_0) for the distance (x) from windward trench A

from the snow surface by impact and the wind carries them away with successively saltating snow particles. The author previously mentioned the condition of erosion taking place on the snow surface in the case of unsaturated snow-drift. The mechanism of snow-drift growth is similar to that of the erosion discussed in Chapter III. So the newly added rate dQ of snow-drift, between the distances x and $x+\mathrm{d}x$, will be proportional to the erosion shear force $(\tau_{wB}-\tau_{wt})\,\mathrm{d}x$, where τ_{wB} is the wind shear force when the drift rate is Q_B at the distance x and τ_{wt} is the threshold wind shear force. The threshold wind shear is assumed to be constant during a run of snow-drift. In this case the threshold wind shear force will be equall to τ_{wA}, which is the wind shear force in the case of the stationary snow-drift Q_A.

$$\mathrm{d}Q \propto (\tau_{wB}-\tau_{wA})\,\mathrm{d}x\,. \tag{V. 1}$$

The wind shear force τ_{wB} will decrease as the snow-drift rate Q_B increases and as the drag by saltating snow particles τ_{sB} increases. The added drift rate d$Q(x)$ of snow-drift in the distance dx will, therefore, decreases gradually as it goes down leeward.

These are represented mathematically as follows. In Section III-6 it was shown that the drag τ_s is proportional to the drift rate Q and that the total shear stress $(\tau_s+\tau_w)$ is constant.

$$\tau_s \propto Q\,. \tag{III. 11}$$

$$\begin{aligned}\tau_0 &= \tau_{sA}+\tau_{wA}\\ &= \tau_{sB}+\tau_{wB}\,. \end{aligned} \tag{III. 12}$$

From eqs. (III. 11) and (III. 12)

$$\begin{aligned}\tau_{wB}-\tau_{wA}&=\tau_{sA}-\tau_{sB}\\&\propto Q_A-Q_B\,. \qquad \text{(V. 2)}\end{aligned}$$

Thus eq. (V. 1) is expressed with the drift rates Q_A and Q_B using eq. (V. 2)

$$\mathrm{d}Q \propto (Q_A-Q_B)\,\mathrm{d}x\,. \qquad \text{(V. 3)}$$

Here introducing the constant of proportionality $1/\alpha$ and replacing Q_B by Q and Q_A by Q_0, eq. (V. 3) becomes

$$\frac{\mathrm{d}Q}{\mathrm{d}x}=\frac{1}{\alpha}(Q_0-Q)\,. \qquad \text{(V. 4)}$$

Integration of eq. (V. 4) under the boundary condition $Q=0$ for $x=0$ gives

$$\frac{Q}{Q_0}=1-\mathrm{e}^{-\frac{x}{\alpha}}\,. \qquad \text{(V. 5)}$$

To determine the value of the constant α, the values $(1-Q/Q_0)$ are plotted against the distance x in Fig. 32 by using the same data in Fig. 31. It is found that α ranges from 13 m to 26 m by calculating the slopes of the two straight lines in Fig. 32 covering the domain of the plots of the observed data. This means that the growth length, required for drifting snow to develop to 90% of the snow transport capacity of the wind, ranges between 30 m and 60 m. These distances are shown in Fig. 32 on the line $1-Q/Q_0=0.1$. These two lines are also entered in Fig. 31. The observed data at the shore of the Ishikari River also shows that snow-drift develops to the stationary state in a distance shorter than 70 m.

The mean length $\bar{L}$ of saltating snow particles must be relatively long at the initial stage and decreases gradually as snow-drift develops. This

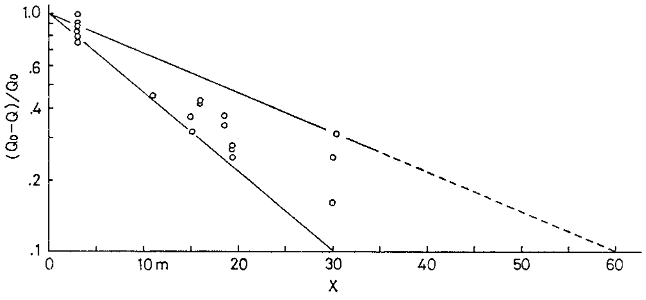


Fig. 32. Logarithmic representation of drift development of Fig. 31 for determination of growth length for 90% saturated drift rate

estimation is reasonable on the basis of the observed data in Chapter III. However, there is no data on actual lengths of saltation paths at the initial stage of drift development. The mass of rebounding snow particles G on a unit area per unit time is logically zero at the initial stage of snow-drift development and G will gradually increase. If G is assumed to increase in proportion to the distance x as a first approximation, the saltation length $\bar{L}$ may be estimated to decrease linearly with x, because the drift rate Q given by the snow-drift development equation (V. 5) is approximately represented by a quadratic equation of the distance x on the way of development when adequate coefficients are adopted. This is expressed by the following formulae. From eq. (V. 5)

$$Q = Q_0(1-e^{-\frac{x}{\alpha}})$$
$$\doteqdot -mx^2+nx\,,$$

where m and n are positive constants and $0<x<n/2m$. Assuming that

$$G = ax\,,$$

and considering the relation

$$Q = G\cdot\bar{L}\,, \qquad \text{(III. 3)}$$

$\bar{L}$ is given by

$$\bar{L} = -bx+c\,,$$

where a, b and c are also positive constants.

At the initial stage of snow-drift development, the number of bouncing snow particles is small but each snow particle has a comparatively high speed and has large erosive force. As the snow drift develops, drifting snow particles increase their number but each snow particle has not so high speed as that in the initial stage and its erosive force decreases. So the above assumption that the increasing rate a of G is constant seems not so unnatural except near the range of the final stage of snow-drift development.

According to the above assumption, the constant a representing the newly added mass of snow-drift in a distance of 1 cm in a lane of 1 cm in width within a second is estimated to range from 0.4×10^{-6} (wind speed: 5 m/s) to 7×10^{-6} g/cm²·s/cm (10 m/s) from the observed data in Fig. 16 when snow-drift develops to the 90% saturated value in a distance of 30 m.

The effect of a snowfall on snow-drift will be as follows: The snowfall supplies almost all free snow particles on the snow surface and when the wind speed is relatively low for snow-drift to occur, the snowfall plays a role of a trigger for the generation of snow-drift. Since there were often snowfalls when the author was observing snow-drift as seen in Table 4, the distances of snow-drift development described in this paper may be somewhat short compared with those in the case of the hard snow surface without a newly deposited snow layer. The snow condition for the occurrence of snow-drift is, however, very complicated especially when the wind speed is lower than 6～7 m/s. There are many cases when merely a trigger cannot generate snow-drift. In the field, soon after natural snow-drift ceased and when the wind speed is 6～7 m, the author failed many times to generate snow-drift artificially by supplying snow particles on the snow surface.

The effects of wind speeds on the growth lengths of snow-drift development are not clearly seen in the observed data. KAWAMURA (1951) studied the same problem on blowing sands in a wind tunnel and reported that strong winds lengthened the saltation paths of sand particles and that for this reason the rate of increase of sand-drift became small as the wind speed increased. It may be said that in the case of a snow storm in the field the snow particles which elongate saltation paths have stronger erosive force than those with shorter paths and that the effect of the wind speed on the distance of snow-drift development is not so simple as KAWAMURA pointed out in the case of a sand storm.

VI. Concluding remarks

Observations were performed as regards snow-drift with an aim to cover drift in close proximity to the snow surface, where the heaviest drift takes place, for any investigators had never undertaken such a study as covered snow-drift at levels so close to the snow surface as this one. The results and discussions offered in the preceding chapters are summarized as follows.

1. The behaviour of drifting snow particles was observed by taking photographs, which showed that low-level snow-drift was maintained mainly by saltation motion and that drift concentration increased exponentially as the level lowered downward to the snow surface.

2. By use of box-type drift gauges for the clarification of the mechanism of saltation motion, the following empirical formulae were obtained for the case in which the snow-drift rate was in a saturation state:

$$\bar{L} = 0.011\, V$$

$$G = 3.0\,(V - 2.1)^2$$

$$Q=0.03\,(V-1.3)^3$$

where $\bar{L}$ is the mean saltation length in m, V is the wind speed at a 1 m level in m/s, G is the rebound mass on the snow surface in g/m^2·s and Q is the drift rate in g/m·s. The mean length $\bar{L}$ was elongated when the drift rate was in an unsaturrted state and the upper limit of observed lengths was about three times the lengths represented by the above formula. These data on the saltation motion obtained under various drifting conditions gave some clue to a reasonable explanation accounting for the deposition or erosion of the snow surface. The drift rate Q and the rebound mass G on the erosion surface are smaller than those on the depositional surface and the saltation length $\bar{L}$ on the erosion surface is longer than that on the depositional surface.

3. The measurement of the mass of snow-drift is the main purpose of the drift study. However, no investigator has hitherto been successful in direct measurements of the total amount of snow-drift because of the difficulties in observing drift fluxes at levels close to the snow surface, where the heaviest drift takes place. Direct measurements of the total amount of snow-drift were tried in this work by use of wide trenches dug in the snow cover, over which drifting snow particles with saltation motion could not pass. This trench method revealed that the maximum snow-drift rate Q in g/m·s was related to the wind speed V at a 1 m level in m/s by the empirical formula $Q=0.03\,V^3$. The maximum snow-drift rate will give a clue to construct a theory of snow transport by the wind. This value is also useful for the planning of controlling drift deposits and for the estimation of water balance in the polar regions.

4. The development of snow-drift was observed by the same trench method, where by growth lengths for 90% saturated drift were determined to be in a range from 30 to 60 m. The data of growth lengths are practically useful for selecting the efficient location of a snow fence and are helpful for clarifying the mechanism of snow transport.

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