Studies on Accumulation-Ablation Processes and Distribution of Snow in Mountain Regions, Hokkaido

by

Tomomi YAMADA
山 田 知 充
The Institute of Low Temperature Science

Received February 1983

Abstract

Orographic characteristics of solid precipitation and accumulation-ablation process of snow in the mountain regions were studied based on the areal distributions of newly fallen snow and of deposited snow in typical mountain regions in Hokkaido throughout accumulation and ablation seasons for several winters. Some simple general rules were found of the distribution of snowfall and the increase and decrease of deposited snow in mountain slopes. The rules allow one to estimate the snow amount at an arbitrary altitude and time from the data of solid precipitation and temperature at the piedmont observatory together with the data of only one snow survey at an altitude.

*Contribution No. 2527 from the Institute of Low Temperature Science
北海道大学審査学位論文

Contents

I. Introduction 3
II. Areas and methods of observation 4
III. Results of observation 8
III. 1. General remarks on the accumulation-ablation process of snow 8
III. 2. Altitudinal distribution of the amount of snow 10
III. 3. Correlation among snow increases at various altitudes on a mountain slope 13
IV. Estimation of snow amount in a mountain slope 15
IV. 1. Method of estimation 15
IV. 2. Example of the estimation of snow amount 15
V. Consideration of ablation process 17
V. 1. Possibility of estimating maximum amount of snow from snow-line observation 17
V. 2. Heat balance of snow layer in ablation period 18
V. 3. Estimation of melting amount of snow 19
VI. Synoptic Analysis of snow distribution in Hokkaido 20
VI. 1. Estimation of maximum amount of snow in Hokkaido 20
VI. 2. Winter monsoon and the estimated snow distribution 25
VI. 3. Remarks on snow in the alpine zone 26
VI. 4. Accumulated snow in a drainage basin of a river 27
VII. Concluding remarks 30
Acknowledgement 31
References 32

I. Introduction

Water consumption of Japan, amounted to some 1.15×10^{11} ton already in 1977 (United Nations, Statistical Yearbook, 1977), has been and will be growing with the upgrading of civil life as well as the increse of industrial and agricultural production. On the other hand, the annual amount of the precipitation over Japan is estimated some 6.7×10^{11} ton (Yamazaki, 1981). Though 2.0×10^{11} ton is lost by evapo-transpiration, the residue seems to be enough to meet the ever-increasing demand far in the future. However, the precipitation distributes in time and place not coincidentally with the demand and one needs some forms of water reservoir for the effective use of the precipitation.

Fortunately in the regions between Japan sea coast and the central divide, a considerable part of the annual precipitation is snow caused by the prevailing northwesterly wind in winter monsoon season. For instance, snow exceeds 30% of the annual precipitation in Ishikari plain, Hokkaido (43°N) and 50% in coastal plains in Hokuriku prefectures (38°N). Though observation are lacking, the percentage is certainly larger in the mountain regions than in plains. The deposited snow, especially in the mountain regions, melting gradually from early spring to summer to flow into rivers and to cultivate ground water systems, serves as a good natural water reservoir.

The importance of the deposited snow in mountain regions as water resources having been fully appreciated, snow surveys in mountain regions had been actively performed after the Second World War, surveying area reaching some 8600 km^2 till 1954 (Ishihara, 1956). These surveys were aimed, however, rather to know the maximum amount of deposited snow in a particular year over a particular drainage basin than to clarify orographic characteristics of precipitation.

The latter clarification is important because if one knows some general rules governing the increase and decrease of deposited snow in the mountain regions one may be able to estimate the maximum amount of deposited snow in any year over any drainage basin by much an easier way than a laborious snow survey over an entire basin.

I had carried out for several years snow surveys in typical mountain regions in Hokkaido not only at the end of the accumulation season but at a few times through the accumulation and ablation seasons every year and found some of such general rules.

In the present paper, first the method of investigation and the choice of surveyed area are described (Chapter II) and the results are summarized and the rules concerning the altitudinal distribution of snow amount are deduced (Chapter III). Then it is shown that the rules allow one to estimate the snow amount at an arbitrary altitude and at an arbitrary time from the data of the piedmont observatory together with the data of one snow survey at an altitude (Chapter IV) or with the knowledge of the snow-line altitude at an arbitrary time in the ablation season (Chapter V). Since the snow-line altitude over a wide area at a time can be

known from a satellite image, the last method is very useful to estimate, though only in retrospect, the snow amount over a wide area. The distribution of snow amount over Hokkaido in 1978-79 winter is estimated by this method from the satellite images taken on May 21 and 22, 1979 (Chapter VI.1). The comparison of the estimated snow amount over a drainage basin and the discharge data of the river shows that the estimation is not unreasonable (Chapter VI.4). Also, some qualitative characteristics of snow on mountain slopes are discussed (Chapter VI. 2, 3).

Though the rules are deduced from the observations in mountains in Hokkaido, it seems likely that the rules are valid and the methods of estimation of snow amount described in this paper may be applicable for the mountains in Honshu if there is clearly definable accumulation and ablation seasons.

II. Areas and methods of observation

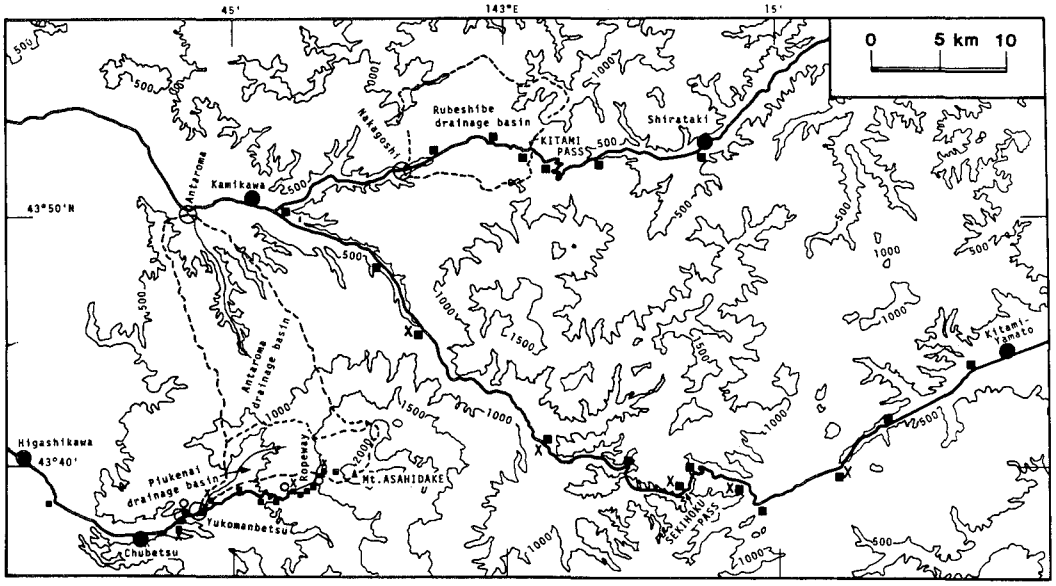
Observation areas should be easy to access because for the purpose of the present study frequent snow surveys are necessary. They should naturally be typical of mountain slopes in Hokkaido. From these two criteria I chose as the observation areas the western slope of Mt. Asahidake (2290 m a.s.l.), the highest mountain in Hokkaido, the eastern slope of Mt. Teine (1024 m a.s.l.) on the western rim of Sapporo, Mt. Youtei (1893 m a.s.l.), an isolated peak, and both western and eastern slopes of several passes going through the central divide of Hokkaido. The western slopes are all windward and the eastern leeward of the prevailing northwesterly in the winter monsoon season. The areas are tabulated in Table 1 together with the years and the items of observation, and also indicated by squares is Fig. 1 on the map of Hokkaido with 200, 600, 1000 and 1400 m a. s. 1. contours, the last being the boundaries of black areas. Because timberlines are at 1300 to 1400 m a. s. 1. in Hokkaido, the black areas are considered alpine zones.

The detailed arrangements of observational sites in the three most intensively observed areas, Mt. Asahidake, Sekihoku Pass, and Mt. Teine are shown in Figs. 2 and 3, where solid squares denote the sites of snow survey (Items 1, 2 and 4 in Table 1), crosses the sites where a snow depth recorder was set (Item 3) and open circles the sites of meteorological observation (Items 5 and 6).

As seen in Fig. 2, the observational sites in Mt. Asahidake were distributed from 300 to 1800 m a. s. 1. in the drainage basin of River Chubetsu. There the area below 400 m is the continuation of comparatively flat cultivated land, the area from 400 to 1400 m is a forest of coniferous trees with 20 to 30 m high, and above 1400 m a shrubbery zone gradually changes to an alpine flora zone with increasing altitude. On the both sides of Sekihoku Pass, shown also in Fig. 2, the 400 m altitude is the boundary of a forest zone and a cultivated land.

At Mt. Teine, as shown in Fig. 3, observations were mainly made on a wide gentle ridge entirely covered from the top (1000 m a. s. 1.) to the foot (100 m a. s. 1.) with a mixed forest

Fig. 1 Areas of observation shown by squares on the topographical map of Hokkaido with the contours of 200, 600, 1000 and 1400 m a. s. l., the last being the boundaries of solid areas; the area enclosed by dotted line showing the drainage basins discussed in Section VI. 4



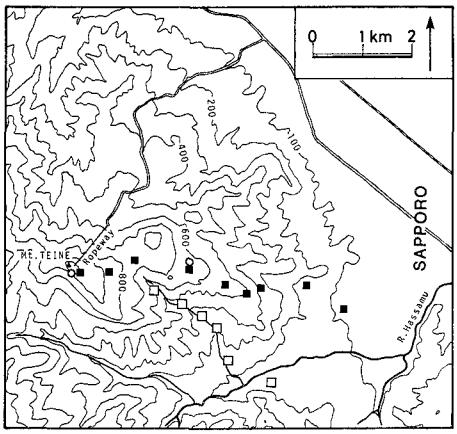


Fig. 2 Observational sites along the courses of snow survey in the west slope of Mt. Asahidake, Sekihoku Pass and Kitami Pass regions; solid squares denote the sites of snow survey, crosses the sites where snow depth recorders were set up, open circles the sites of meteorological observation and solid circles meteorological observatories; the areas enclosed by dotted line show the drainage basins discussed in Chapter VI. 4; the big open circles at the lower part of the drainage basins indicate the hydrological observatories

Fig. 3 Observational sites in Mt. Teine region; solid squares and open squares denote the sites of snow survey on the ridge and in the valley, respectively; open circles the sites of meteorological observation

of coniferous and deciduous broadleaf species. The sites denoted by open squares in Fig. 3 along the neighboring valley were snow-surveyed only once in April 1978.

The main purpose of snow survey is to measure the water equivalent of snow, H_W , that is, the weight of snow cover over horizontal unit area, which is the most important quantity in this study (Item 1). One can most easily measure H_W by taking vertical cores from the surface to the bottom of snow cover. By definition

$$H_W = W/A, \tag{1}$$

Where W is the total weight of the cores and A the cross-sectional area.

Since on a mountain slope H_W varies from point to point even in a small area, many

Table 1 Areas, years and items of observation

observation area	year	items of observation
Mt. Asahidake	1977-78	1,3,4,5,6
	1978-79	1,3,4
	1979-80	1,2,3,4,5,6
Sekihoku Pass	1978-79	1,3
	1979-80	1,3
Mt. Teine	1977-78	1,4
	1978-79	1,4,5,6
	1979-80	1
Mt. Youtei	1977	1,4,5,7
Kitami Pass	1979-80	1
Karikachi Pass	1979-80	1
Nisshou Pass	1979-80	1
Nakayama Pass	1979-80	1

1. Water equivalent of snow and snow depth
2. Amount of solid precipitation in short period
3. Snow depth measured by snow depth recorder
4. Amount of snowmelt and snow temperature
5. Air temperature
6. Wind velocity
7. Altitude of snow line in melting season

measurements and some averaging procedure is necessary to get a representative valve of H_w at a site. To take cores to the bottom being laborious, the following procedure was adopted:

The above equation is transformed into

$$H_w = (W/AH) \cdot H, \tag{2}$$

where H is the total length of the cores or the depth of snow cover and the factor (W/AH) is the mean density of snow over the depth. A measuring area of 10 to 20 m^2 was assigned to a site and three to five series of coring to the bottom were done to give an average of the first factor, while ten to twenty measurements of the depth with a snow sonde gave an average of the second factor. The product of the two average values was taken as the representative value of H_w at the site.

A snow sampler 20 cm^2 in cross section and 3 m long, decomposable to four tubes each 75 cm long, was used to take cores for this measurement.

A series of measurements were carried out in 1980 at Mt. Asahidake of the contribution of each snowfall to H_w (Item 2). The contribution, h_w, which is by definition the difference of H_w after and before the snowfall, was directly measured as follows: Colour paint was

sprayed over snow surface. After the snow-fall, a core was taken down to below the colored stratum with a short sampler 50 cm long and 25 cm^2 of cross section.
Apparently,

$$h_w = W'/A, \tag{3}$$

where W' is now the weight of the part of core above the colored stratum. To get a representative value, similar procedures to the case of H_w were used where, however, the depth of the stratum was measured on the wall of a pit.

As mentioned before, snow depth recorders were set at a number of points (Crosses on Fig. 2) to monitor the change of the snow depth. The recorder which utilizes a bundle of optical fibers ingeniously and is powered by a battery can record snow depth up to 2 m in an accuracy of 1 cm at hourly intervals for 3600 hours (Takahashi and Aburakawa 1976; Aburakawa 1979). The most important knowledge obtained from the record was the number of snowfalls between two successive snow surveys.

An important quantity in ablation season is the amount of melted snow, M, from time t_1 to t_2, which is defined by

$$M = H_w(t_1) - H_w(t_2), \tag{4}$$

where $t_2 > t_1$ and both are in ablation season. The quantity M was estimated either according to the definition or as the product of the density of melted layer and the depression of snow surface measured by a snow pole. The depression in ablation season can be regarded entirely due to melting. Together with M, the temperature distribution of snow was measured to check the occurrence of runoff which takes place when snow cover warms up to 0°C throughout.

In Mt. Teine, air temperature, wind velocity, net radiation and humidity were measured together with the amount of melted snow at the sites 650 m and 1015 m a. s. 1. from April to May 1979 for the study of heat budget in ablation season, while in Mt. Asahidake, air temperature and wind velocity were recorded at the sites 630 m, 1015 m and 1595 m a. s. 1. by battery-powered recorders from Dec. 1977 to May 1978 and from Dec. 1979 to May 1980. A long-term temperature recorder made by Akitaya (1978) was used for the measurement of air temperature.

III. Results of observation

III. 1. *General remarks on the accumulation-ablation process of snow*

Data from many meteorological observatories have revealed that at a ground air temperature above 4°C precipitation is generally liquid (rain) while below 0°C solid (snow) and that in the transitional zone between 4°C and 0°C the probability of precipitation being solid

increases from 0% to 100% with the decreasing ground air temperature. Because of this fact, in order for snow cover to increase its amount over a certain period, the ground air temperature T_a (the daily mean, or more adequately the running mean over a few days) should be below 0°C during the period. Otherwise, would-be snowfall may be melted away by would-be rainfall.

In a cold region where such a period exists, the ground air temperature T_a and the amount of snow H_w may change as schematically shown in Fig. 4. Though the first snowfall may occur before the day t_b when T_a reaches 0°C in early winter, the steady snow cover is formed around that day. Then, until the day t_e when T_a comes back to 0°C in spring, H_w is steadily increasing. Appreciable melting occurs only after the day t_m when T_a climbs to 4°C.

The period from t_b to t_e is henceforth called the accumulation period, and that from t_m to the day t_d of the disappearance of snow cover in the ablation period. From t_e to t_m, H_w may oscillates around an average value, which, for convenience's sake, is considered the maximum amount of snow H_{wmax} in the season.

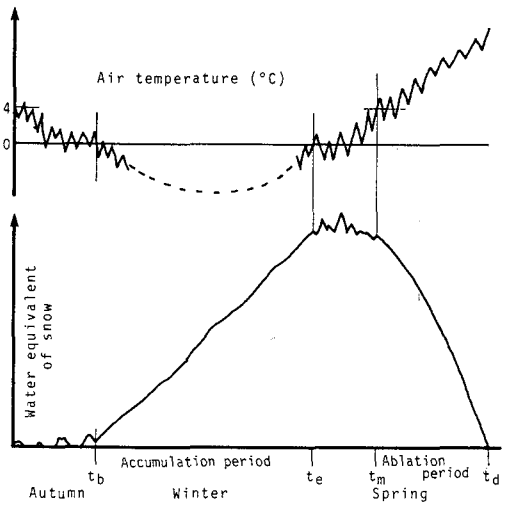


Fig. 4 Relationship between the variations of air temperature and water equivalent of snow with time and definition of critical date for accumulation and ablation process at a site

Now the above consideration concerns the accumulation-ablation process at a site. On a mountain slope, T_a and hence the dates t_b etc. should depend on the altitude z. Generally, the higher the altitude, the lower the air temperature and hence the earlier the date t_b and the later the dates t_e, t_m and t_d,. Thus, on a mountain slope the amounts of snow cover at various altitudes change as schematically shown in Fig. 5.

Several notations and terminologies will be added here concerning Fig. 5 for later use. The date t_b at the top of the slope, that at the piedmont of the slope, the date t_e at the piedmont, the date t_m at the top, the date t_d at the piedmont and that at the top are respectively denoted t_A, t_B, t_E, t_M, t_L and t_D. The period from t_B to t_E is called the accumulation season of the slope because accumulation occurs all over the slope. Similarly the period from t_M to t_D is called the ablation season of the slope. The period from t_E to t_M is the transitional season. Snow-line is discending during the period from t_A to t_B while ascending during the period from t_L to t_D.

Most detailed observations of accumulation-ablation process were carried out at Mt. Asahidake in 1979-80 season. The result of the observations of the daily mean air tempera-

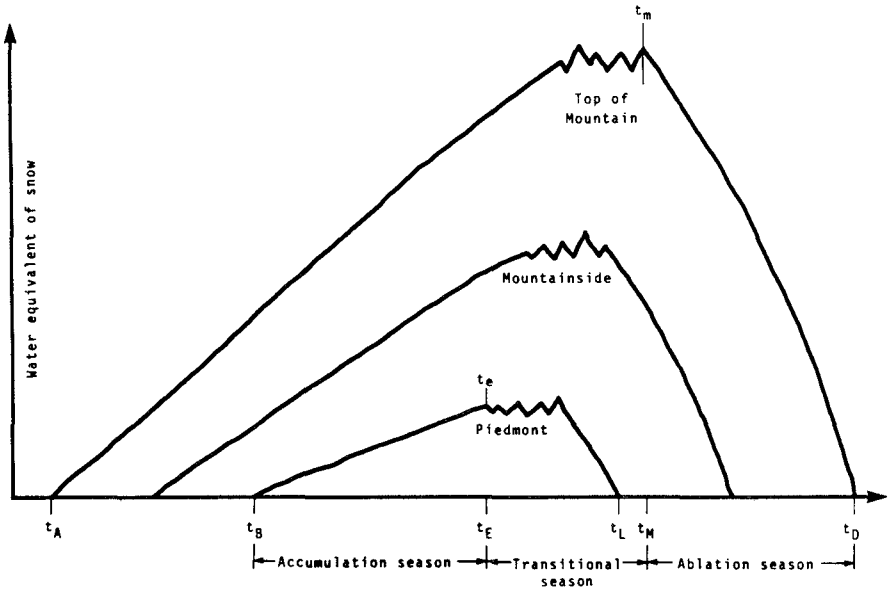


Fig. 5 Variation of water equivalent of snow with time along the mountain slope and definition of critical date

ture T_a at 630 m a. s. 1. and of the amount of snow H_W at various altitudes are shown in Fig. 6, where one can clearly notice that the measured quantities behaved as expected. In this case the accumulation season ended around March 30 and the ablation season bagan around May 10.

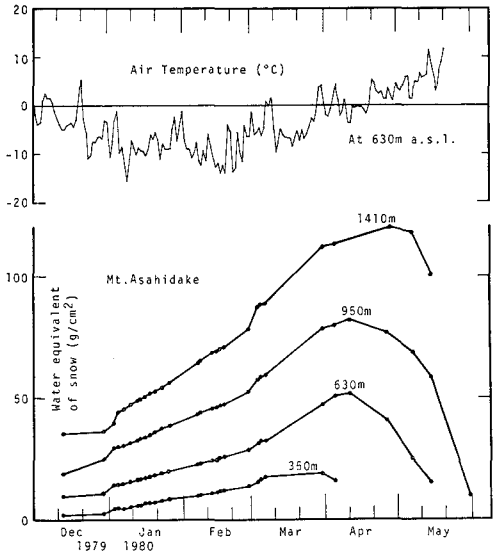


Fig. 6 Accumulation-ablation process along the west slope of Mt. Asahidake and variation of air temperature at 630 m a. s. 1.

III. 2. *Altitudinal distribution of the amount of snow*

Data shown in Fig. 6 are rearranged in Fig. 7 to show the altitudinal distribution of H_W

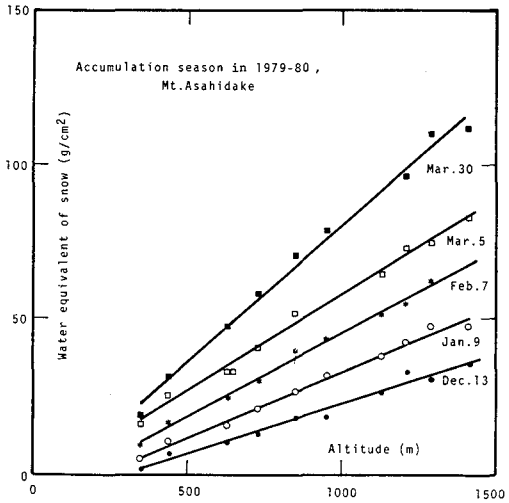
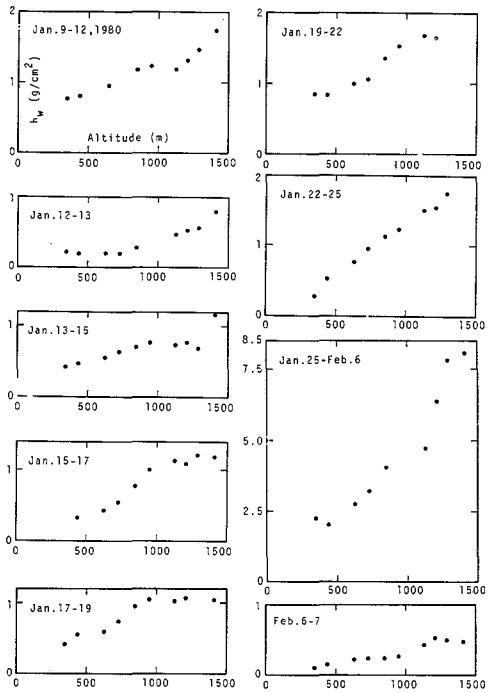


Fig. 7 Altitudinal distribution of water equivalent of snow during accumulation season in 1979-80 in the west slope of Mt. Asahidake



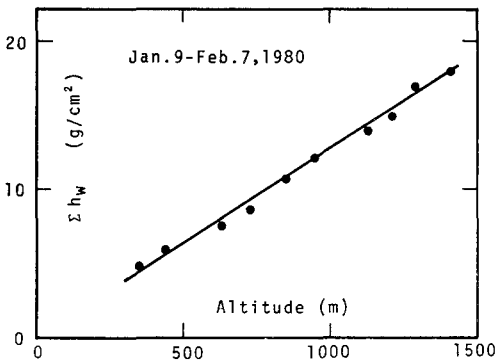


Fig. 8(a) Altitudinal distribution of the amount of newly fallen snow in short periods in the west slope of Mt. Asahidake

(b) Altitudinal distribution of cumulative amount of newly fallen snow in Fig. 8(a) for some one month

at various dates in the accumulation season. As seen from the figure, H_W depends on altitude z approximately linearly throughout the accumulation season, with the slope of the regression line increasing with time. This means that the accumulation amount ΔH_W (z, t_2, t_1) from the date t_1 to the date t_2 is also linearly increasing with z as long as the time interval is about four weeks or longer. To see if such a linear dependence of ΔH_W on z is valid for a shorter interval, I tried to measure the amount of each snowfall h_W from December 29 to March 30. The results from January 9 to February 7 are shown in Figs. 8 (a). Though h_W generally increases with z, it is not necessarily well approximated by a linear function of z. The total amount of snowfall between January 9 and February 7, obtained by adding h_W 's in Figs. 8 (a), which schould be and actually is equal to ΔH_W (z, Feb. 7, Jan. 9) obtained from Fig. 7, is well approximated by a linear function of z as shown in Fig. 8 (b). It seems that for ΔH_W (z, t_2, t_1) to depend on z linearly several snowfalls during the interval are necessary.

As typical altitudinal distributions of H_W in transitional and ablation seasons, the result of observations at Mt. Teine in 1979 are shown in Fig. 9. The distributions are again well approximated by linear functions of z as seen from the figure. Here the transitional season began on March 17 and the ablation season on May 2. The slope of the regression line increases with time during the transitional season because snow melt occurred at the piedmont while snow still accumulated in the upper part of the slope. An unexpected result is that the slope of the regression line remains constant during the ablation season, a fact which will be discussed later in Chapter V.

Though only two examples, one for the accumulation and the other for the transitional and ablation season, are shown, all the other observations listed in Table 1 showed

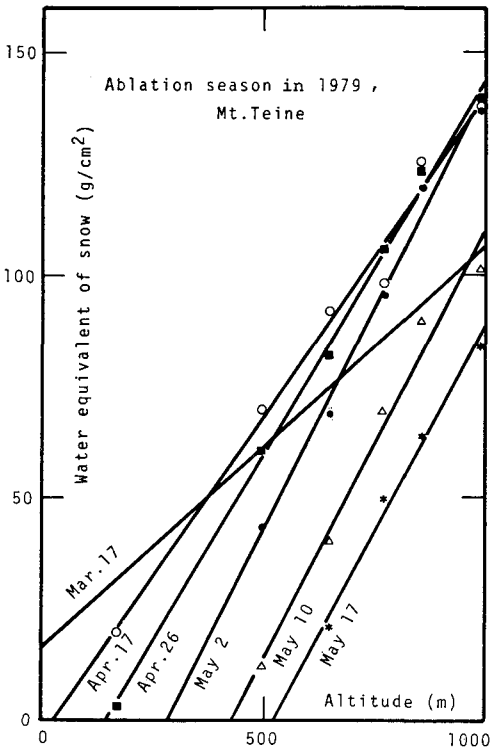


Fig. 9 Altitudinal distribution of water equivalent of snow during ablation season in 1979 in the east slope of Mt. Teine

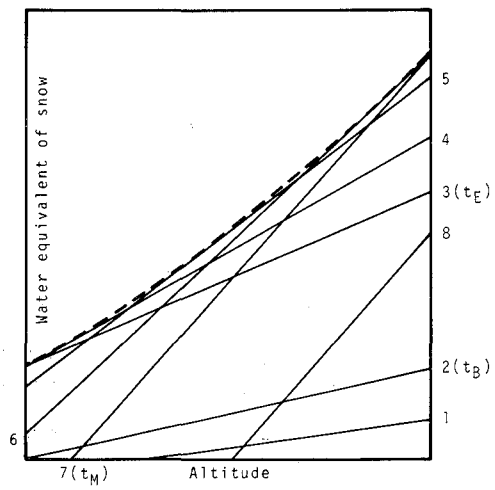


Fig. 10 Variation of altitudinal distribution of water equivalent of snow with time during snow season; dashed line showing altitudinal distribution of maximum amount of snow

similarly the approximately linear dependence of H_W (z) on z (Yamada et al., 1978; Yamada et al., 1979 ; Yamada et al., 1981), which, hence, can be considered a general rule of the amount of snow on a mountain slope. Summarized, the rule is stated as follows:

$$H_W(z) = a(t)z + b(t), \qquad (5)$$

where $a(t)$ is increasing during the accumulation and transitional season while constant in the ablation season and $b(t)$ is decreasing during the transitional and ablation season. The amount of snow on a mountain slope distributed according to the

rule is schematically shown in Fig. 10, where the numbers indicate the progress of the time.

III. 3. *Correlation among snow increases at various altitudes on a mountain slope*

As mentioned in the previous section, the amount of each snowfall $h_W(z_0)$ was measured from December 29, 1979 to March 30, 1980 at various altitudes on the west slope of Mt. Asahidake. Also, the daily record of the amount of precipitation h' at 370 m a. s. l. of the same slope is available from Chubetsu meteorological observatory situated there, which is chosen as the reference site of the altitude z_0. It must be noted here that, as long as the summation is taken in the accumulation season of the slope, $\Sigma h'$ is conceptionally the same as $\Sigma h_W(z_0)$ but their values are not necessarily the same because of the difference of the measuring method of h' from that of $h_W(z_0)$.

Now, the cumulative value of $h_W(z)$ from December 29 to each observation time is plotted against the cumulative value of h' over the same time interval in Fig. 11, which clearly shows the proportionality of the two quantities. Hence,

$$\Sigma h_W(z) = \alpha(z)\Sigma h'. \qquad (6)$$

Evidently, the summation interval is arbitrary as long as it falls in a period from December 29 to March 30 or more generally in the accumulation season of the slope.

The proportional coefficienct $\alpha(z)$, which will be hereafter called the distribution factor, is plotted against z in Fig. 12, which

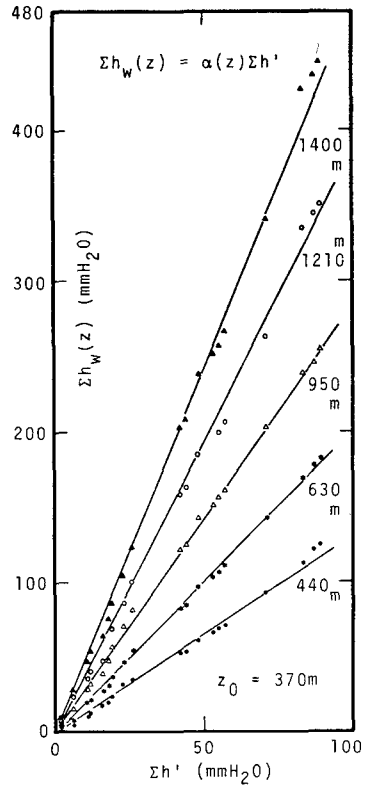


Fig. 11 Relationship between cumulative values of solid precipitation at Chubetsu meteorological observatory of 370 m altitude (z_0) and at various snow survey sites in the west slope of Mt. Asahidake during accumulation season in 1979-80 winter

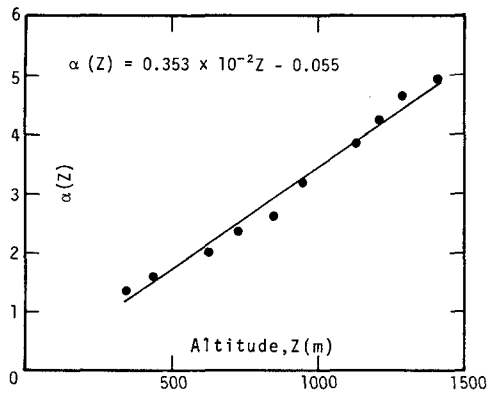


Fig. 12 Altitudinal distribution of distribution factor of solid precipitation, α, in the west slope of Mt. Asahidake in 1979-80 winter

shows that $\alpha(z)$ is approximated by a linear function of z:

$$\alpha(z) = C_1 z + C_2 = \{C(z\text{-}z_0)+1\}/R, \tag{7}$$

$$C_1 z_0 + C_2 = 1/R. \tag{8}$$

The factor R is evidently due to the difference of the measuring methods of $h_W(z_0)$ and h'. If the measurement of $h_W(z_0)$ is considered exact, then R is the capture rate of the precipitation gauge used at the meteorological observatory. In this case from the obtained values $C_1 = 0.353\text{x}10^{-2}(\text{m}^{-1})$ and $C_2 = -0.055$ as shown in Fig. 12 and the assigned value of $z_0 =$ 370 m, R is calculated 0.8.

Any observation site may be chosen as the reference site instead of the meteorological observatory, to give similar relations to (6) and (7). Let the altitude of the new reference site be denoted $\bar{z}_0$. Then from relation (6),

$$\Sigma h_W(\bar{z}_0) = \alpha(\bar{z}_0)\Sigma h' \tag{9}$$

and hence

$$\Sigma h_W(z) = \bar{\alpha}(z)\Sigma h_W(\bar{z}_0), \tag{6'}$$

where

$$\begin{aligned}\bar{\alpha}(z) &= \{C(z-z_0)+1\}/\{C(\bar{z}_0-z_0)+1\} \\ &= [C/\{C(\bar{z}_0-z_0)+1\}](z-\bar{z}_0)+1 \\ &= \bar{C}(z-\bar{z}_0)+1.\end{aligned} \tag{7'}$$

The correction factor R is disappeared in relation (7') as expected.

An interesting conclusion from relations (5), (6) and (7) must be noted here. From the relations, one has

$$\begin{aligned}\Sigma h_W(z) &= \{a(t_2)-a(t_1)\}z + \{b(t_2)-\text{b}(t_1)\} \\ &= (C_1\Sigma h')z + (C_2\Sigma h')\end{aligned} \tag{10}$$

for arbitrary z. This implies that

$$\left.\begin{aligned}\Delta a = a(t_2)-a(t_1) = C_1\Sigma h', \\ \Delta b = b(t_2)-b(t_1) = C_2\Sigma h'\end{aligned}\right\} \tag{11}$$

and hence

$$\Delta a/\Delta b = C_1/C_2. \tag{12}$$

One can easily show that the coordinate z_1 of the intersection of the two regression curves in

Fig. 7 is equal to C_2/C_1. Therefore all regression curves in Fig. 7 should intersect at a single point. This fact seems approximately fulfilled in Fig. 7.

IV. Estimation of snow amount in a mountain slope

IV. 1. *Method of estimation*

The empirical relations (6) and (7) have been derived in the previous section under the condition that the summation interval is in the accumulation season of the slope. Since there is no reason that the precipitation mechanism changes suddenly at the beginning and the end of the accumulation season of the slope, it is natural to consider that the relations are valid even if the summation interval is extended in such periods before and after the accumulation season that precipitation is solid in the higher part of the slope while liquid at the reference site. Then taking the summation from the beginning of the accumulation period at an altitude z, one has

$$H_{\mathrm{w}}(z, t) = \alpha(z) \sum_{t_b(z)}^{t} h', \quad t < t_e(z) \tag{13}$$

and specially

$$H_{\mathrm{wmax}}(z) \simeq \alpha(z) \sum_{t_b(z)}^{t_e(z)} h', \tag{14}$$

where $t_{\mathrm{b}}(z)$ and $t_{\mathrm{e}}(z)$ are respectively the beginning and the end of the accumulation period at an altitude z (see Fig. 4).

The dates, $t_{\mathrm{b}}(z)$ and $t_{\mathrm{e}}(z)$, can be estimated from the record of daily mean air temperature at the reference site with the aid of a suitable lapse rate. Now, the distribution factor $\alpha(z)$ has essentially only one unknown constant C, because the capture rate R is in general a known constant. Hence, in principle, one measured value $H_{\mathrm{w}}(z_1, t_1)$ where t_1 is not later than $t_{\mathrm{e}}(z_1)$ and the record of h' at the reference site together with the knowledge of $t_{\mathrm{b}}(z_1)$ are enough to determine $\alpha(z)$ from relation (13). It seems that the higher the altitude z_1 and the later the date t_1, the better the estimation of $\alpha(z)$. Once the distribution factor obtained, the value of $H_{\mathrm{w}}(z, t)$ at an arbitrary point in the accumulation period, that is, a point (z, t) where $t_{\mathrm{b}}(z) < t < t_{\mathrm{e}}(z)$, can be estimated from relation (13) by $t_{\mathrm{b}}(z)$ and the record of h'.

Summarized, the records of air temperature and of precipitation at the reference site and one measured value $H_{\mathrm{w}}(z_1, t_1)$ are enough to estimate $H_{\mathrm{w}}(z, t)$ at any point in the accumulation period.

IV. 2. *Example of the estimation of snow amount*

In this section, the method described in the previous section will be applied for the west slope of Mt. Asahidake in 1978-79 season and the results of estimation will be compared with the observed values.

In the estimation, one first needs the lapse rate of air temperature, which was assumed 0.5°C/100 m, a value computed by Kikuchi et al. (1979) from their continuous measurements of air temperature at 1070 m and 1595 m a. s. l. on the slope and the data from Chubetsu observatory and confirmed by the similar temperature measurements in 1979-80 season.

From this value of the lapse rate and the air temperature data at Chubetsu observatory in 1978-79 season (Hokkaido Kisho Geppo), the beginning date $t_b(z)$ and the ending date $t_e(z)$ of the accumulation period at six altitudes were estimated and tabulated in Table 2. (Of six values of $t_e(z)$, only t_e(1400 m) is used in the estimation of snow amount.)

Table 2 Estimations of distribution factor and water equivalent of snow at various sites in the west slope of Mt. Asahidake using the maximum amount of snow at 1410 m site and precipitation data at Chubetsu meteorological observatory

Altitude z (m a.s.l.)		z_0=370	600	800	1000	1200	1400
$t_b(z)$	1978	Dec. 3	Nov. 20	Nov. 20	Nov. 7	Nov. 1	Oct. 26
$t_e(z)$	1979	Apr. 5	Apr. 8	Apr. 14	Apr. 20	Apr. 24	May 2
$\alpha(z)$		1.25	1.67	2.03	2.40	2.77	3.13
$\sum_{t_b}^{t_1} h'$	(g/cm²)	6.7	10.5	10.5	14.8	15.7	19.2
$H_w(t_1, z)$	(g/cm²)	8.4	17.5	21.4	35.5	43.4	60.1
$\sum_{t_b}^{t_2} h'$	(g/cm²)	22.1	25.9	25.9	30.2	31.0	34.5
$H_w(t_2, z)$	(g/cm²)	27.6	43.2	52.7	72.5	85.7	108.1

Now, the maximum amount of snow at 1410 m was 147 g/cm² by actual observation while the cumulative value of precipitaion at Chubetsu observatory from t_b(1400 m) (Oct. 26, 1978) to t_e(1400 m) (May 2, 1979) was calculated as 46.7 g/cm². From relation (6), α(1400 m) was estimated as 147/46.7=3.13. On the other hand, α(370 m) should be 1.25, because the capture rate of the precipitation gauge at Chubetsu observatory was known 0.8. These two values of $\alpha(z)$, which were indicated by crosses in Fig. 13, determine the distribution factor as

$$\alpha(z)=0.183\text{x}10^{-2}(\text{m}^{-1})\ z(\text{m})+0.57. \tag{15}$$

The other values of $\alpha(z)$ in Table 2 than the two are calculated from the above equation.

The knowledge of $\alpha(z)$ and $t_b(z)$, and the data of precipitation at Chubetsu observatory allow one to estimate $H_W(z, t)$ at any point. Here, estimations on two dates, Dec. 15, 1978 (designated t_1) and Mar. 2, 1979 (designated t_2), were made. Necessary cumulative values of precipitation at Chubetsu observatory and corresponding estimated values of $H_W(z, t)$ were

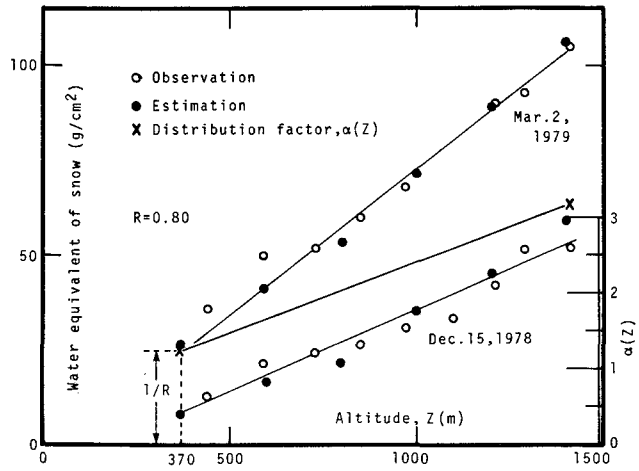


Fig. 13 Comparison between observation and estimation value of altitudinal distribution of water equivalent of snow and altitudinal distribution of distribution factor of solid precipitation estimated in the west slope of Mt. Asahidake in 1978-79 winter

tabulated in Table 2, the latters also being plotted by black dots in Fig. 13, where measured values of $H_W(z, t)$ on the same dates were shown by circles. Comparison of black dots and circles shows that the estimation is considerably good.

V. Consideration of ablation process

V. 1. *Possibility of estimating maximum amount of snow from snow-line observation*

The method of estimation of snow amount described in the previous chapter requires one measured value of snow amount, $H_W(z_1, t_1)$, in the accumulation period besides the temperature and precipitation data at a reference site. Even at only one point actual measurement of snow amount at a high altitude being still laborious, some easier way to substitute the measurement is desirable.

As stated before, if seems that the higher the altitude z_1 and the later the date t_1 the better the estimation. Hence, in the estimation $H_{wmax}(z_1)$ should be used as done in Section IV. 2. It is evident from the discussion in Section III. 1 that

$$H_{wmax}(z)=H_W(z, t_m(z))=M(z, t_d(z), t_m(z)), \tag{16}$$

where $M(z, t_1, t')$ means the decrease in snow amount at z from t to t' both the dates being in the ablation period at z.

Now, let the altitude of snow-line on a date t_0 be z_s. Evidently, $t_d(z_s)$ is equal to t_0.

Hence,

$$H_{\mathrm{wmax}}(z_{\mathrm{s}})=M(z_{\mathrm{s}},\ t_0,\ t_{\mathrm{m}}(z_{\mathrm{s}})). \tag{17}$$

Since the date $t_{\mathrm{m}}(z_{\mathrm{s}})$ is the day when air temperature at z_{s} reaches 4°C, it can be estimated from the temperature data at the reference site with the aid of a suitable value of the lapse rate of air temperature. Thus, one can estimate the duration of the ablation period at z_{s}.

Governed only a few local factors such as air temperature, radiation, and wind velocity, mechanism of ablation is so simpler than that of accumulation that the amount of ablation during a specific period such as $M(z_{\mathrm{s}},\ t_0,\ t_{\mathrm{m}}(z_{\mathrm{s}}))$ may be estimated by some simple procedures, which will be sought in the following sections.

V. 2. *Heat balance of snow layer in ablation period*

In the ablation period, temperature is 0°C throughout the snow layer. Hence, the net heat gain of the snow layer is entirely used up to melt snow. Neglecting heat exchange at the bottom, one has

$$Q_{\mathrm{m}}=Q_{\mathrm{R}}+Q_{\mathrm{A}}+Q_{\mathrm{E}}+Q_{\mathrm{r}}, \tag{18}$$

where Q_{m} is the net heat gain used to melt snow while Q_{R}, Q_{A}, Q_{E} and Q_{r} are the heat gains due to radiation, sensible heat exchange between air and snow, latent heat exchange between air and snow and rain, respectively. For the sake of definiteness, the quantities will hereafter be considered those over a day in the ablation period. Then, Q_{R}, Q_{A} and Q_{r} are positive while Q_{E} is generally negative (net evaporation of water and/or sublimation of snow). The daily decrease in snow amount, M, is evidently given by

$$M=Q_{\mathrm{m}}/L_{\mathrm{m}}-Q'_{\mathrm{E}}/L_{\mathrm{s}}, \tag{19}$$

where L_{m} is the latent heat of melting and L_{s} that of sublimation while Q'_{E} is a part due to sublimation of snow of Q_{E}. Since snow particles are considered to be covered by water film in the ablation season, sublimation of snow is unlikely to occur and Q'_{E} may be better put zero in the above equation.

Kojima (1979) gave a detailed discussion of ablation mechanism in his summary paper, where many empirical formulas are given of the quantities in relation (18). As seen from these formulas, the higher the air temperature and the stronger the wind, the larger the value of Q_{A}. Though expressed as a function of absolute humidity in these formulas, the absolute value of Q_{E} may behave similarly to Q_{A}. On the other hand, Q_{R} is independent of wind and very weakly dependent on air temperature.

Generally, the higher the altitude, the lower the air temperature and the stronger the wind, making the dependence of Q_{A} and Q_{E} on the altitude rather weak. Moreover, in the ablation period, the sum of Q_{A} and Q_{E} is much smaller than Q_{R} which is almost independent of the altitude. Hence, the dependence of Q_{m} on the altitude may be considered very weak.

The argument may explain the constancy of a (t) in relation (5) in the ablation season which means that the amount of melting is independent of the altitude.

A preliminary observation of heat balance was made at Mt. Teine in May 1979. At 650 m a. s. l., the daily mean value over a period from May 2 to 17 of Q_R about 200 cal/cm^2 while that of the sum of Q_A and Q_E about 17 cal/cm^2 (Suizu et al., 1979).

V. 3. *Estimation of melting amount of snow*

From relations (17), (18) and (19), neglecting Q'_E, one has

$$M(z_s, t_o, t_m) = \sum_{t_m}^{t_o} (Q_R + Q_A + Q_E + Q_r)/L_m. \tag{20}$$

Of the four quantities in the right hand side, Q_r may be estimated from weather record and radiation data at a reference site. Data of air temperature and wind at the reference site may allow one to estimate corresponding quantities at z_s, and hence Q_A and probably Q_E. The latter may be better estimated from humidity data at the reference site. Lastly, Q_r may be estimated from temperature and precipitation data at the reference site. Thus, all the quantities may be estimated from meteorological data at the reference site.

Unfortunately, at most of all small meteorological observatories usable as a reference site, only temperature and precipitation data are available.

Now, it has been long recognized empirically that melting amount of snow at a site is approximately proportional to the degree-day of warmness, that is, the cumulative value of daily mean temperature in °C:

$$M(z, t', t) = k \sum_{t}^{t'} T_a(z), \tag{21}$$

where the proportion factor k is called the degree-day factor (Ishii 1959). Because radiation is a large contributor to the melting, the degree-day factor is supposed to depend on the direction and the inclination of a slope. It is larger on a south slope than on an east or west slope and least on a north slope (Kubota et al., 1978).

That radiation is a large contributor to the melting is somewhat contradictory to the constancy of k, because Q_R is weakly dependent on T_a. This contradiction may appear especially when T_a is low. The values of k obtained by the present observations on the west slope of Mt. Asahidake (circle) and on the east slope of Mt. Teine (square) are

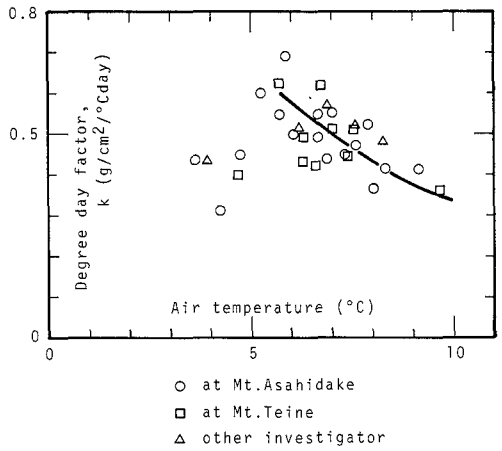


Fig. 14 Observed relationship between degree day factor, k, and averaged value of daily mean air temperature during ablation season

plotted in Fig. 14 against the mean value of T_a in each considered interval, which was chosen as nearly as possible to the melting period at each observed site. The triangles are the values derived from the data, air temperature and amount of melt snow, obtained by other investigator at various places in Honshu Island (Kimura 1977, Kodama et al., 1979). The circles, the squares and the triangles combinedly show, though somewhat obscurely, a maximum at around 5°C. The increase in k with the decrease in the temperature down to 5°C may be attributed to the increase in the proportion of the contribution of Q_R to Q_m, while the decrease in k with the decrease in the temperature from 5°C may reflect the fact mentioned in Section III. 1 that melting water runoff from snow cover actually occurs not at 0°C but a few degrees above zero of air temperature. It is easily shown that if one refers the degree-day of warmness to, say, 4°C instead of 0°C, k will increase monotonously and sharply in the temperature range down to 4°C.

VI. Synoptic analysis of snow distribution in Hokkaido

VI. 1. *Estimation of maximum amount of snow in Hokkaido*

Satellite photographs allow one to estimate snow-line altitude over a wide range. As discussed in Chapter V, from the snow-line altitude on a certain day on a slope and the temperature record at a suitable reference site, one can estimate the maximum amount of snow at the snow-line altitude only if one knows the degree-day factor of the slope. No complete knowledge of the degree-day factors of mountain slopes in Hokkaido has yet been available, but the curve in Fig. 14 may and will be considered to give the zeroth-approximation values of the degree-day factor. Once the maximum amount of snow at the snow-line altitude being known, the method given in Chapter IV allows the estimation on the maximum amount of snow at any altitude on the slope.

Snow-covered areas in Hokkaido on May 21 (east of 142°E) and 22 (west of 142°E) 1979 determined from the photographs taken by Landsat on the corresponding days are shown in black in Fig. 15.

Because of overcast, snow-covered areas cannot be determined in the following mountain regions: Shokanbetsu (43°N, west of 142°E), Akan and Shiretoko (east of 144°E), a southern part of Yubari (142°E, south of 43°N) and a southern part of Hidaka (143°E, south of 42.5°N).

Comparing the photographs enlarged to a scale of 1/200,000 with a contoured map of the same scale, one can estimate the altitude of snow-line in an accuracy of ± 50 m, the results of the estimation being crudely shown in Fig. 15. The altitude varied widely from 350 m a. s. l. in Teshio and North Kitami ranges to 1200 m a. s. l. in the eastern part of Daisetsu range.

In Fig. 15, thirty three meteorological observatories usable as a reference site are indicated by solid circles. The lapse rate of air temperature being assumed 0.5°C/100 m, daily mean air temperatures at various altitudes, $T_a(z, t)$, near each reference site were

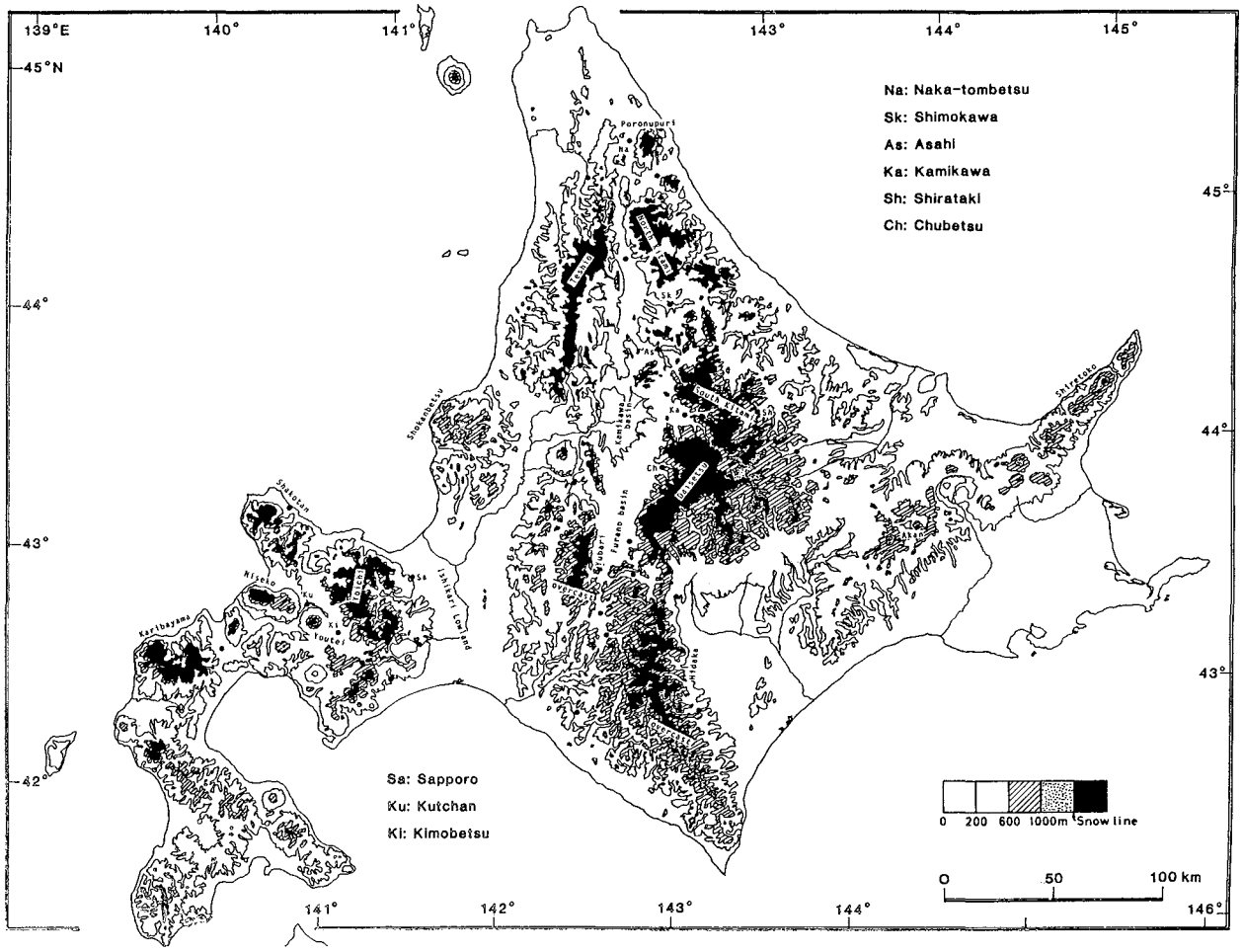


Fig. 15 Distribution of snow covered area in Hokkaido on May 21 and 22, 1979; solid circles showing meteorological observatories located in the piedmont of mountains

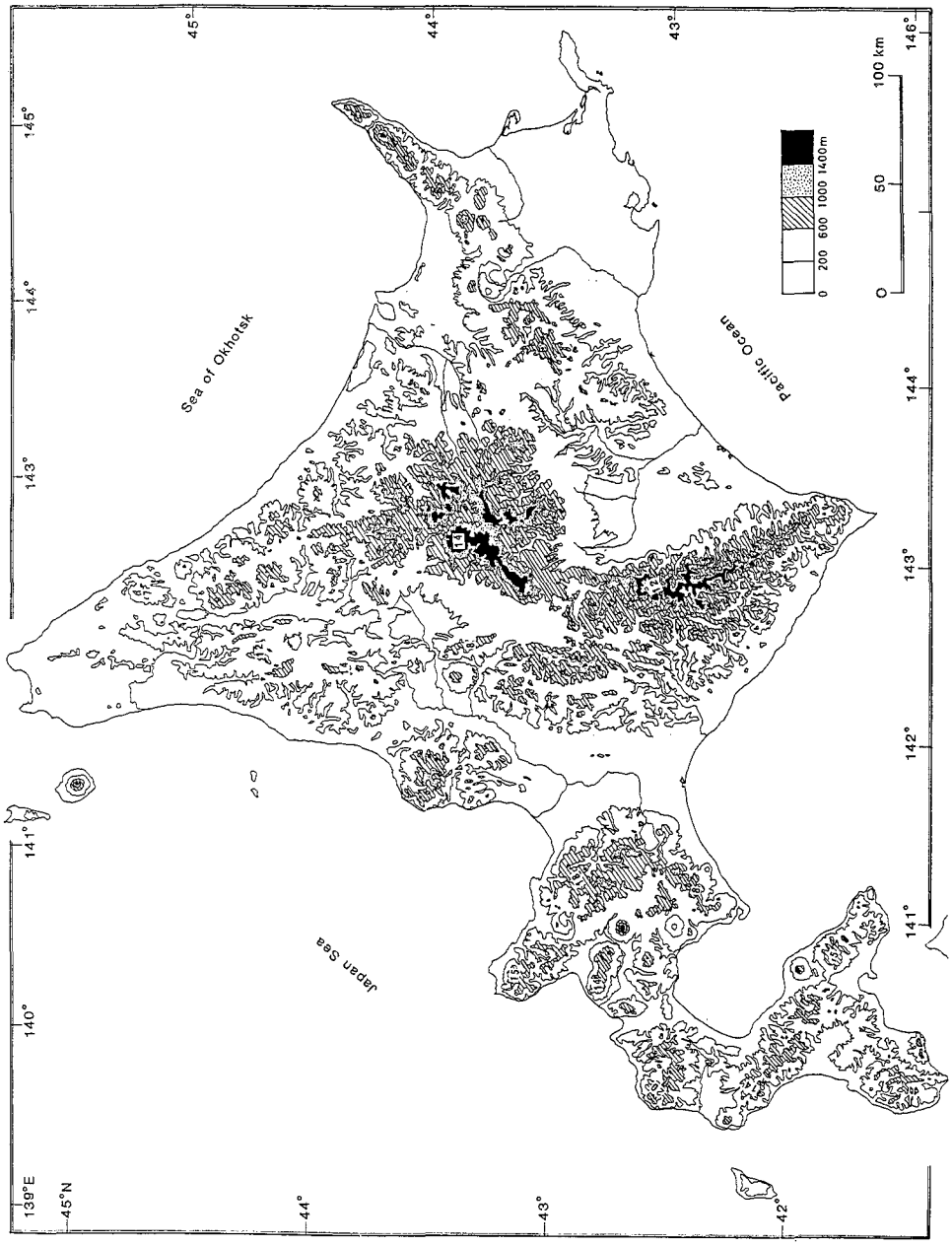

Sea of Okhotsk
Pacific Ocean
Japan Sea
0 200 600 1000 1400m
0 50 100 km
139°E
45°N
44°
43°
42°
140°
141°
142°
143°
144°
145°
146°

Fig. 17 Distribution of maximum amount of snow (x 10 g/cm²) in Hokkaido in 1978-79 winter

estimated by

$$T_a(z, t) = T_a(z_0, t) - (z\text{-}z_0) \times 0.5/100\,(^\circ\mathrm{C/m}), \tag{22}$$

where z_0 was the altitude and $T_a(z_0, t)$ the daily mean air temperature of the reference site (Hokkaido Kisho Geppo). Then, the dates, $t_b(z)$, $t_e(z)$ and $t_m(z)$, introduced in Section III. 1 were estimated by the following criteria:

$$\begin{aligned} &T_a(z, t_b(z)) = 0^\circ\mathrm{C}, \\ &T_a(z, t_e(z)) = 0^\circ\mathrm{C}, \\ &T_a(z, t_m(z)) = 4^\circ\mathrm{C}, \\ &T_a(z, t) < 0^\circ\mathrm{C} \quad \text{for } t_b < t < t_e, \\ &T_a(z, t) < 4^\circ\mathrm{C} \quad \text{for } t_e < t < t_m. \end{aligned} \tag{23}$$

Now, the maximum amount of snow at the altitude of snowline z_s on May 21 or 22 (denoted by t_0 hereafter) on a slope referable to the reference site was estimated according to the equations (17) and (21):

$$H_{\mathrm{wmax}}(z_s) = M(z_s, t_o, t_m(z_s)) = k \sum_{t_m}^{t_o} T_a(z_s), \tag{24}$$

where k was read from Fig. 14. The estimated values $H_{\mathrm{wmax}}(z_s)$, $t_b(z_s)$ and $t_e(z_s)$ together with the precipitation data at the reference site allowed the estimation of $\alpha(z_s)$ by the equation (14), and in turn, with the assumption of $R = 0.8$, determined $\alpha(z)$ of the site. With the knowledge of $\alpha(z)$, $t_b(z)$ and $t_e(z)$, the equation (14) was used to estimate $H_{\mathrm{wmax}}(z)$ for arbitrary value of z. The calculated results for the four reference sites, Kutchan, Nakatonbetsu, Asahi and Shirataki observatory, to which the south slope of Mt. Niseko, the west slope of Mt. Poronupuri, the west slope of Kitami Range and the east slope of Kitami Range are respectively referable, were shown in Fig. 16.

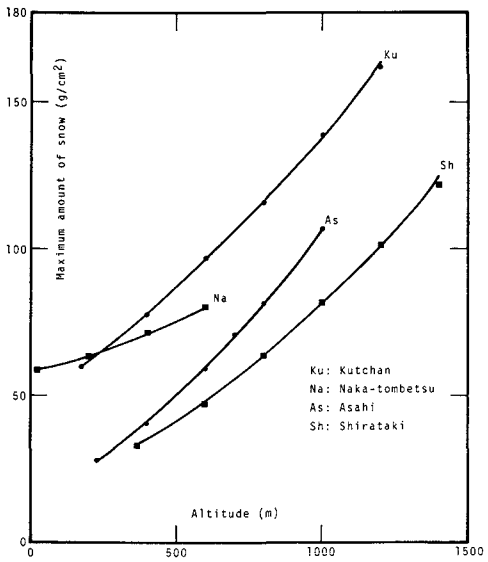


Fig. 16 Estimated value of altitudinal distribution of maximum amount of snow in the mountain slopes near various meteorological observatories

In total, some 160 estimations of H_{wmax} were done and plotted on the map of Hokkaido. Then, the isopleths of H_{wmax} of 1, 3, 5 and 10 ($\times$ 10 g/cm^2) were drawn as shown in Fig. 17.

The total amount of snow accumulated in 1978-79 winter over Hokkaido was estimated as 3.3×10^{10} ton, which gave an average value H_{wmax} of 42 g/cm^2.

VI. 2. *Winter monsoon and the estimated snow distribution*

As mentioned in the introduction, snow in Hokkaido is considered mainly due to wet air mass brought by the prevailing north-westerly winter monsoon travelling over Japan Sea. The estimated snow distribution shown in Fig. 17 seems to confirm the consideration. Namely, the estimated maximum amount of snow is less then 30 g/cm^2 in such areas shaded their north or west side by mountains as Okhotsk coast, Pacific coast, Furano basin etc., while more than 50 g/cm^2 in the coastal regions along Japan Sea. Also, at the same altitude, the estimated maximum snow amount is much larger in the mountain ranges facing Japan Sea, i. e. North Kitami-Teshio-Shakotan-Karibayama Ranges, than in the central divide, i. e. South Kitami-Daisetsu-Hidaka Ranges, showing that the wet mass travelling south-eastward lost a large part of its moisture in the first encounter to the mountain range.

More evidences of such a shading effect of a mountain are found in the following examples: Simultaneous snow surveys were conducted in the west slope of Sekihoku pass

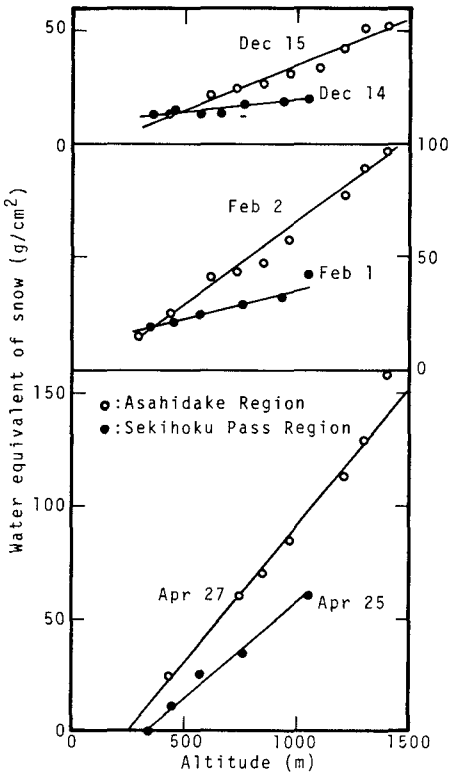


Fig. 18 Comparison of water equivalent of snow between of west slope of Mt. Asahidake and of west slope of Sekihoku Pass in 1978-79

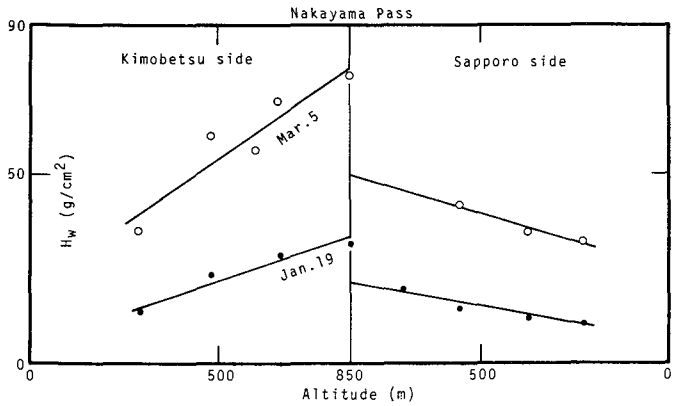


Fig. 19 Altitudinal distribution of water equivalent of snow in the slopes of Kimobetsu side and Sapporo side of Nakayama Pass in 1980

and in the west slope of Mt. Asahidake in winter 1978-79. The results are shown in Fig. 18. Though both the slopes face the same direction and are only 20 km apart, snow amount was always larger in Asahidake than in Sekihoku pass which is in the shade of Mt. Daisetsu Range as seen in Fig. 2. In Fig. 19 is shown the result of snow survey along Nakayama pass which runs roughly vertical to the prevailing winter monsoon. The less snow accumulation in Sapporo side can be attributed to Sapporo mountain range (Mt. Muine, Mt. Yoichi, etc.) situated windward of that side of the pass.

VI. 3. *Remarks on snow in the alpine zone*

The method of estimation of snow amount described and used hitherto is based on the equation (6) which is only established for a slope below a timberline, and hence seems to be unapplicable for an alpine zone above the timberline. The alpine zone in Hokkaido can be considered the area above 1400 m a. s. 1. as stated before, which is painted black in the upper figure of Fig. 17.. As seen from the figure, the total area of the alpine zone in Hokkaido is so small (less than 3 % of the total area of Hokkaido) that snow accumulated there is unimportant from the point of view of water resources. However, the accumulation and ablation process of snow in the alpine zone is interesting from the scientific view point and some result of observation should be added below.

Snow depths were continuously recorded with the automatical snow depth recorders at

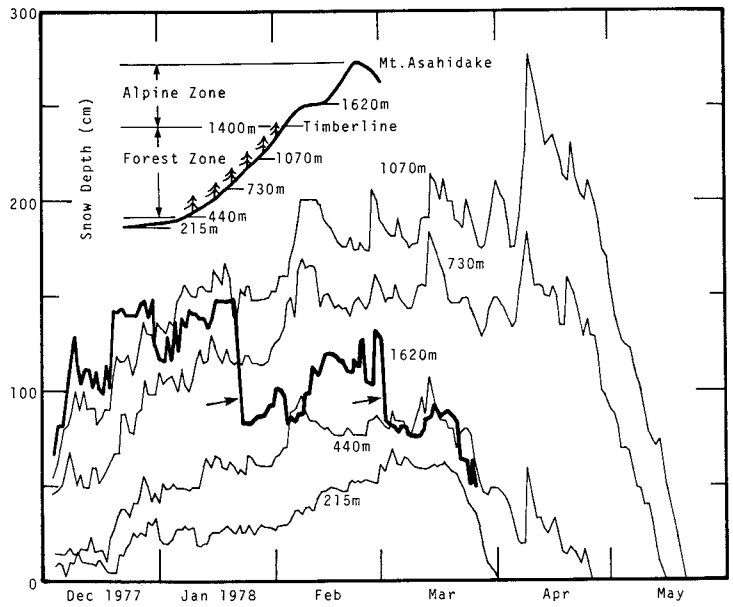


Fig. 20 Variations of snow depth with time at the sites of various altitude in the west slope of Mt. Asahidake in 1977-78 winter measured by snow depth recorders

various altitudes on the west slope of Mt. Asahidake throughout the 1977-78 snow season. The results are shown in Fig. 20. Changes in snow depth below the timberline, i. e. at 1070 m, 730 m, 440 m and 215 m a. s. 1., show rather good correlation, indicating that snowfall occurred simultaneously over these altitude, a fact required for the validity of the equation (6). But, snow depth at 1620 m a. s. 1. in the alpine zone changed quite differently from that at the other altitudes. Especially, it decreased abruptly on January 22 and March 1 as indicated by arrows in the figure. In this season, wind was also continuously recorded at 1595 m a. s. 1. on the slope. (Kikuchi et al, 1979.) According to their record, wind speed exceeded 30 m/s on both January 22 and March 1. The abrupt decreases were certainly due to erosion of snow cover by strong wind.

The critical wind speed causing blowing snow is about 7 m/s (Yamada, 1974). The wind record at 1595 m a. s. 1. cited above showed that in snow season, the frequency of occurrence of wind stronger than 7 m/s was more than 50 %. Snow cover in the alpine zone should be frequently eroded on other days than January 22 and March 1.

The phenomena of blowing snow not only causes very uneven distribution of snow depth at the same altitude as naturally expected but also seems to decrease the total amount of snow in the alpine zone. In the 1977 ablation season, the change of snow-line height on the slope of Mt. Youtei was observed by means of time-lapse photography. The daily mean air temperature at Kutchan observatory being used as $T_a(z_0, t)$ in the equation (22) and t_0 in the equation (24) being determined from the time-lapse photography for a given z_s, $H_{wmax}(z_s)$ at various altitudes z_s was calculated by the equations (22), (23) and (24) and plotted in Fig. 21. In the alpine zone, H_{wmax} decreased rapidly with increase in the altitude. Sugaya (1949) reported a similar tendency in the alpine zone of Mt. Asahidake. These may be explained by the increase in the effect of blowing snow with the increase in the altitude.

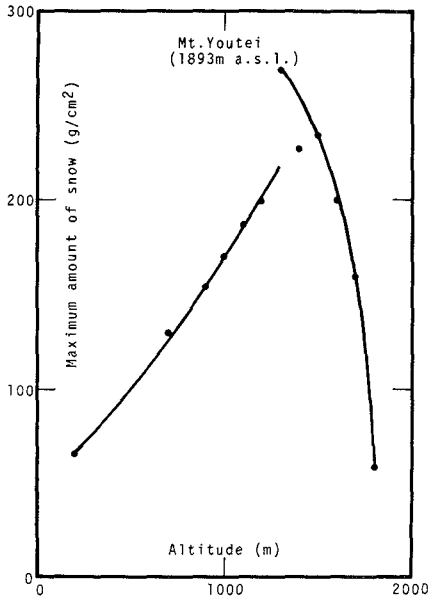


Fig. 21 Altitudinal distribution of maximum amount of snow in Mt. Youtei in 1976-77 winter estimated by snow line observations

VI. 4. *Accumulated snow in a drainage basin of a river*

As stated in the introduction, during the melting season (the transitional and the ablation seasons combined) which may be last three to four months in Hokkaido, accumulated snow

gradually melts and cultivates rivers and ground waters. Over this melting season, the following balance equation will hold of a drainage basin of a river:

$$W_s + W_r = R + G + E, \tag{25}$$

where W_s is the total amount of accumulated snow in the basin and W_r is the total amount of rainfall during the melting season while R, G and E are respectively the amount of river discharge, the amount used to cultivate ground water and the amount lost by evaporation during the season. The quantity W_s is by definition the integrated value of H_{wmax} over the area of the basin, and hence can be estimated. It will be interesting to study the balance equation using the estimated value of W_s. Inversely, the study will serve to see the validity of the estimation of H_{wmax}.

Four drainage basins with suitable meteorological and hydrological data were found and studied. Some characteristics and the estimated values of W_s, W_r and R of them were tabulated in Table 3. Now, before discussing the results of the study, I will first describe in detail the procedures of the estimation for the case of Shiribetsu river basin.

The hydrograph of Shiribetsu river obtained at Kimobetsu hydrological observatory (maintained by Hokkaido Electric Power Co.) is given in Fig. 22, which indicates that the discharge due to snow melt occurred on around March 27 and ended around June 27 in 1979. For the sake of simplicity, these dates were assumed the beginning and the end of the melting season. The total amount of discharge R over the season was calculated from the hydro-

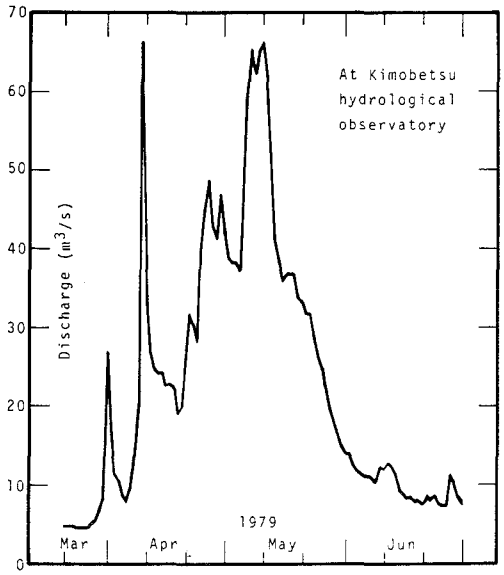


Fig. 22 Hydrograph at Kimobetsu hydrological observatory in Shiribetsu drainage basin

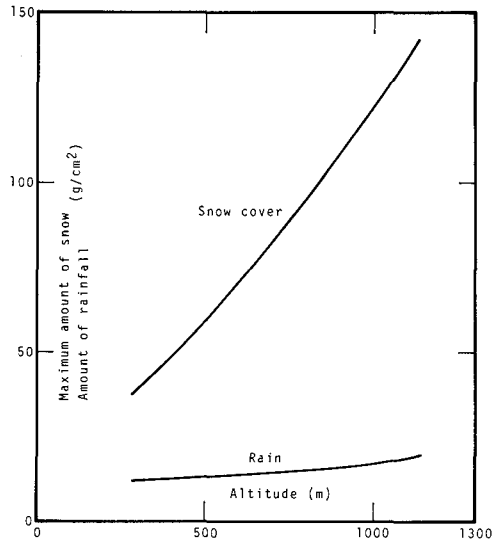


Fig. 23 Estimated altitudinal distribution of maximum amount of snow in 1978-79 winter and amount of rainfall during the ablation season in 1979 in Shiribetsu drainage basin

graph as 1.95×10^8 ton, as tabulated in Table 3. On the other hand, the altitude of snow-line in the basin was 730 m a. s. l. on May 22. Based on this datum and the records of daily mean air temperature and precipitation at Kimobetsu meteorological observatory, $H_{wmax}(z)$ in the basin was estimated with the method described in Section VI. 1 The total amount of rainfall at an altitude z in the basin from the beginning of the melting period there to June 27, which will hereafter denoted $r(z)$, was estimated by

$$r(z)=\alpha(z)\sum_{t_m(z)}^{\text{June 27}} h' \tag{26}$$

where h' is the daily amount of precipitation collected by the precipitation gauge at Kimobetsu meteorological observatory and $\alpha(z)$ is the distribution factor derived in the

Table 3 Comparison of runoff coefficient between various drainage basins derived from areal amount of H_{wmax} in 1978-79 winter, areal rainfall and discharge during ablation season in 1979; also basic items of the drainage basins

Drainage Basin	Catchment Area (km^2)	Range of Altitude (m)	Period of snow melting	Areal amount of H_{wmax} ($x10^8$ ton)	Areal rainfall ($x10^8$ ton)	Discharge ($x10^8$ ton)	Runoff coefficient (%)	Meteorological observatory	Hydrological observatory
Shiribetsu	342.0	246-1176	27 Mar~20 Jun	2.40	0.48	1.95	68	Kimobetsu	Kimobetsu
Rubeshibe	78.4	475-1253	18 Apr ~ 20 Jun	0.65	0.18	0.66	80	Kamikawa	Nakagoshi
Antaroma	114.0	355-2020	18 Apr ~ 26 Jun	0.80	0.24	0.57	55	kamikawa	Antaroma
Piukenai	41.0	530-2290	18 Apr ~ 15 Jul	0.39	0.22	0.42	69	Chubetsu	Yukomanbetsu

Table 4 Areal amount of H_{wmax} (x 10^4 ton) in 1978-79 winter and areal rainfall (x 10^4 ton) during ablation season in 1979 in Shiribetsu drainage basin computed by the area, averaged value of H_{wmax} and amount of rainfall in sections bounded by 100 m contour lines

Range of Altitude (m)	Area (km^2)	H_{wmax} (g/cm^2)	Areal Amount of H_{wmax} ($x10^4$ ton)	Amount of Rainfall (g/cm^2)	Areal Rainfall ($x10^4$ ton)
264- 300	15.9	36.5	580.4	12.1	192.4
300- 400	54.0	45.0	2430.0	12.6	680.4
400- 500	66.0	55.5	3663.0	13.2	871.2
500- 600	58.4	66.5	3883.6	13.8	805.9
600- 700	57.0	78.0	4446.0	14.4	820.8
700- 800	52.3	91.5	4785.5	15.1	789.7
800- 900	27.4	104.0	2849.6	15.8	432.9
900-1000	9.5	117.5	1116.3	16.7	158.7
1000-1100	1.2	130.5	156.6	17.9	21.5
1100-1176	0.3	142.0	42.6	19.5	5.9
Total	342.0		23953.6		4779.4

estimation of $H_{wmax}(z)$. The estimated $H_{wmax}(z)$ and $r(z)$ are shown in Fig. 23.

Estimation of W_s and W_r were done by dividing the basin into subareas according to the altitude as shown in Table 4. The estimated values of them were about 2.4×10^8 and 0.48×10^8 ton, respectively, as shown in Tables 3 and 4.

Arai (1980) estimated that in Hokkaido evaporation loss is about 55 g/cm^2/year. Under a very simple assumption that the loss is evenly distributed over year, E can be estimated 0.44×10^8 ton, giving 0.49×10^8 ton as an estimation of G, a value not so unreasonable.

An important index in hydrology is the runoff coefficient which is defined by the ratio of the discharge in a river versus the total input in its basin. Of the studied four basins, the runoff coefficient varied from 55 % to 80 % as shown in Table 3. Several estimated values of the runoff coefficient had been reported of the other basins in Hokkaido; for instance, 79 to 91 % of Chubetsu drainage basin (Sugaya, 1949, Higashi and Higuchi, 1952; Higuchi and Itagaki, 1953) and 45 to 55% of Shikaribetsu drainage basin (Higashi et al., 1956; Magono and Orikasa, 1957; Orikasa et al., 1960). Comparing with these values, the estimated values given in Table 3 seem to be reasonable ones.

VII. Concluding remarks

From the viewpoint of snow as water resources, the most important quantity in this study is the total amount of accumulated snow in a drainage basin introduced and denoted W_s in Section VI. 4, where its estimation was done based on equations (6), (7), (17) and (21). The use of equation (17) makes the estimation to be retrospective. In the case treated in Chapter VI, the estimation used the data on May 21 or 22, when, as seen in Fig. 22, the melting had already approached to the end. To be predictive for the river discharge, the estimation should be based only on equations (6) and (7) as in Section IV. 2. This requires to know at least one value of $H_w(z, t)$ at a place other than the reference site. In this respect, development of a simple snow gauge allowing remote sensing is urgently hoped.

The retrospective estimation is nevertheless important from scientific viewpoint. Combined with synoptic weather records in the previous winter, a retrospectively constructed map of snow distribution such as Fig. 17 will be valuable for the understanding of the mechanism of snowfall. In the use of equation (21) in Chapter VI, k is estimated from Fig. 14. More field data should be collected than given in Fig. 14, for obtaining a more reliable value of k, or more fundamentally, for verifying the validity of equation (21) itself.

Another important empirical formula obtained in this study, relation (5), seems to hold in previous snow surveys in Hokkaido made by other authors; in the west slope of Mt. Asahidake in 1948 (Sugaya, 1949), 1949 (Chiba, 1950), 1952 (Higashi and Higuchi, 1952) and 1953 (Higuchi and Itagaki, 1953) and in Shikaribetsu drainage basin in 1954 (Higashi et al., 1956), 1955 (Magono and Orikasa, 1957) and 1958 and 1959 (Orikasa et al., 1960).

This linear relationship may be presumed to hold in any mountain slopes other than

those in Hokkaido, though few observations have been available. It was observed on the northwest slope of Mt. Hakusan, Ishikawa Prefecture in Honshu, that the amount of newly fallen snow deposited from 27 February to 1 March, 1979, linearly increased with the elevation on the slope, as shown in Fig. 24. This suggests that the relationship (5) may be applicable in any mountain slopes.

Mechanism of rainfall along a mountain slope was summarized by Kawabata (1961). Whether similar consideration can be used to explain the empirical relations (5), (6) and (7) or not, remains to be studied.

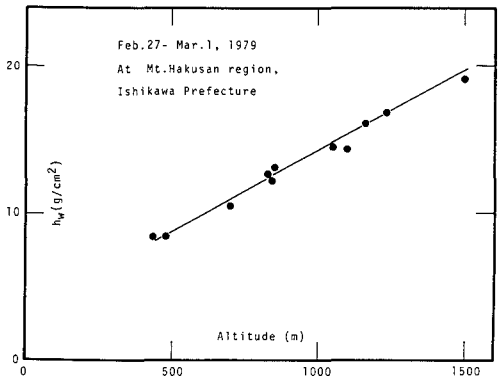


Fig. 24 Altitudinal distribution of the amount of newly fallen snow deposited from 27 February to 1 March, 1979, on the northwest slope of Mt. Hakusan, Ishikawa prefecture

Acknowledgement

The author would like to express his gratitude to Professor G. Wakahama of the Institute of Low Temperature Science, Hokkaido University, for his encouragement and many useful suggestions throughout the course of the study. He is greatly indebted to Professor Y. Suzuki of the Institute for his critical reading and revising the manuscript. Thanks are also due to Dr. Kuroiwa, Professor emeritus of Hokkaido University, Professor K. Kojima of the Institute, Professor K. Kikuchi of the Faculty of Science, Hokkaido University, and Dr. D. Kobayashi of the Institute for giving the author valuable comments and suggestions.

He is also grateful to Dr. E. Akitaya and Mr. H. Aburakawa, both of the Institute, who devised and provided respectively automatic temperature recorders and automatic snow depth recorders used in this study, to Dr. S. Kobayashi and Dr. Y. Furukawa, both of the Institute, and Dr. M. Matsuda, Mr. H. Nishimura, Mr. S. Suizu, Mr. Y. Nishimura, Dr. T. Kikuchi, Mr. H. Ohmae, Mr. H. Fukami and Mr. Y. Kaneda, all of them had been graduate students at the Institute, for their support in field works extended for several years.

He is also thankful to Hokkaido Electric Power Co. for providing him hydrographs and to Daisetsu Highland Co. for logistical supports.

Finally he is indebted to Ms. F. Sugawara and Ms. M. Kumao for their assistance in preparing the manuscript.

This study was supported financially in part by a Special Research Fund (Principal Investigator: Professor G. Wakahama) and a Scientific Research Fund (Principal Investigator: Professor K. Higuchi of Water Research Institute, Nagoya University), both of

Japanes Ministry of Education.

References

Aburakawa, H. (1979): D-Type Snow Depth Recorder Using Optical Fibers. *Low Temp. Sci.* **A 38**, 73-79.

Akitaya, E. (1978): Development of a Long-Term Temperature Recorder. *Low Temp. Sci.* **A 37**, 167-169.

Arai, T. (1980): Jōhassan ryo no suitei to mizu shushi (Estimation of evapo-transpiration and water budget). *in* Nippon no mizu (Waters in Japan), 57-69, pp 278 (Pub. by Sansei-do).

Chiba, T. (1950): Jitsuyou teki houhou ni yoru Daisetsu-zan no sekisetsu suiryo chōsa (Snow survey in the Daisetsu mountain region by a convenient method). *in* suigai no sōgō-teki kenkyu (Synthetic studies of flood damage), **2**, 125-135, (Pub. by Hokkaido Government and The Institute of Agricaltural Physics).

Higashi, A. and Higuchi, K. (1952): Snow Survey in the Chūbetsu River Basin by the Method of Long Snow Course. *Geophys. Bull. Hokkaido Univ.* **2,** 1-12.

Higashi, A., Higuchi, K. and Itagaki, K. (1956): Snow Survey in the Lake Shikaribetsu Basin. *Geophys. Bull. Hokkaido Univ.* **5,** 65-79.

Higuchi, K. and Itagaki, K. (1953): Snow Survey in the Chubetsu River Basin by the Method of Long Snow Course. *Geophys. Bull. Hokkaido Univ.* **3,** 51-62.

Hokkaido Kisho Geppo (Monthly Meteorological Data in Hokkaido), Nov. 1977-May 1978, Nov. 1978-Jun. 1979, Nov. 1979-May 1980, (Pub. by Sapporo Meteorological Observatory).

Ishihara, K. (1956): Nihon ni okeru setsuryo chōsa (Snow surveys in Japan). Denryoku Renraku Syūhou (Meteorological Bulliten for Electric Power), **2**, (6), 69-84.

Ishii, Y. (1959): Yūsetsu no kenkyu (Studies on snow melting). pp 84, (Pub. by Hokkaido Electric Power Co., Inc. and Sapporo Meteorological Observatory).

Kawabata, Y. (1961): Kousui (Precipitation). *in* Suimon Kisyo-gaku (Hydro-meteorology), **2,** 17-134, pp 268, (Pub. by Chijin shokan).

Kikuchi, T., Kaneda, Y. and Yamada, T. (1979): Daisetsu-zan ni okeru sekisetsuki no kishojōkyō ni tsuite (On the meteorological conditions of snow season in the Daisetsu mountain region, Hokkaido). Tenki (Weather), **26**, 751-757.

Kimura, T. (1977): Pressure pillow ni yoru sekisetsu soutou suiryo no kansoku (Observation of water equivalent of snow using pressure pillow). *Seppyo,* **39,** 126-131.

Kodama, M., Nakai, K., Kumanashi, J., Kamota, F. and Sato, S. (1979): Continuous Observations of Water-Equivalent of Snow-Depth by Cosmic-ray Snow Gauge. *Seppyo,* **41,** 109-114.

Kojima, K. (1979): Yūsetsu kikou to netsu shūshi (Mechanism of snow melting and heat budget). Kisho Kenkyu nōto (Note of Meteorological Research), **139**, 1-33.

Kubota, H., Fukami, H., Ohmae, H., Kaneda, Y. and Yamada, T. (1978): A study of Snow Melting in Mt. Asahidake, Hokkaido. *Low Temp. Sci.* **A 36,** 181-188.

Magono, C. and Orikasa, K. (1957): Hydrological Investigations in the Lake Shikaribetsu Basin. *Geophys. Bull. Hokkaido Univ.* **5,** 45-65.

Orikasa, K., Magono, C., Kikuchi, K., Takahashi, T. and Nakamura, T. (1960): Hydrological Investigation in the Lake Shikaribetsu Basin II. *Geophys. Bull. Hokkaido Univ.* **7,** 1-16.

Sugaya, J. (1949): Sekisetsu suiryō no teiryō teki chōsa ni tsuite (On the quantitative research of water equivalent of snow). *in* Daisetsu-zan sekisetsu suiryo oyobi ryushutsu chōsa (Water equivalent of snow and discharge in the Daisetsu mountain region), 1-42, (Pub. by Keizai antei Honbu and Hokkaido-cho).

Suizu, S., Yamada, T. and Wakahama, G. (1979): Teine-yama no sekisetsu tokusei to netsu syūshi

(Distribution characteristics of snow and heat budget study in Mt. Teine, Hokkaido). Syowa 54 nendo Nippon Seppyo Gakkai syuki taikai kōen yokō-shu (Proceedings of Japanese Society of Snow and Ice), **206**.

Takahashi, S. and Aburakawa, H. (1976): A snow depth recorder using optical fibers. *Low Temp. Sci.* **A 34,** 79-86.

United Nations, Statistical Yearbook, 1977.

Yamada, T. (1974): Surface Meteorological Condition in the Region Between Syowa Station and Mizuho Camp, Mizuho Plateau, East Antarctica. *The Antarctic Record,* **50,** 1-20.

Yamada, T., Nishimura, H., Suizu, S. and Wakahama, G. (1978): Distribution and Process of Accumulation and Ablation of Snow on the West Slope of Mt. Asahidake, Hokkaido. *Low Temp. Sci.* **A 37,** 1-12.

Yamada, T., Nishimura, H., Suizu, S. and Wakahama, G. (1979): Distribution of Water Equivalent of Snow in Mt. Daisetsu, Hokkaido. *Low Temp. Sci.* **A 38,** 63-71.

Yamada, T., Suizu, S., Nishimura, H. and Wakahama, G. (1981): Relationships Between Snow Distribution and Climate in Mountain Areas. Sea Level, Ice and Climatic Change (Proceedings of the Canberra Symposium, Dec. 1979). IAHS Publ. No. **131**, 109-118.

Yamazaki, F. (1981): Wagakuni no suishigen ryo (The Amount of water resources in Japan). *in* Suishigen o kangaeru (Consideration of water resources), 43-44, pp 252, (Pub. by Sankyo Shuppan).