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Article

Formation processes of ice body revealed by the internal structure of perennial snow patches in Japan

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Abstract

To clarify the transformational processes from firn to ice of perennial snow patches in Japan on the basis of their characteristics of internal structure, core drillings were carried out during the ablation periods of 1995 and 1996 on eight perennial snow patches, located in different mountain areas. The core analyses including stratigraphy, density and liquid water content revealed that the existence of an ice body was a common feature of perennial snow patches nourished mainly by drifting snow in Japan. In addition, a water-saturated firn layer (firn aquifer) is formed just above the firn-ice transition during the ablation period. In this type of snow patch, the transformation from firn to ice may be completed in a single year by early-winter freezing of water-saturated firn which was highly densified in the firn aquifer. In perennial snow patches nourished mainly by snow avalanches, the existence of ice bodies could not be ascertained, because debris embedded in the snow interrupted the drilling. However, it is unlikely that an ice body can be formed by the same processes as in snow patches nourished by drifting snow. Avalanche-fed snow patches exist at relatively low altitudes and air temperatures prior to new snow accumulation are not low enought to freeze the water-saturated firn layer.

1. Introduction

Although no glaciers exist in Japan now, many perennial snow patches are found in the high mountains facing the Japan Sea. They are nourished by extremely heavy snowfall, drifting snow and snow avalanches with maximum accumulation depth at the end of winter reaching 20 m. Rapid metamorphism from snow to firn, as well as heavy melting, occurs during the ablation period. Some perennial snow patches in the Northern Japan Alps of central Japan, and the Daisetsu mountains of Hokkaido have continuous ice masses at their lowest parts (Yosida, 1964 ; Yoshida *et al.*, 1990 ; Kawashima *et al.*, 1993). The formation of an ice body has important implications in clarifying transitional processes from a perennial snow patch to a glacier. However, because no systematic work has been done on the internal structure of perennial snow patches, it is not clear whether or not the existence of an ice body is a common feature of perennial snow patches in Japan under present climatic conditions.

To investigate the regional characteristics of perennial snow patches with special reference to the internal structure and formation processes of ice bodies, core drillings were done during the ablation periods of 1995 and 1996 on eight perennial snow patches in Japan.

2. Distribution of perennial snow patches in Japan

Distribution of perennial snow patches in Japan is not clear because little inventory work has been completed, except for the inventory in the Northern Japan Alps, conducted by Higuchi *et al.* (1980). Many glaciological studies on snow patches in Japan conclude that perennial snow patches are maintained under present climatic conditions in the mountainous regions, shown in Fig. 1. Moreover, perennial snow patches may exist on Mt. Uenshiri, Hidaka mountain range, Asahi mountains, Mt. Fuji and Mt. Daisen.

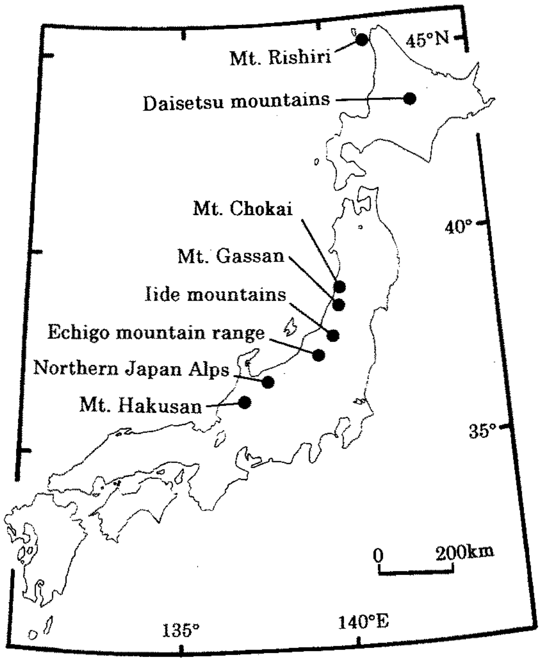

Fig. 1. Distribution of the mountainous regions in Japan where perennial snow patches exist.

Perennial snow patches are widely distributed in the mountains of Japan with latitude ranging from 36 to 45°N. Table 1 lists the altitude range of perennial snow patches and major source of nourishment other than direct snowfall. We call perennial snow patches developed mainly from snow avalanches, type-A, and those from drifting snow, type-B. The lower limits of altitude of type-A reach 900 m a.s.l. or less, which is lower than those of type-B by 500 m or more. This difference results partly from more snow accumulation by avalanches, and partly from debris entrained in avalanches, including soil, rocks and plants, which insulate the snow surface during the ablation period to retard melting.

3. Sites and methods of investigation

Investigations were made on eight perennial snow patches distributed in the districts shown in Table 1 except for the Iide mountains. Table 2 lists the locations of drilling site, drilling dates and the type of major source of nourishment. During the ablation period in 1995 or 1996, a core was taken near the center of each perennial snow patch, using a hand auger at all snow patches except for the Hisago snow patch where an electro-mechanical drill (Suzuki and Shimbori, 1984) was used. Soon after taking the core, it was analyzed for stratigraphy, density and liquid

Table 1. Altitudinal of perennial snow patches in Japan and their major source of nourishment other than direct snowfall.

District	Range of altitude m a. s. l.	Major source of nourishment
Mt. Hakusan	2500-2600	drifting snow
Northern Japan Alps	1800-2800	avalanche and/or drifting snow
Echigo mountain range	700-1900	avalanche
Iide mountains	900-2000	avalanche
Mt. Gassan	1500-1900	drifting snow
Mt. Chokai	1400-2000	drifting snow
Daisetsu mountains	1400-2200	drifting snow
Mt. Rishiri	700-1200	avalanche

Table 2. Location and altitude of studied perennial snow patches, together with type and date when drilling was done.

Name	Mountain	Latitude	Longitude	Altitude	Type	Date
Senjagaike	Mt. Hakusan	36°09′N	136°46′E	2580 m	B	13 Sept. 1995
Kuranosuke	Northern Japan Alps	36°35′N	137°37′E	2700 m	B	8 Oct. 1995
Shirouma	Northern Japan Alps	36°45′N	137°46′E	2000 m	A	6 Sept. 1995
Kuwanokizawa	Echigo mountain range	37°09′N	139°05′E	800 m	A	20 Sept. 1995
Oyukijiro	Mt. Gassan	38°32′N	140°02′E	1800 m	B	27 Aug. 1995
Shinjiyuki	Mt. Chokai	39°05′N	140°02′E	1750 m	B	19 Aug. 1995
Hisago	Daisetsu mountains	43°33′N	142°52′E	1750 m	B	28 July 1995
Yamunaisawa	Mt. Rishiri	45°10′N	141°15′E	850 m	A	21 Sept. 1996

water content. Values of density were obtained by means of weight and volume measurements made for selected segments of the core. The liquid water content of firn was measured using a snow-water content meter of the calorimeter type, designed by Kawashima *et al.* (1996) to determine the water content of wet snow by weight (percentage of water weight to total weight of wet snow). For ice, the water content was assumed to be 0 % and we did not measure it. On the Hisago snow patch, measurements of density and water content were made a day after drilling. Because the water content could have changed due to the movement and drainage of water. Thus, only values of dry density, calculated from wet density and water content, are meaningful in the Hisago snow patch.

4. Results

The results of core analyses at eight perennial snow patches are summarized in Fig. 2. We could bore through the full thickness of only Oyukijiro and Hisago snow patches. Coring was interrupted in the other snow patches because of performance limitations. Especially, in the type-A snow patches including Shirouma, Kuwanokizawa and Yamunaisawa, the embedded debris caused problem.

4.1 Stratigraphic features

Continuous masses of ice were found under the firn layer in the type-B snow patches including Senjagaike, Kuranosuke, Shinjiyuki and Hisago. The thickness of the ice body in Hisago was 4.6 m, which is approximately the same as that observed in 1986 by Kawashima *et al.* (1993). From the surrounding topography, the ice thickness can be estimated to about 5 m in Senjagaike and Shinjiyuki, while the ice in Kuranosuke may be much thicker as indicated from the impulse radar sounding by Yamamoto and Yoshida (1987). Because of drilling problems with the entrained debris, we could not ascertain the existence of ice body in type-A snow patches.

A water-saturated firn layer was found just above the firn-ice transition in all type-B snow patches. This layer occurs where the vertical percolation of meltwater is interrupted by the firn-ice transition. Such a layer, which is often called a "firn aquifer", has been found in the wet-snow zone of temperate glaciers throughout the world (Sharp, 1951 ; Vallon *et al.*, 1976 ; Ambach *et al.*, 1978 ; Oeschger *et al.*, 1978 ; Oerter and Moser, 1982 ; Yamada, 1987 ; Fountain, 1989 ; Kameda *et al.*, 1993 ; Schneider, 1994 ; Ren *et al.*, 1995). Firn aquifers are formed early in spring, and are preserved during the ablation period in temperate glaciers. The same must be true for perennial snow patches in Japan. Observations show that the thickness of firn aquifer lies in the range from 1 m to 2 m in the snow patches except for Yamunaisawa which has a layer about 0.2 m thick. The thickness of firn aquifer depends mainly on the melting rate of snow, the water permeability of firn, the inclination of the firn-ice interface and the catchment area.

Well-defined dirt layers with thicknesses of 5−20 cm were formed at 0.3−2.6 m spacing in the snow patches. Since they correspond to the snow surface at the end of the ablation period, we can regard firn and/or ice layers sandwiched between two dirt layers as annual layers if the mass budget is positive every year. Years of a negative mass budget, however, are possible, in which case the uppermost dirt layer can combine with lower dirt layers and invade lower annual layers. It is interpreted that the firn and ice above the uppermost dirt layer accumulated during the previous winter. Ice layers with thicknesses of 10−30 cm were seen just above the uppermost dirt layer in Senjagaike, Kuranosuke and Shinjiyuki. They can be taken as superimposed ice formed at the beginning of the ablation period of 1995 by refreezing of meltwater on the ice body. In addition, the transformation from firn to ice may be completed in a single year in these snow patches, and consequently 0.3−2.3 m of ice is added to the ice body each year when the mass budget is positive. In connection with the formation of ice body, it is interesting to note that the annual ice layer is nearly equal to the firn aquifer in thickness.

4.2 Liquid water content

Measurements of temperature and liquid water content of cores revealed that the surface firn layers ranging from 0 to 3 m in depth were frozen by cold wave penetration in Senjagaike and Kuranosuke. All the other firn cores were wet and contained liquid water. Most of the water content in the upper unsaturated firn layer ranged 0−10 % and 10−20 % in the firn aquifer.

4.3 Density profiles

To eliminate the difference in density due to the difference in water content and to know to what

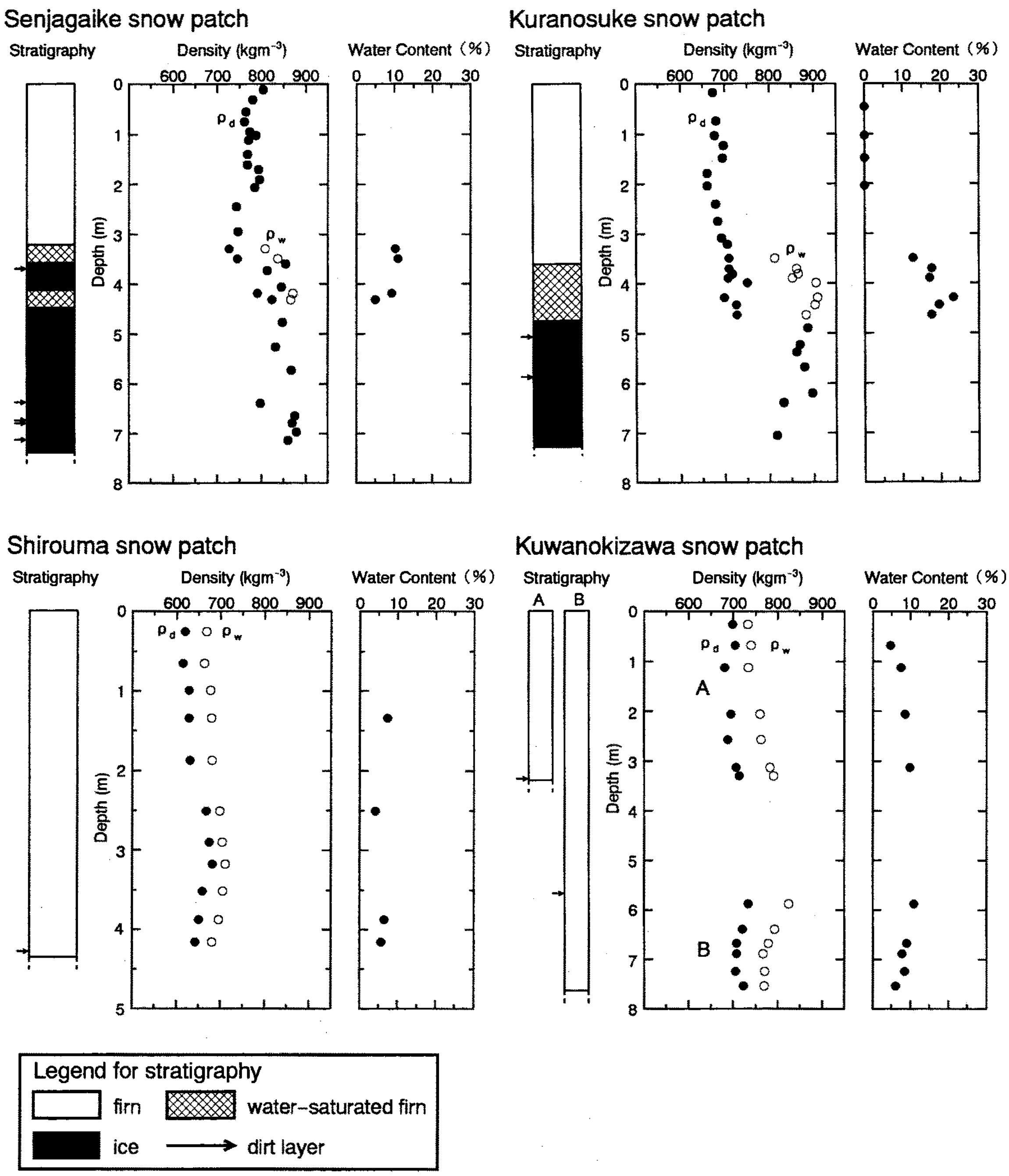

Fig. 2. Stratigraphy, density profiles and liquid water content observed at eight perennial snow patches in Japan during the ablation periods of 1995 and 1996. As seen in stratigraphic profiles, an ice body and a water-saturated firn layer (firn aquifer) were formed in many perennial snow patches.

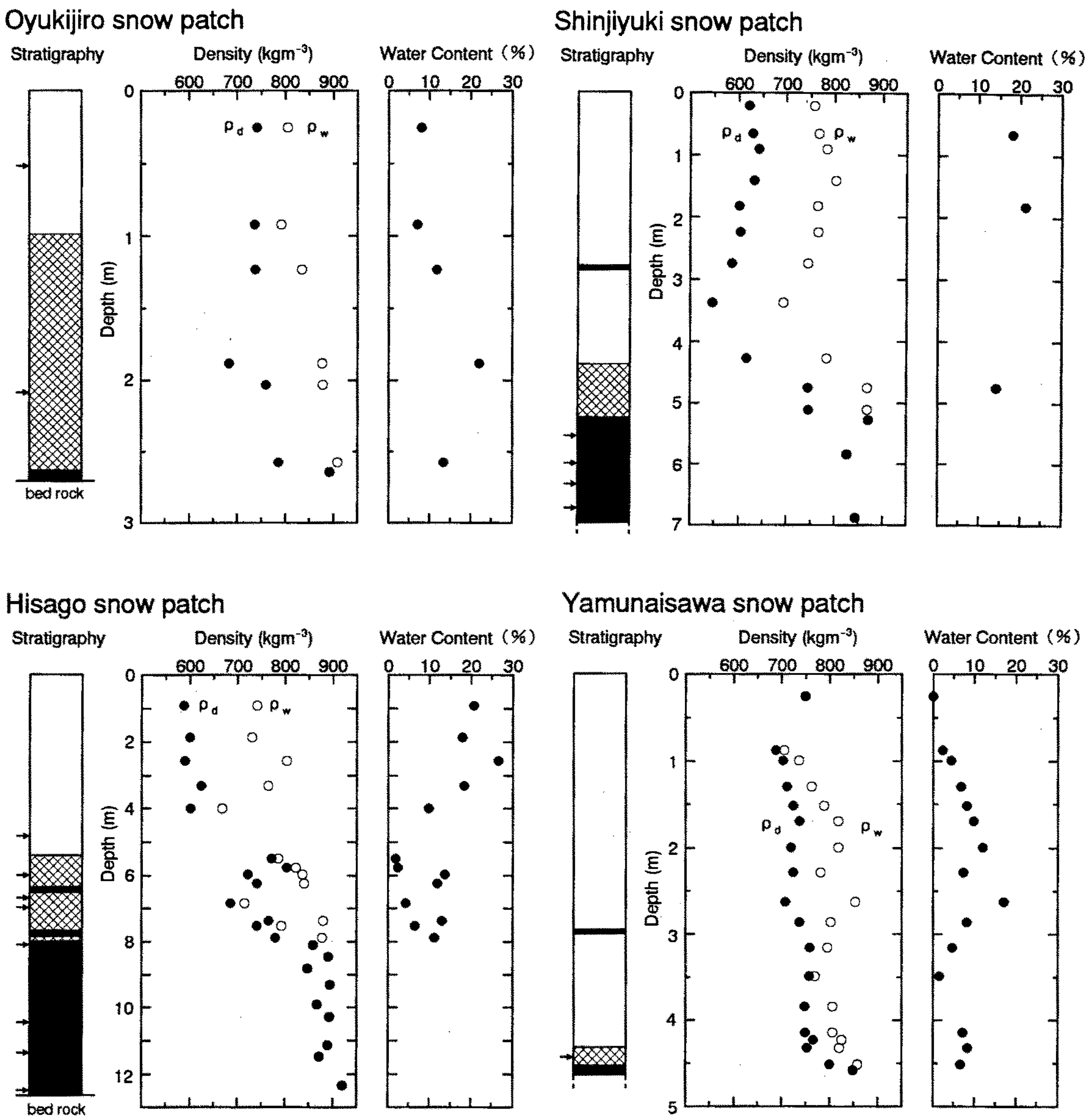

Fig. 2. (continued)

extent the densification has proceeded in each snow patch, the dry density ρ_d of ice alone is calculated from the wet density (total density) ρ_w and the liquid water content W using the equation :

$$\rho_d = (1 - W/100)\rho_w. \quad (1)$$

In Shinjiyuki and Hisago, the dry density increased suddenly from 600 kgm^{-3} to 700–800 kgm^{-3} at the level of the water table, as shown in Fig. 2. This indicates that the immersion of snow in water accelerates the densification, as pointed out by Wakahama (1968). The reason why a similar discontinuous increase in dry density was not seen at the water table in Senjagaike and Kuranosuke is considered to be that the refreezing of meltwater increased the dry density in the surface firn layer. In Yamunaisawa, the dry density was shifted from 700 kgm^{-3} to 750 kgm^{-3} at the depth of 3 m, suggesting that the water table rose up to that level during the peak period of snow melting. The difference in dry density between the 1-year-old firn and the 2-year-old firn in the Kuwanokizawa snow patch was as little as 20 kgm^{-3}, indicating that densification is slow in unsaturated firn with high density.

5. Discussion

We found ice bodies in almost all of the type-B snow patches, indicating that the formation of an ice body is not unusual but a common feature for type-B. It is clear that the snow patch with an ice body develops a firn aquifer just above the firn-ice transition during the ablation period. These characteristic features of type-B snow patches are similar to those of the wet-snow zone of temperate glaciers except that the firn-ice transition of temperate glaciers emerges at a depth of 20–30 m.

A few mechanisms have been proposed for the formation of ice body in perennial snow patches in Japan. Ogasahara (1964) considered early-winter refreezing of meltwater in the firn to be the major transformational process of the Hamaguriyuki snow patch in the Northern Japan Alps. Wakahama and Narita (1975) pointed out that the immersion of the bottom layer of firn in water due to water-impermeable bed rock accelerated the densification to result in the quick transformation from firn to ice in the Yukikabe snow patch in the Daisetsu mountains. Kawashima *et al.* (1993) concluded that the formation mechanism of ice body of the Hisago snow patch in the Daisetsu mountains comprised three processes : the formation of superimposed ice, the densification of a water-saturated firn layer and the freezing of wet and/or water-saturated firn by cold wave penetration.

The results of our investigation showed that the formation of a superimposed ice with thicknesses of 10–30 cm is possible for snow patches having an ice body. However, annual ice layers with thicknesses of 0.3–2.3 m, formed during years of positive mass budget, can not be explained by superimposed ice. Now we consider quantitatively how the formation of an annual ice layer can be completed in a single year in type-B snow patches, assuming that the ice layer formed by the process other than the superimposed ice formation has a thickness of 1 m.

The densification of water-saturated firn, which is the predominant transformational process from firn to ice in the wet-snow zone of temperate glaciers, may contribute to the ice formation in type-B snow patches. The relation between the time necessary for ice formation by densification in the firn aquifer and the overburden pressure acting on the water-saturated firn was shown experimentally by Kawashima and Yamada (1997) (Fig. 3). The overburden pressure

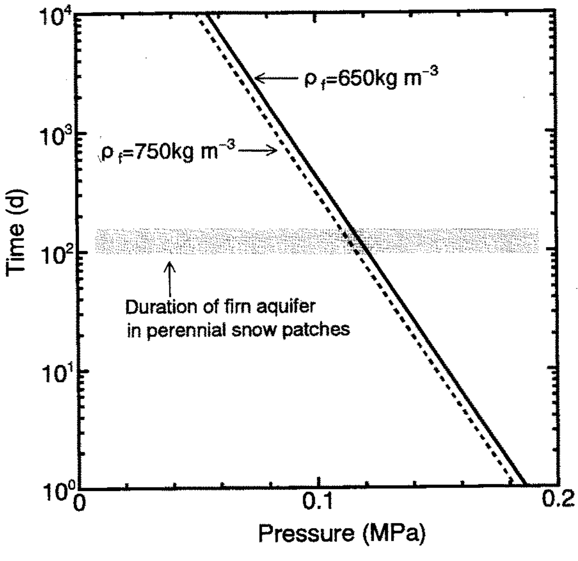

Fig. 3. Time required for the transformation from firn to ice by densification of water-saturated firn as a function of the overburden pressure (after Kawashima and Yamada (1997)). The necessary time was shown in two cases when initial firn density (ρ_f) is 650 kgm^{-3} (solid line) and $\rho_f = 750$ kgm^{-3} (broken line). Grey area represents the range of period when firn aquifers exist in perennial snow patches.

estimated from the depth-density profiles of type-B, shown in Fig. 2, is less than 0.04 MPa, and its maximum value at the beginning of the ablation period is believed not to exceed 0.1 MPa. If the average overburden pressure is taken as 0.07 MPa, the time necessary for ice formation is 6.7 years for an initial firn density of 750 kgm^{-3}. Therefore, the transformation from firn to ice can not be completed in a single year by densification alone in type-B snow patches.

A highly probable process is the freezing of water-saturated firn by cold wave penetration early in winter. We assume that the unsaturated firn layer melts entirely by the end of ablation period and that a cold wave penetrates directly into the water-saturated firn layer. This assumption is supported by the fact that the annual ice layer is nearly equal to the firn aquifer in thickness. Even if the firn aquifer has disappeared at that moment, enough liquid water for ice formation may be held in the firn by capillary attraction. It must be necessary for this process to be completed before the new snow accumulation on the snow patch to accomplish the formation of an annual ice layer, because the snow cover will act as thermal insulation to prevent the penetration of cold wave.

The cold wave penetration is a physical process that can be treated mathematically as a problem of one-dimensional heat conduction accompanied by freezing of water. To estimate the thickness of ice with density of 830 kgm^{-3} formed by freezing of liquid water in firn with dry density of ρ_d, Kawashima *et al.* (1993) introduced the following equation using the Stefan model :

$$I = 0.966\sqrt{\frac{1}{830-\rho_d}\int(3-T_a)dt}\,, \qquad (2)$$

where I is the thickness of ice in meters, T_a is the daily mean air temperature in Celsius, t is the time in days, and $\int(3-T_a)dt$, which is called the accumulated freezing index (AFI) in this paper, is the cumulative value of $(3-T_a)$ from the date when T_a drops to below 3°C for the first time to the date when I is calculated, provided that $3-T_a=0$ when $T_a>3$. The reason for using $(3-T_a)$ in the calculation of AFI is that the temperature of snow surface is lower than the air temperature by 3 degrees on average, which was obtained from field observations by Motoyama *et al.* (1986).

Values of AFI at the perennial snow patches were estimated from the daily mean air temperature of their nearest weather stations using the altitudinal lapse rate of air temperature (6.5°C/km). Fig. 4 shows changes in AFI at the drilling sites and the new snow depth observed in mountainous regions, during the period of transition from ablation to accumulation in 1995. The observational sites of snow depth include Kurobeko (1460 m a.s.l.), 4 km southeast of Kuranosuke, Okutadami (800 m a.s.l.), 15.5 km east of Kuwanokizawa, and Sugatami (1600 m a.s.l.), 12.5 km north of Hisago. Values of AFI at Senjagaike, Kuranosuke and Hisago start to increase rapidly at the beginning of October, while those at Oyukijiro and Shinjiyuki increase slowly during October. In contrast, the new snow depth starts to increase at the beginning of November simultaneously for all mountain regions irrespective of latitude and altitude. Of course, snow depth increases with altitude. This means that the winter climate of Japan is largely subject to the northwesterly monsoon which becomes dominant in November, bringing heavy snowfalls to wide areas facing the Japan Sea. The ice thickness calculated using equation (2) is shown in Fig. 5 as a function of AFI for various values of ρ_d. Since freezing occurs in the water-saturated firn layer, the dry density of firn can be taken to be 750 kgm^{-3}. There-

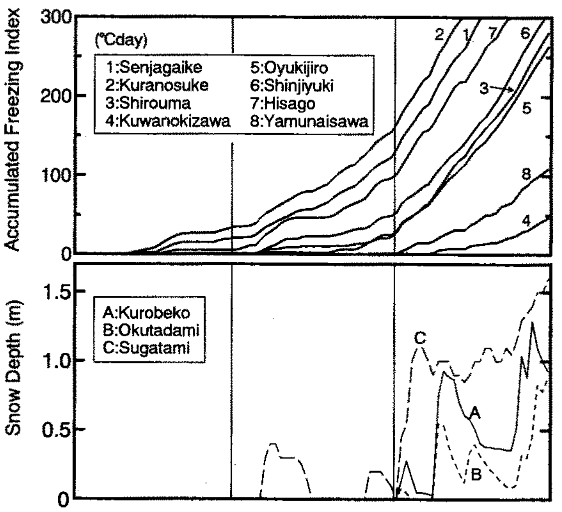

Fig. 4. Changes in accumulated freezing index (AFI) at the drilling sites of eight perennial snow patches from September to November in 1995, together with variations in new snow depth observed in mountainous regions in Japan. The time when AFI begins to increase markedly differs depending on the locality of the snow patch, while the new snow depth begins to increase in November almost simultaneously.

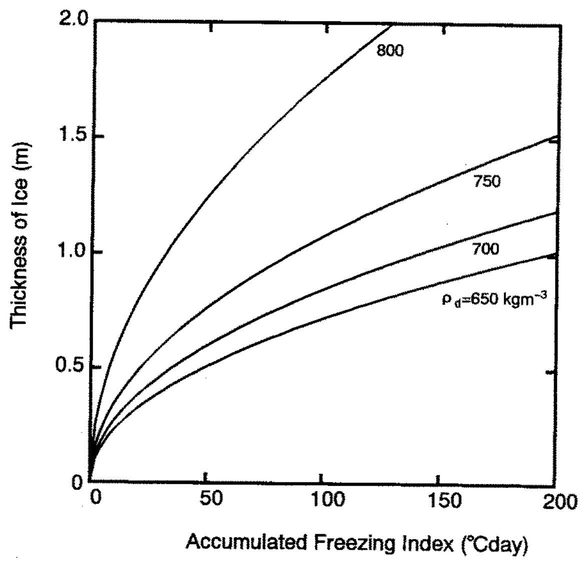

Fig. 5. Thickness of ice with density of 830 kgm^{-3} formed by the freezing of wet firn with dry density of ρ_d as a function of AFI. The curves clearly show that the ice thickness increases rapidly when ρ_d is large.

fore, the formation of a 1-m thick ice layer requires an AFI of 86°Cday. Comparisons between this critical value and values of AFI at the end of October show that the critical value is exceeded at Senjagaike, Kuranosuke and Hisago. Therefore, these snow patches can complete the formation of annual ice layer in a single year by the freezing of the saturated layer. At Oyukijiro and Shinjiyuki, the AFI values do not reach the critical value, so that the continuous mass of ice can be formed only where the annual layer is not so thick, as in the case of the Shinjiyuki snow patch.

These results may be true for other years in addition to 1995. Monthly mean values of air temperature in October for 17 years (1979–1995) were estimated for the perennial snow patches using the above lapse rate (Table 3). The AFI of 86°Cday is roughly equivalent to a monthly mean air temperature of 0.2°C if we suppose that freezing starts in October. By comparing monthly mean air temperature in October with 0.2°C, the same results as mentioned above are obtained. Although no reference was made to the thermal effect of new snow cover on cold wave penetration and the distribution of liquid water in the firn layer during freezing, it was confirmed in principle that this process makes possible the formation of an ice body under present climatic conditions in type-B snow patches in Japan.

Drillings could not reveal whether or not ice bodies exist in type-A snow patches. Processes of ice formation in type-A, if they also have ice bodies, must differ from those in type-B, because extremely small AFI values, as show in Fig. 4 and Table 3, does not allow deep penetration of cold wave. This is attributable to the fact that they are located at relatively low altitudes of less than 1000 m a.s.l. Thus, the densification of water-saturated firn may be the predominant mechanism of ice formation in type-A snow patches, with the result that the depth and age of firn-ice transition become much larger than those in type-B snow patches and are similar to those of temperate glaciers.

6. Concluding Remarks

The results from ice-core studies demonstrate that most perennial snow patches nourished mainly by drifting snow in Japan have continuous masses of ice at their lowest parts. The water-saturated firn layer, formed just above the firn-ice transition during the ablation period, contributes to the formation of highly densified firn which can be transformed into ice easily by freezing of a small amount of liquid water in firn early in winter. The transformation from firn to ice in this type of perennial snow patch is completed in a single year in most cases, which is much shorter in comparison with temperate glaciers. In perennial snow patches nourished mainly by snow avalanches, because the air temperature prior to new snow accumulation is not reduced sufficiently, the cold wave penetration can not be an effective process of ice formation. If this type of snow patch has an ice body,

Table 3. Monthly mean values of air temperature in October for 17 years (1979-1995) at the eigth snow paches, estimated from those at their nearest weather stations (Japan Meteorological Agency) using the altitudinal lapse rate of air temperature (6.5°C/km).

Senjagaike	Kuranosuke	Shirouma	Kuwanokizawa	Oyukijiro	Shinjiyuki	Hisago	Yamunaisawa
-1.2	-2.0	2.7	9.6	1.6	0.8	-1.7	5.6

the densification of water-saturated firn due to overburden pressure must dominate the ice formation, resulting in much larger depth and age of firn-ice transition like temperate glaciers.

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