FORMATION OF SURFACE SNOW LAYER AT MIZUHO STATION, ANTARCTICA

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Abstract: On the basis of year round observations of surface snow condition in 1977 and snow stake measurements carried out from 1972 to 1978 at Mizuho Station, which is located at 70°42′S, 44°20′E and 2230 m a.s.l. in the katabatic wind region, daily, seasonal and secular changes of surface condition and surface layer formation are studied. The surface level changes gradually by sublimation in summer and condensation in winter, and rapidly by deposition and wind erosion of snow. Surface features change much in the intermediate seasons, when low pressure disturbances is active, between summer and winter. The alternative years variation is seen in the mean annual balance of 202 stakes in 1973–1977, being high in 1973, 1975 and 1977 and low in 1974 and 1976. Formation of an annual layer occurs once in two or three years on the average. The mean, maximum and minimum annual balance of 202 stakes in 1973–1977 are 1.5–14.8 cm, 36.0–52.1 cm and −10.4∼−14.9 cm, respectively. The absence of annual layer or layers is mainly due to no deposition of snow and to sublimation of a pre-formed annual layer or layers. A model of transmigration of the surface condition is proposed.

1. Introduction

The process of surface snow layer formation is complicated at Mizuho Station (70°41′53″S, 44°19′54″E, 2230 m a.s.l.; Fig. 1.), where deposition and erosion of snow occur throughout a year due to a strong katabatic wind. According to OKUHIRA and NARITA (1978) and WATANABE (1978), surface snow conditions and layer formation at Mizuho Station are characterized by both a deposition-erosion process and the existence of a glazed surface. The deposition-erosion process depends on snow surface conditions such as microrelief, undulation, texture and structure, and meteorological conditions. An interruption in surface layer formation during some seasons and years is observed commonly when there is a glazed surface composed of a multilayered ice crust. An understanding of the process and the variability in the surface layer formation are important for the proper interpretation of ice core stratigraphy and for the study of the relation to short-term climatic variations.

Since the IGY, stratigraphic studies on the surface snow layer have been made by many investigators over the Antarctic ice sheet, but some problems, such as the

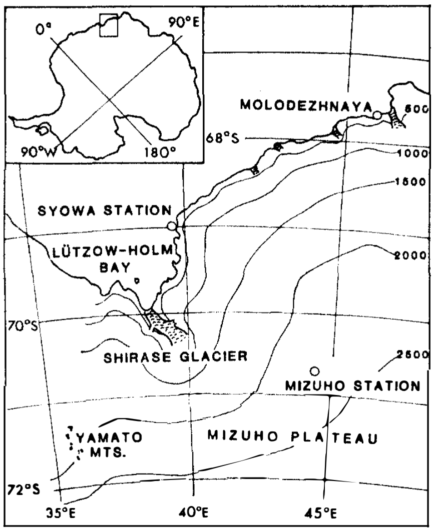


Fig. 1. Location of Mizuho Station.

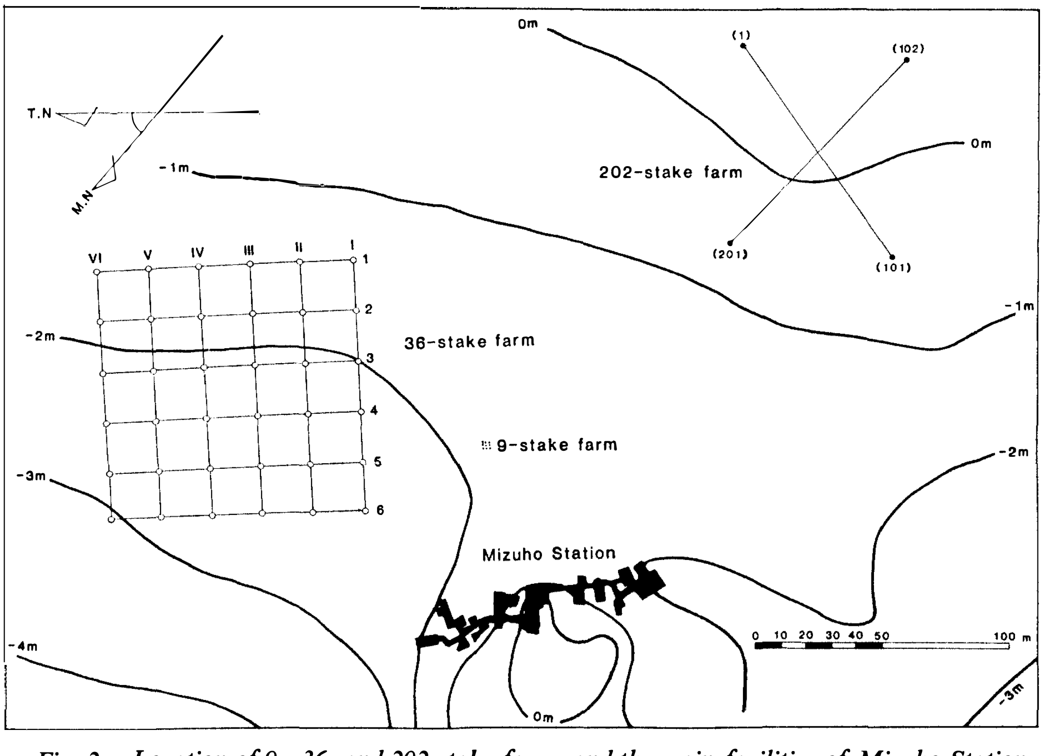


Fig. 2. Location of 9-, 36- and 202-stake farms and the main facilities of Mizuho Station (black part).

variability of surface layer formation and the relation to short-term climate, still remain unsolved.

The present study was done to clarify the daily, seasonal and annual variability of surface layer formation on the basis of snow stake measurements and areal mapping of surface conditions carried out in 1972–1978. Furthermore, the absence of an annual layer or layers is discussed, and a concept of transmigration of the surface layer is proposed.

Snow stake measurements were made using a 9-stake farm with 1 meter grid interval, a 36-stake farm with 20 meter grid interval and a 202-stake farm composed of two cross lines with a stake interval of 1 meter. The grids of the 36-stake farm were established to be parallel to the prevailing wind direction and at a right angle to it. Figure 2 shows the locations of these stake farms. All of the data used in the present study are reported in JARE Data Reports, No. 17 (1972), No. 27 (1975), No. 36 (1977), No. 44 (1978) and No. 48 (1979).

2. Daily Change of Snow Surface Level in 1977

In order to know the daily change of the surface level owing to the deposition-erosion process of snow and condensation-sublimation process on the surface throughout a year, daily readings of nine stakes to the nearest mm were made at 15 LT throughout 1977. Simultaneously, the surface condition at each stake was recorded (FUJII, 1979a). The surface was classified genetically into three major types, that is, a glazed surface consisting of multilayered ice crust, depositional surface consisting of barchan or snow dunes and erosional surface consisting of sastrugi, erossional pits or smooth surface.

Figure 3 shows the daily change of the snow surface level of the No. 3 stake of the 9-stake farm. The surface condition of the stake is shown in solid circles for glazed surface, open circle for depositional surface and triangle for erosional surface. After the heavy snow deposition occurred in the 9-stake farm from the end of October to early November, an additional stake was set in the glazed surface to compare deposition-erosion and condensation-sublimation processes on the surface under different conditions. The daily change of surface level at the additional stake is also shown in Fig. 3.

The glazed surface fell rapidly in summer and reached the minimum level in the middle of April. Then it gradually rose until the glazed surface was covered by snow deposition in early August. According to the measurements of condensation and sublimation at Mizuho Station (FUJII, 1979b), these surface lowerings and risings are due to sublimation (annual amount, 5.5 $g\cdot cm^{-2}$) and condensation (annual amount, 0.2–0.6 $g\cdot cm^{-2}$). From the end of October to early November, the surface level rose about 14 cm due to snow deposition. Then the surface level fluctuated due to the deposition-erosion process, falling gradually by sublimation from the surface.

Almost of the deposited snow was eroded within 1 to 3 days after snow deposition, as is shown by the pulse-like level changes in Fig. 3. Though deposition of

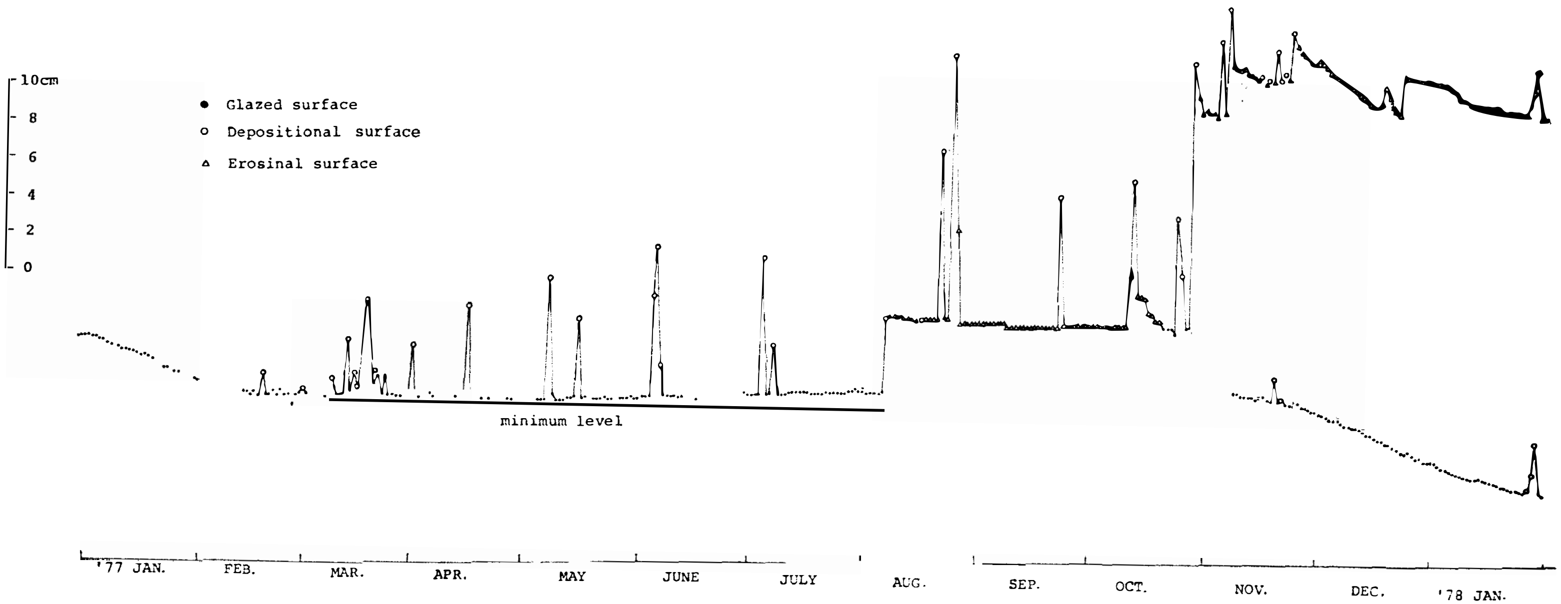


Fig. 3. Daily change of surface level at No. 3 stake of the 9-stake farm in 1977 (after FUJII, *1979a).*

snow was observed throughout 1977 except in January, it was concentrated in March (7 times) and October–November (7 times). Among 28 times of snow deposition in 1977, only the two times in early August and the end of October contributed to the annual layer formation. In other words, the 1977 annual layer was composed of two unit layers. An interruption in the seasonal layer formation causes the disappearance of seasonal sequence of the oxygen isotope composition ($\delta^{18}O$) and stratigraphic structures in the vertical profiles, as is pointed out by WATANABE (1978).

Comparing the occurrences of snow deposition on the erosional and the glazed surfaces in November 1977 to January 1978, the process occurred more on the erosional surface than on the glazed surface. The snow deposition depends much on the roughness of the surface.

3. Variation of Areal Surface Condition in 1977

Year-round observations of the surface conditions of both 36-stake farm area (100×100 m in area) and 202-stake farm were carried out from February 1977 to January 1978 to clarify the horizontal continuity of layer formation and its seasonal variation. Detailed mapping of surface conditions of the 36-stake farm was carried out occasionally before July, and then once a month. The observational results are shown in the JARE Data Reports, No. 48 (FUJII, 1979a).

Representative seasonal surface conditions of the 36-stake farm area in 1977 are shown in Fig. 4, in which (a), (b), (c) and (d) are the conditions of February 15, April 15, July 18 and November 16, respectively; white indicates a glazed surface, black a depositional surface, and the dotted part indicates an erosional surface. The direction of the prevailing katabatic winds, ESE, is parallel to the stake line for each Roman numeral. During a synoptic scale disturbance, the wind direction turns northward by 20°–50° from the direction of the prevailing winds.

At the end of the austral summer, a glazed surface was well developed in the farm, occupying 77% of the whole area (Fig. 4a). After storms occurred in the middle of March, the surface exhibited considerable change, that is, the glazed surface occupied as little as 38% of the whole area and the erosional surface (newly formed sastrugi) occupied 45%. These appeared alternately at 20 to 30 m intervals parallel to the prevailing wind direction during the synoptic scale disturbances (Fig. 4b). In winter, buried glazed surface was gradually exposed to 67% of the whole area due to the erosion of snow deposited on it in March (Fig. 4c). During the period from mid-October to early November, considerable snow deposition occurred, and the deposited snow successively changed into a stable erosional surface which lasted at least until January 1978. The areal ratio of the erosional surface on November 16 amounted to 80% (Fig. 4d). About 14% of the whole area was occupied by glazed surface throughout the present observation period from February 1977 to January 1978.

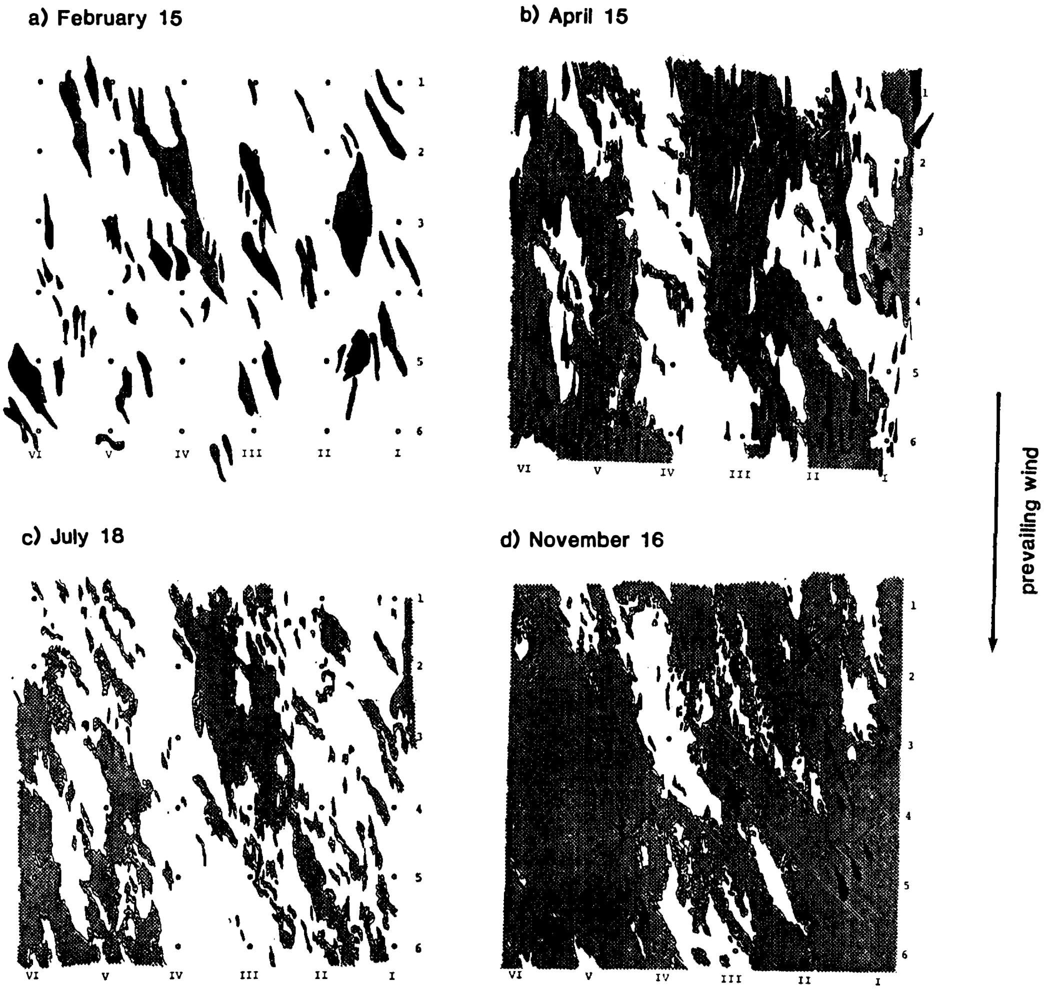


Fig. 4. Surface conditions of 36-stake farm (100 m × 100 m) on February 15 (a), April 15(b), July 18 (c) and November 16 (d). (after FUJII, 1979a).

Seasonal variations in the areal ratio with regard to the surface condition in the 36-stake farm and along a line of 202-stake farm are shown in Fig. 5. The similar tendencies are recognized in the seasonal variations of the areal ratio of both the 36- and 202-stake farms, that is, the extensive distribution of glazed surface in February to mid-March and mid-April or mid-May to September, and the restricted distribution of it in mid-March to early May and after mid-October. Especially, the invariable areal ratio observed in both stake farms from April or May to July indicates that little deposition and erosion of snow occurs in winter in the vicinity of Mizuho Station. No deposition of snow was observed in 10 to 14% of the observational area of 36- and 202-stake farms throughout 1977; it occurred on the glazed surface.

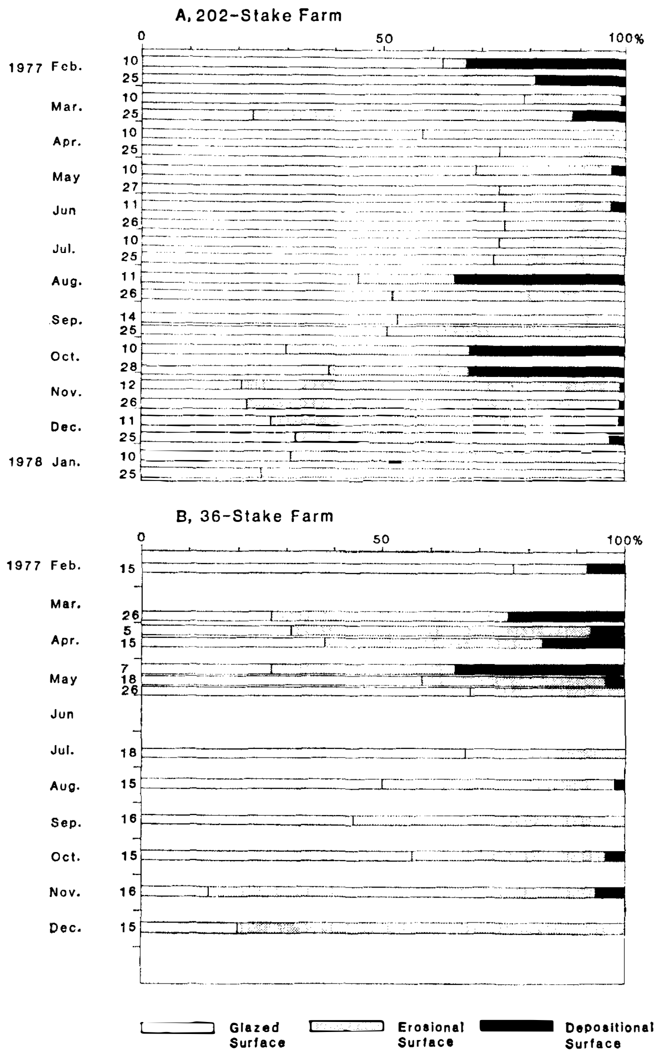
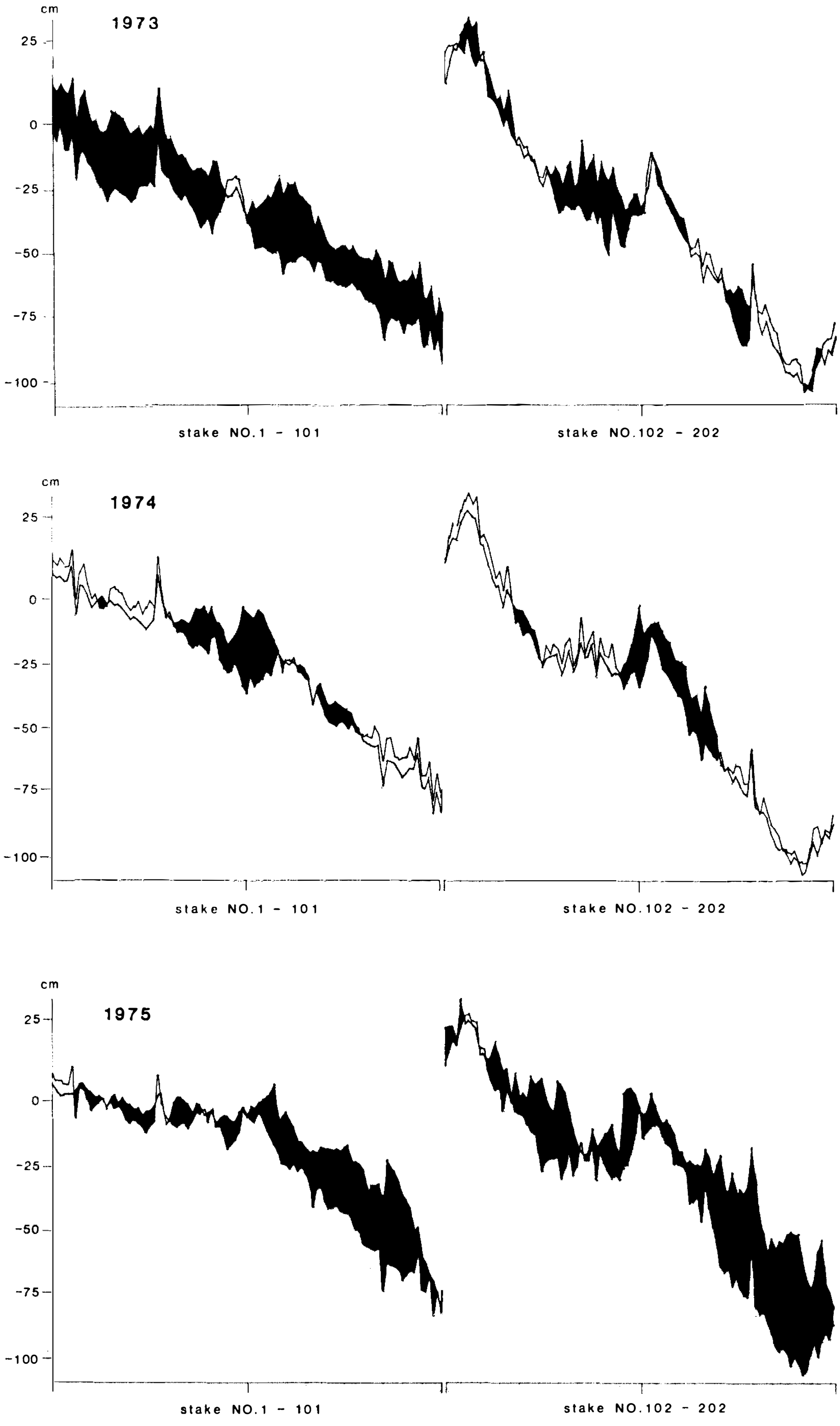


Fig. 5. Seasonal change of aerial ratio of different snow surface along a No. 102 to No. 202 stake line of 202-stake farm (A) and in 36-stake farm (B) in 1977.

4. Surface Mass Balance Variability in 1973–1977

Since a 202-stake farm was established at Mizuho Station in May 1972 (YAMADA *et al.*, 1975), the measurements of stake height have been carried out at bimonthly to semimonthly intervals by YOKOYAMA (1975), SATOW (1977), NISHIO (1978) and FUJII (1979a) except from February 1975 to May 1976, when no measurements were made. In this paper, an annual balance is defined as net accumulation of snow during the summer-to-summer measurement period which is selected among the measurements to be the nearest to one year. Figure 6 shows the sequences of annual


cm
1973
25
0
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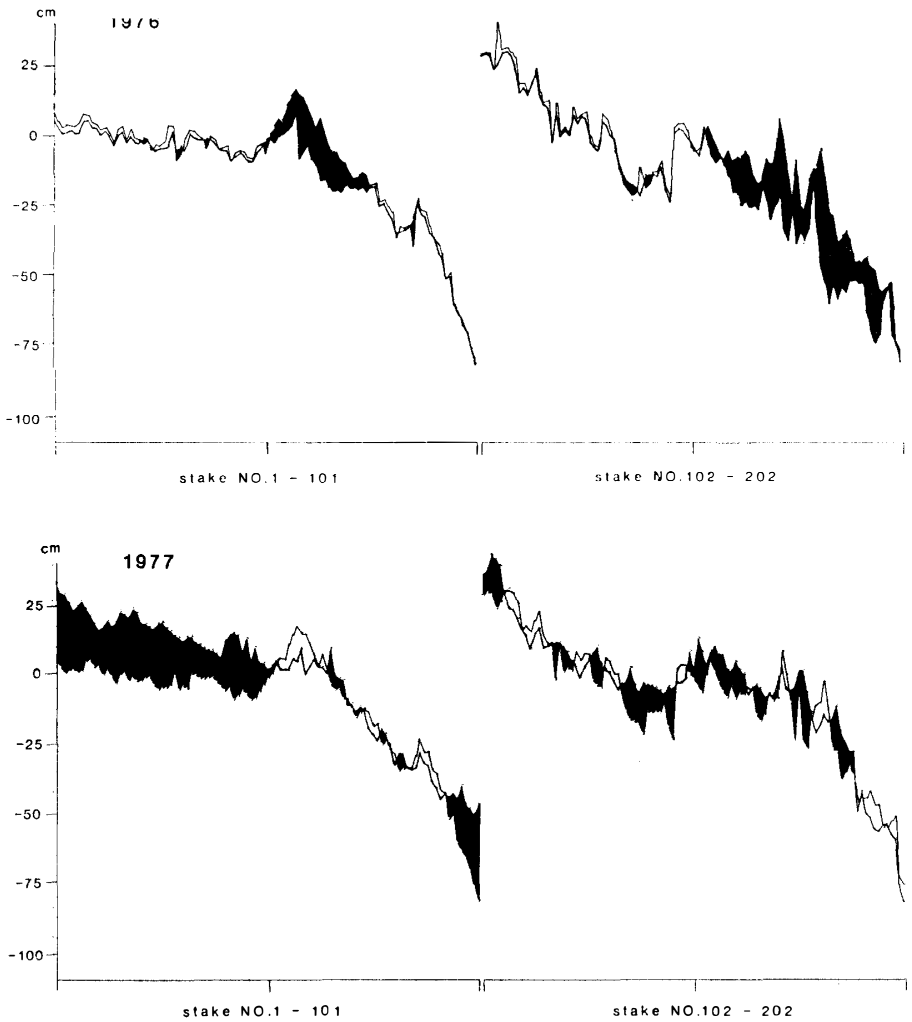

Fig. 6. Sequences of an annual layers along No. 1–101 and No. 102–202 stake lines from 1973 to 1977. The black and white parts between two successive profiles are equivalent to the positive and negative annual balance respectively.

layers along the No. 1–101 and No. 102–202 stake lines in 1973 to 1977. The black parts between two successive profiles of surface relief indicate a positive annual balance, and the white parts between them indicate a negative annual balance. The reference level, 0 cm in the ordinate of the figure, takes the surface level of the No. 1 stake at the time of establishment in May 1972. Table 1 gives the statistics of the annual balance from 1973 to 1977.

Mean mass balance shows the alternate years variation, being relatively high in 1973, 1975 and 1977 and low in 1974 and 1976. The secular variation of standard deviation of annual balance shows the same tendency as that of the mean mass bal-

Table 1. Ratios of positive and negative balance and mean, standard deviation, maximum and minimum of annual balance at 202 stakes from 1973 to 1977.

Year	Duration	Ratio of balance		Balance in cm of show			
		Positive	Negative	Mean	St. dev.	Max.	Min.
1973	'73 Jan.–'74 Jan.	78	22	11.0	11.0	31.0	−12.0
1974	'74 Jan.–'75 Feb.	45	55	1.5	8.9	32.0	−12.0
1975	'75 Feb.–'76 May	92	8	14.8	13.8	52.1	−10.4
1976	'76 May–'76 Dec.	43	57	4.5	9.4	45.1	−14.9
1977	'76 Dec.–'77 Dec.	70	30	7.1	10.4	34.6	−13.7

ance. In other words, the variability of the mass balances is high in the years when the mean annual balance is high.

The alternate years variation is observed not only in the mean annual mass balance but also in the balance of some successive stakes. As is seen in Fig. 6, and was reported by OKUHIRA and NARITA (1978), positive mass balance tends to occur at stakes where negative or low positive mass balance was observed in the previous year.

The secular variations of the maximum and the minimum annual balance show no relation to that of the mean mass balance. The maximum and minimum annual balance range from 31 to 52 cm and −10 to −15 cm respectively. The value of the minimum balance indicates the posibility of erosion of the layers formed in previous few years.

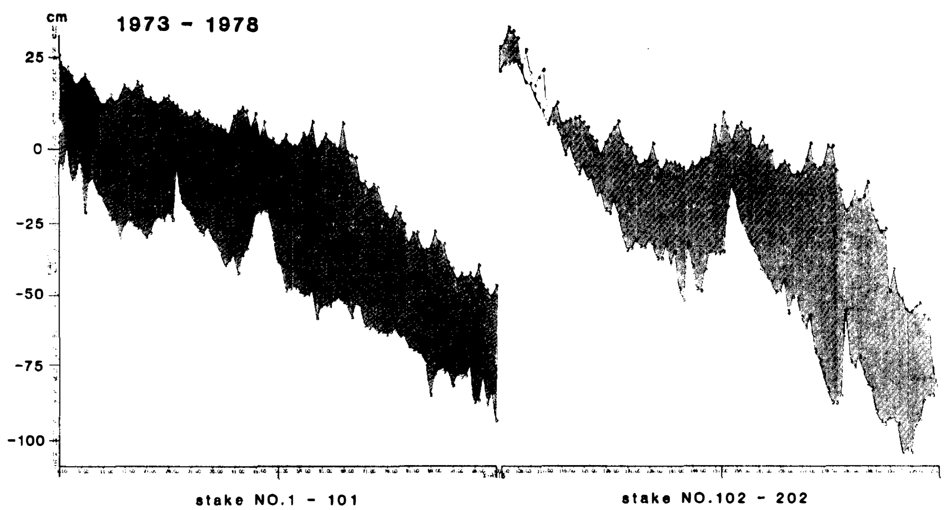

Fig. 7. Sequence of total mass balance during five years from January 1973 to December 1977 along the No. 1–101 and No. 102–202 stake lines.

The sequence of total mass balance during the five years from January 1973 to December 1977 along the stake lines consisting of stakes No. 1–101 and No. 102–202 is shown between two surface profiles (Fig. 7). The net mass balance during the five years is 38.8 cm of snow, which corresponds to a mean annual balance of 7.8 cm of snow. The standard deviation is 17.2 cm. The total mass balance was negative during the five years 1973–1977 at the stakes from No. 108 to No. 113, being a minimum of −14.0 cm of snow at stake No. 112. The surface at these stakes was a glazed surface in 1977, except during periods of temporary snow deposition on it.

5. Discussion

5.1. Absence of an annual layer(s)

Absence of annual layers is a phenomenon which usually occurs in the altitudinal range of 1800 m to 3200 m on the Mizuho Plateau (WATANABE, 1978). The analysis of the surface level changes of 202 stakes during May 1972 to January 1978 shows that the maximum duration of absence of layer formation at each stake is from 1 year to 2 years, accounting for 46% of the 202 stakes as shown in Fig. 8, where the dashed part indicates the case in which the absence dated back before May 1972. A maximum absence of more than 1, 2, 3, 4 and 5 years occurred at 86%, 40%, 18%, 8% and 2% of the 202 stakes respectively. It is, therefore, clear that an absence which continues for more than a year is a quite ordinary phenomenon at Mizuho Station.

An absence of an annual layer(s) at Mizuho Station is thought to be mainly due to no occurrence of snow deposition in a given year, especially on a glazed surface, and to disappearance of pre-formed annual layer(s) due to sublimation and wind erosion.

Deposition and erosion of snow are difficult on a glazed surface, and occur occasionally on a wind packed smooth surface. As is shown in Fig. 7, no deposition of

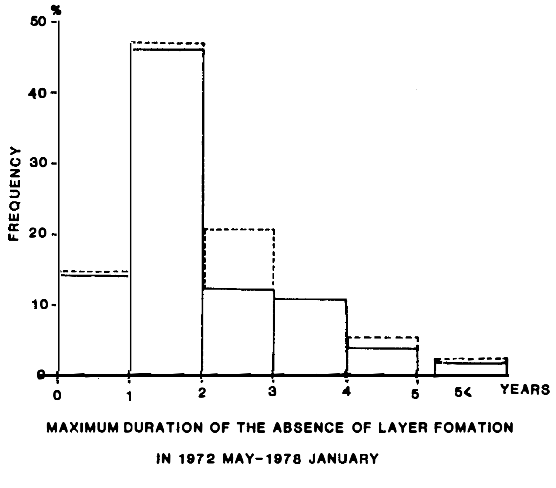

Fig. 8. Frequency distribution of the maximum duration of the absence of layer formation at 202-stake farm during the period from May 1972 to January 1978. The dashed part indicates an absence which started before May 1972.

snow occurred at some stakes on a glazed surface during the five years from 1973 to 1977. According to WATANABE *et al.* (1979), an interruption in annual layer formation is thought to last for several to ten odd years on the glazed surface, so the glazed surface indicates the surface under a relatively long-term interruption.

Judging from the annual sublimation rate measured by FUJII (1979b) at Mizuho Station in 1977, the level of the glazed surface fell at a rate of 7 $cm \cdot a^{-1}$ during the years when no snow deposition occurred, resulting in the disappearance of a pre-formed annual layer or layers.

The long-term existence of the glazed surface, therefore, causes the absence of an annual layer(s) by two different simultaneous phenomena, that is, no occurrence of snow deposition on the surface and disappearance of a pre-formed annual layer due to sublimation at the surface.

In the katabatic wind region where Mizuho Station is located, wind erosion of surface snow occurs not only within a few days after deposition, as is shown in Fig. 3, but also within a few years after the annual layer(s) formation. But the importance of wind erosion on the absence of an annual layer(s) is uncertain.

5.2. Formation of an annual layer and the frequency

Two contrasting types of annual layer formation observed at the 202-stake farm are illustrated in Fig. 9, showing the continuous annual layer formation at stake No. 69 and the long-term absence of annual layer formation at stake No. 113. The figure indicates the change of surface level, disappeared snow layers in the dotted part, and layers which existed in January 1978 and which have been formed since May 1972.

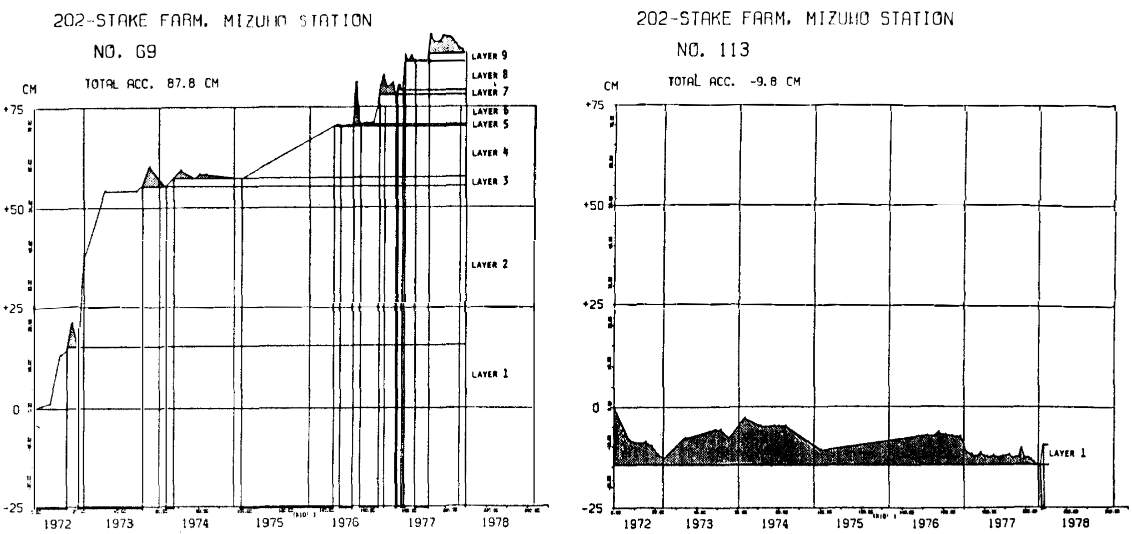

Fig. 9. Change of surface level, layer formation and disappearance of pre-formed layer shown as dotted part at No. 69 and No. 113 stakes of 202-stake farm from May 1972 to January 1978.

Annual layers were continuously formed at stake No. 69 during the period from May 1972 to January 1978 when the total net accumulation of snow was 87.8 cm in depth; 9 (unit) layers were superimposed on the surface in May 1972. "Unit layer" is defined as the snow residue after a cycle of the deposition-erosion process by WATANABE (1978). On the other hand, no annual layers were formed at stake No. 113 during at least 5 years from 1973 to 1977. The lowering of the surface level was 9.8 cm from May 1972 to January 1978. Only a single layer was formed at stake No. 113 in January 1978 during the period from May 1972 to January 1978.

OKUHIRA and NARITA (1978) show the sequence of annual layers and the frequency distribution of the number of annual layers formed in 1972 (May 1972–January 1973), 1973 (January 1973–January 1974) and 1974 (January 1974–February 1975) at 202 stakes at Mizuho Station. Figures 10 and 11 each show the five-years trend from 1973 to 1977 based on their figures and the observational data in 1976 by NISHIO (1978) and those in 1977 by FUJII (1979a).

As is shown in Fig. 10, annual snow layering at Mizuho Station is characterized by discontinuity and high year-to-year variability.

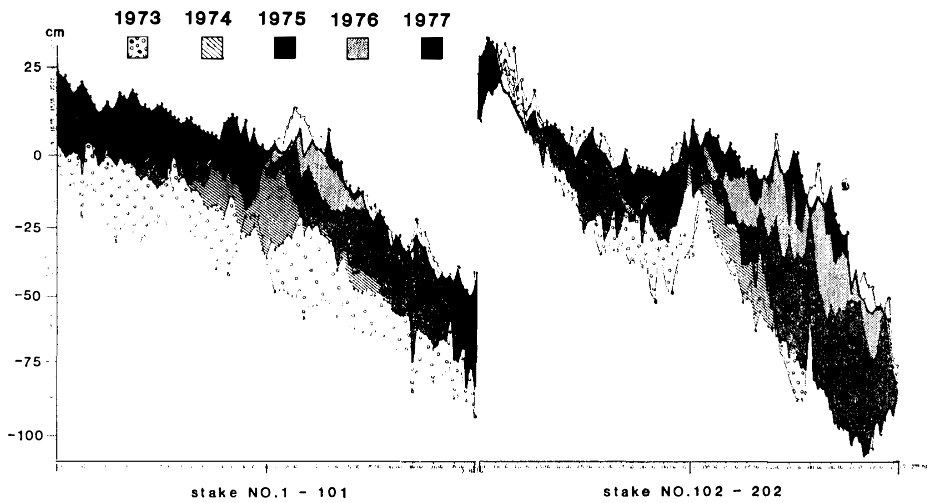

Fig. 10. Cross-sectional sequence of annual layers from 1973 to 1977 along No. 1–101 and No. 102–202 stake lines at the end of 1977.

The frequency distribution of the number of annual layers formed during the 5 years from 1973 to 1977 at 202 stakes is shown in Fig. 11. The number has peaks at 2 and 3 annual layers for 5 years, that is, biyearly layer formation on the average. The statistics for three years from 1972 to 1974 given by OKUHIRA and NARITA (1978) indicate that the formation of an annual layer is predominant in the frequency of once in three years. Taking account of the shortness and the difference of these statistical durations, the results can be thought to coincide with each other, that

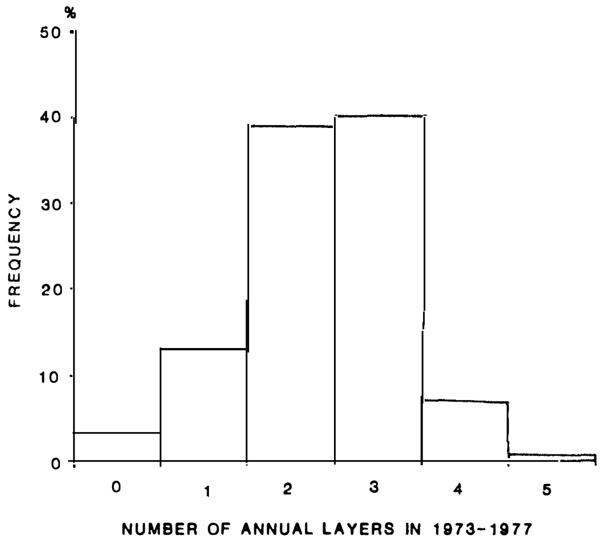

Fig. 11. Frequency distribution of the number of annual layers at 202-stake farm from 1973 to 1977.

is, annual layer formation occurs once in two or three years. The alternate year variation of mean mass balance is the 202-stake farm as is shown in Table 1 seems to relate to the biyearly or three-yearly layer formation on the average.

5.3. Process of surface layer formation

On the basis of the seasonal variation of snow surface condition in 1977 and secular change of the snow surface level in May 1972–January 1978, a model which representates the process of increase of surface level and the absence of surface layer formation at Mizuho Station is illustrated in Fig. 12. Comparing with a model proposed by WATANABE (1978), who emphasizes the negative effect of interruptions on the increase of surface level, the present model shows the roles of sublimation from the surface in the state of a long-term interruption and of wind erosion of pre-formed snow layer(s) in the absence of layer formation.

A model of transmigration of the snow surface at Mizuho Station is shown in Fig. 13, based on year round observation of the changes of the surface condition in 1977.

A long-term interruption in layer formation on a glazed surface ceases when one of the following two processes occurs; one is deposition of snow on the glazed surface and the other is disappearance of the glazed surface by sublimation and wind erosion. Disappearance of a glazed surface, namely, disappearance of a multilayered ice crust was observed at Mizuho Station and the vicinity in January 1978 because of the continuation of a negative mass balance at a multilayered ice crust since mid-October, 1977, being negative at the upper side by sublimation and positive at the

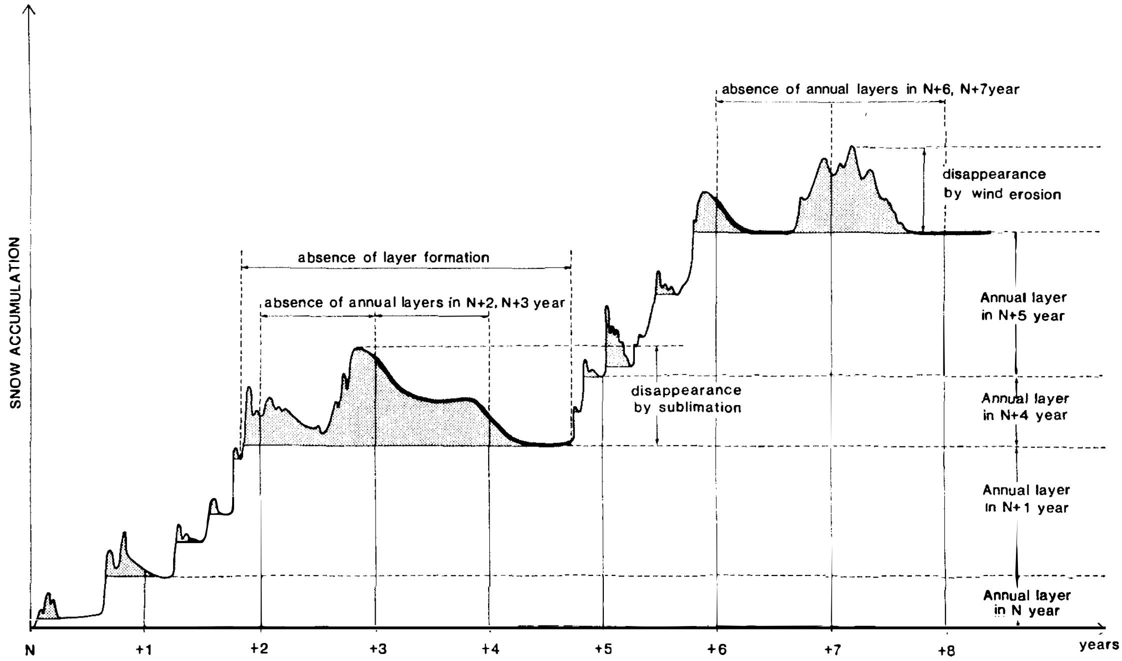

Fig. 12. A model of the process of increase of surface level and process of absence of surface layer formation at Mizuho Station.

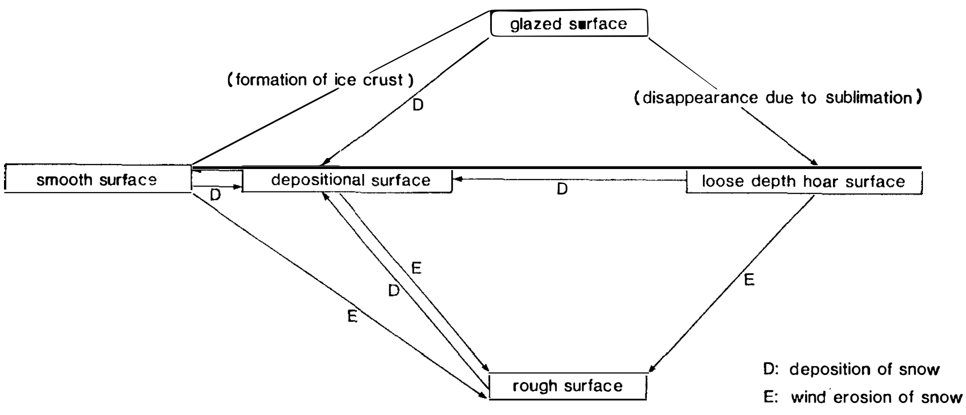

Fig. 13. A model of transmigration of the snow surface at Mizuho Station. The thick solid line indicates a glazed surface.

lower side by condensation of vapor transported from the lower part (FUJII and KUSUNOKI, 1981). Disappearance of the glazed surface causes subsequent exposure of the sub-laid loose depth hoar which seems to be easily eroded by a strong wind (Fig. 14).

Recrystallization of a smooth surface by sintering of snow particles was ob-

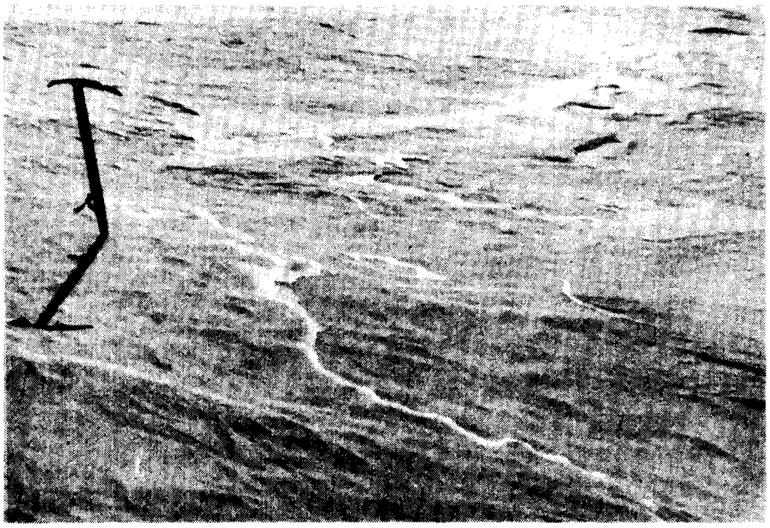

Fig. 14. Surface consisting of loose depth hoar exposed by the disappearance of ice crust, January 22, 1978. Lingering ice crust is seen in the central part of the photo.

served during the summer from November 1977 to January 1978 (FUJII, 1979a) and the metamorphism of the surface snow particles seems to show the transient state from smooth surface to glazed surface, consisting of multilayered ice crust.

As is shown in Fig. 13, both deposition-erosion and condensation-sublimation at the surface determine the surface snow condition and the migration from one surface to the other.

6. Conclusion

The present study shows the daily, seasonal and secular changes of surface condition and surface layer formation at Mizuho Station, which is located in a strong katabatic wind region in Mizuho Plateau on the basis of year-round observation of the surface snow condition in 1977 and snow stake measurements in 1972–1978. Furthermore, a mechanism associated with the absence of an annual layer or layers and a conception of transmigration of surface snow layer are proposed.

A further similar study is recommended in the inland region located above 3000 to 3200 m a.s.l. where relatively thin unit layers with uniform layering are common (GOW, 1965; WATANABE, 1978) to compare the characteristics of surface snow layer formation with those in the katabatic wind region lower than 3000 to 3200 m a.s.l. Studies of the interrelation between surface layer formation and meteorological and climatological conditions are required for the purpose of determining the fundamental relation of climate to the ice sheet.

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