A STUDY OF FORMATION OF A SURFACE SNOW LAYER

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Abstract: The process of surface layer formation was observed in Mizuho Plateau from the coast inland, including Mizuho Camp at the elevation of 2169 m above sea level, by measuring a net snow accumulation at three stations, each with a pair of 100-stake lines set up, each line perpendicularly intersecting, and each stake aligned at a 1 m interval, and at six stations, each with a stake farm consisting of 36 stakes spaced 20 m apart in a 100 m square grid.

The observations disclosed that the characteristics of deposition-erosion process at the surface vary with time and place, that a surface layer is formed annually all over the site of H180 (1540 m) and its vicinities, sporadically at and near S122 (1853 m), as well as at Mizuho Camp where either one or no annual layer was formed during a three-year period, the width of such a layer being less than 15 m in most of cases, and that the formation of a dune, one of the depositional phenomena, is closely related to the temporal variation of wind associated with the occurrence of a cyclone. A proposal is made in this paper for categorizing the process of surface layer formation into three types.

1. Introduction

Process of snow deposition is very complicated at Mizuho Camp, where katabatic wind is strong and blowing snow is severe. In such a place, the snow surface is always covered with drifting snow and falling snow (formation of dune and barchan), or the snow is blown off by wind (formation of sastrugi) [deposition-erosion process]. Therefore, layers of deposited snow are not parallel to each other, and present various types of structure.

In the recent stratigraphic observations, existence of various types of layer structure were recognized in every part of Mizuho Plateau. This indicates that deposition-erosion process varies from place to place. Therefore, in order to obtain quantitative data of the deposition-erosion process at the surface, a stake

line was set up in 1972 at three sites, S16, S122 and Mizuho Camp, and accumulation of snow at each stake was repeatedly measured till 1975.

Based on the measurements, the sequence of annual layer was examined at these sites. Also, the relation between snow deposition and meteorological condition was examined at Mizuho Camp. These data on the stake lines and stake farms were given in JARE Data Reports, No. 27, No. 28 and No. 36 (YAMADA *et al.*, 1975; SATOW, 1977).

2. Observation Points and the Method of Measurement

2.1. Observation points

Variations in surface condition and mass balance in the Antarctic ice sheet are considered to depend on altitude, topography, the distance from the coast and meteorological conditions.

After 1968, snow stakes were set up at intervals of 0.5–2 km along the travers route in Mizuho Camp whenever the new route was exploited, and were repeatedly measured as to the snow deposition and erosion for seven years until 1975.

The result is as follows: An annual net balance in the zone of approximately 80 km inland at the elevation of 1400 m was about 50 cm of snow. It gradually decreased, starting at a place located 80 km inland from the coast and ending at a place 150 km inland at the elevation of 1900 m, where it turned out about 10 cm of snow. Farther inland, an annual net balance was in a range from 10 to 20 cm of snow, though it locally increased or decreased (YAMADA *et al.*, 1978).

The surface in the winter season of 1969 was divided into three zones, namely, depositional, erosional and glazed (WATANABE and YOSHIMURA, 1972).

According to the results of observations of these surface conditions and mass balances, Mizuho Plateau extending from the coast to the inland at an elevation of 2200 m was divided into three areas, as represented by S16, S122 and Mizuho Camp which were observed by means of a pair of 100-stake lines. An outline of meteorological and geographical conditions at the three stations, is given in Table 1 (AGETA and WATANABE, 1972; AGETA and FUKUSHIMA, 1972; KAWAGUCHI *et al.*, 1974; YAMADA *et al.*, 1978; YAMADA and WATANABE, 1978; ENDO, 1973; WATANABE and YOSHIMURA, 1972; WATANABE, 1978).

From the point of zoning of the ice sheet (MÜLLER, 1962a), S16 is situated sometimes below the firn line where surface melting occurs, whereas S122 and Mizuho Camp are situated in the dry snow zone. An annual net balance was approximately 10 cm of snow at S122 where large sastrugi and dunes developed over the surface. The glazed surface was well developed and also large sastrugi and dunes were observed at Mizuho Camp.

2.2. Method of measurement

Two stake lines perpendicularly intersecting each other were set up at S16,

Table 1. Geographical and meteorological conditions at the Stations.

Station	Latitude	Longitude	Elevation	Mean air temperature (°C)				Mean wind speed (m/s)		Prevailing wind direction (16)
				Junuary		June				
S 16	69°01′57″S	40°02′50″E	553	0	−5	−16	−21	8	10	NE
S122	70°01.1′S	43°06.5′E	1853	−13	−17	−29	−21	8	10	ENE
Mizuho Camp	70°42.1′S	44°20.5′E	2169	−18	−20	−38	−41	0	10	E

Station	Annual net accumulation (cm in depth)	Surface condition	Stake line		
			Period	Times	Direction of stake line (360°)
S 16	6 13	Sometimes superimposed ice exposed at the surface	Apr. 12, 1972 Jan. 12, 1973	3	70, *160*
S122	7 17	Surface roughness is large	Apr. 24, 1972 Feb. 7, 1975	10	78, *168*
Mizuho Camp	0 10	Zonal glazed surface exists with large sastrugi and dunes	May 6, 1972 Feb. 5, 1975	17	51, *132*

S122 and Mizuho Camp, and one of the lines comprising 100 to 101 stakes with intervals of 1 m, was oriented parallel or at an acute angle to the prevailing wind direction, namely, 70°, 78° and 51° from the north clockwise respectively (see JARE Data Rep., No. 36). These stake lines were set up in areas free from abnormal sastrugi, dunes and glazed surface.

The buried or exposed length of a stake by accumulation or erosion of snow was calculated from the difference of heights of the stake above the snow surface between two successive measurements; the height of a stake was always measured with accuracy in centimetres (the value thus obtained will be called balance in this paper). The profiles of surface relief along the selected stake lines were surveyed by a simple method of leveling. Since many stakes at S16 were tilted or broken by strong winds, it was impossible to measure the stake lines after February 1973.

The period and the number of times of observation, and the directions of stake lines at each point are also shown in Table 1.

3. Results

3.1. Deposition-erosion process at the surface

The variation in surface relief was caused mainly by the formation or blowning off by wind of sastrugi and dunes. The elongation of a sastrugia is assumed

parallel to the prevailing wind direction and that of a dune oriented at an acute angle (about 30° at Mizuho Camp, WATANABE and YOSHIMURA, 1972) to the direction. So, variations in surface micro-relief indicate directional qualities. In the areas measured at elevations from 500 to 2200 m, a dune was 2–6 m in width, 10–20 m in length and 0.3–0.4 m in height in some cases. The measured values of a deposition or erosion at a point related to the deposition-erosion process is influenced considerably by a topographic arrangement around it in which a major role is played by a nearby dune of such a size, the elongation of which has the direction parallel to the prevailing wind direction over a 100 m stake line. Therefore, the authors intended to examine an effect of a nearby dune on the deposition-erosion process along the stake line parallel to the prevailing wind direction from the results of measurements along the other stake line which was at a right angle or an acute angle to the prevailing wind direction. The direction of the selected stake line was 160°, 168° and 132° at S16, S122 and Mizuho Camp respectively. The balance of deposition-erosion process between two successive measurements at the same position of the surface is shown in Fig. 1 for S16, S122 and Mizuho Camp.

At S16, the deposition-erosion process had a tendency to deposit over the entire stake line for the period from August to October and to erode in the other period. Results obtained from the stake line at S122 showed a tendency to be somewhat low in deposition during the period from October to February in comparison with the other period. The deposition-erosion process occurred sporadically at the S122 stake line. At a part of this stake line, an annual net balance was nearly zero, because snow was deposited and eroded in about the equal amount or deposition and erosion hardly occurred during one year. The erosion surpassed deposition in amount for a certain year, as it was observed that erosion occurred not only at the deposited snow of that year but also that of the previous year.

At Mizuho Camp, the deposition was large during the period from September to November, and it took place sporadically in the appearance of dunes in the stake line. In some cases, once a dune was formed at the surface, it grew with continuation of depositing mainly on the windward side of the dune. At a certain part of the stake line, a layer of about 5 cm of snow was subjected to the repeated process of deposition and erosion, otherwise deposition and erosion hardly occurred. An observation disclosed a case where the surface in February 1975 went down to the level of that in May 1972 because of erosion.

As the result of the deposition-erosion process at the surface, the stake line each at S122 and Mizuho Camp was subdivided into the parts characterized by positive balance, negative balance and equilibrium.

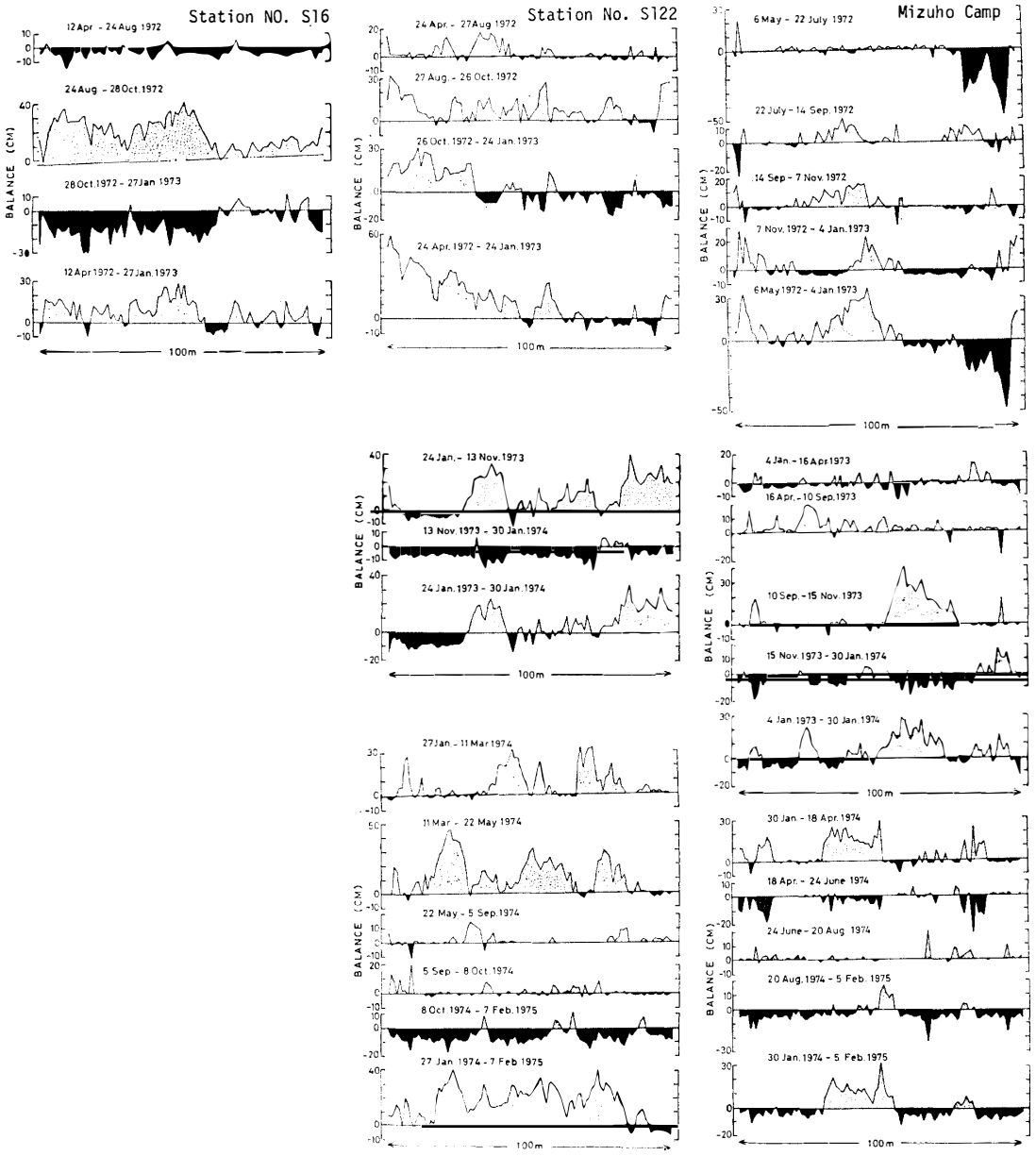

Fig. 1. Temporal variations in balance at S16, S122 and Mizuho Camp. The horizontal axis represents the length of a stake line. At S16 and S122, one of the pair of stake lines intersects the other at an approximately right angle, the other being parallel to the prevailing wind direction; at Mizuho Camp, one of the pair intersects the prevailing wind direction at an angle of nearly 42°.

3.2. Formation of an annual layer

An annual layer is defined as a snow layer formed during a one-year period starting at the end of the previous year's summer season. In Mizuho Plateau it is not easy to determine an annual layer, because the snow surface of the previous

year is not necessarily preserved as a result of erosion.

The sequence of annual layers is shown in Fig. 2 for S16, S122 and Mizuho Camp.

It can be seen from this figure that an annual layer was formed nearly all over the stake line at S16. At S122 and Mizuho Camp, an annual layer spread over different widths, and layers formed adjacently in different years existed in the stake line. An upper layer was not always formed in the following year over the lower layer formed during the previous year; besides, there was a hiatus between

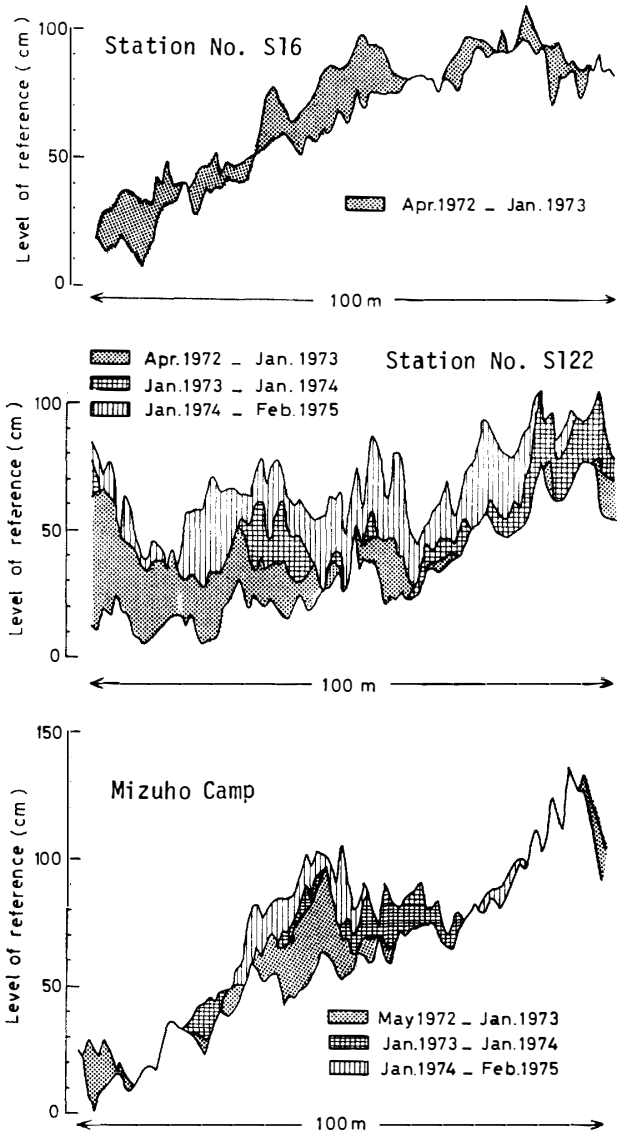

Fig. 2. Profiles of surface relief along the stake lines. A difference between two successive profiles is equivalent to the thickness of an annual layer.

two successive layers in some cases. In other words, annual layers had a discontinuity at S122 and Mizuho Camp. For the clarification of the discontinuity of annual layers, an attempt was made to examine how wide an annual layer was and how many layers were formed at the same position of the stake lines for about three years in the recent past. The results are shown in Fig. 3(a) and (b).

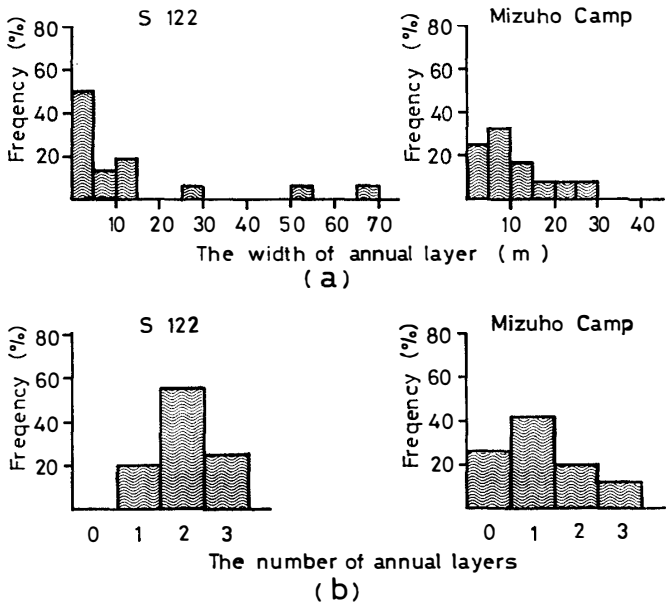

Fig. 3. Frequency distribution of width and number of annual layers for three years.

According to Fig. 3(a), the width of an annual layer reached as much as 70 m at S122 and 30 m at Mizuho Camp. But the width was mostly less than 15 m. As for the number of annual layers which were formed at every stake position for three years, as shown in Fig. 3(b), there were two, three and one in the decreasing order of frequency at S122, and one, zero, two and three in the same order at Mizuho Camp.

At S122 and Mizuho Camp, several annual layers less than 15 m in width were formed discontinuously on the 100 m stake line during the same period of time, whereas no annual layer was formed on the same positions for one to two years out of the three years in point.

3.3. Areal variations of balance

The deposition-erosion process at the surface and the sequence of annual layers were examined, on the basis of the observations of stake lines oriented normal to the prevailing wind direction. But, there may be a limit in estimation of the deposition-erosion process in a large area from the result of observation at only one stake line.

In order to know if those stakes placed at intervals of 0.5–2 km on the traverse routes can represent the entire area, YAMADA *et al.* (1973) placed 36 stakes spaced 20 m apart in a 100 m square grid at each of six points from S16 to Mizuho Camp. These grids called stake farms were subjected to measurements of deposition and erosion regularly during the period from 1971 to 1975 (YAMADA *et al.*, 1975; SATOW, 1977). One example of analyses of the data is shown in Fig. 4.

As seen in this figure, S122, Z40 and Mizuho Camp stand out by an irregular distribution of patches of positive balance, negative balance and equilibrium in a 100 m×100 m stake farm. This result coincided with the deposition erosion process which occurred sporadically on the stake lines of S122 and Mizuho Camp. Therefore, the deposition-erosion process at the surface obtained from the stake lines can be applied even to some other sites than them.

The area in which the balance remained negative for two years was found in some parts of the stake farms of S122, Z40 and Mizuho Camp. This means that

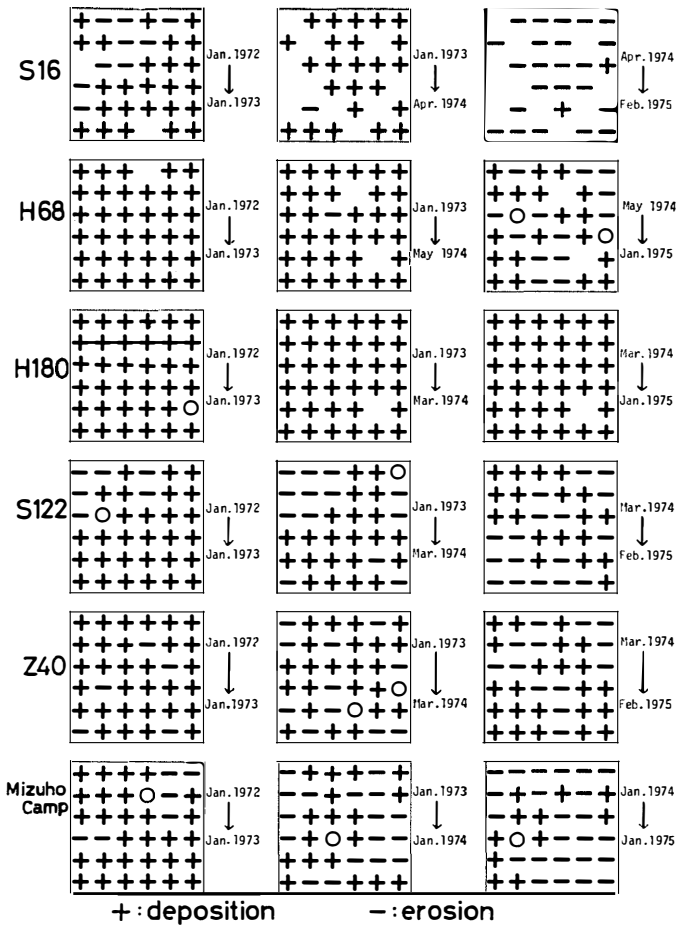

Fig. 4. Areal variations of balance.

an annual layer was not formed in these parts of the stake farms for two to three years. This result coincided with the discontinuity of an annual layer revealed by the measurements of the stake lines. Differing from that of S122 and Mizuho Camp the positive balance occurred all over the stake farm of H180, and nearly all over the stake farm of H68.

Since ablation at S16 was caused not only by wind erosion but also by melting at the surface during the period from 1974 to 1975, the negative balance was shown nearly all over the surface.

This measurement revealed that the positive balance took place widely in areas from the firn line to near H180 at the elevation of 1540 m and locally in areas from S122 to Mizuho Camp.

YAMADA *et al.* (1978) found that the values of positive balance and the pattern of deposition changed at the elevation of about 1900 m. Their results can be explained by the difference of the deposition-erosion process between them.

3.4. Meteorological conditions for deposition

In the Antarctic ice sheet, not only falling snow but also deposited snow were transferred by winds as drifting snow and redeposited eventually. Deposition occurs under certain meteorological conditions suitable for falling snow and drifting snow. Therefore, a study was made of the meteorological conditions during the occurrence of deposition.

The variations with time of micro-relief along the stake line of Mizuho Camp were observed by taken photographs during the period between 24 November 1972 and 23 January 1973. Fig. 5 shows examples of the observation. The sequential variation of surface condition is illustrated in Fig. 6 in terms of the direction, position and duration of a dune, because the variation of micro-relief is caused mainly by the formation of dunes and their being blown off by wind. Fig. 7 shows the meteorological data during the same period of time at Mizuho Camp.

According to the observation, dunes were formed on 4, 19, 23 and 28 December, when the mean wind speed was below 8 m/s. On preceding days to these, namely, 3, 18, 22 and 27 December, the wind direction and the wind speed were almost invariably ENE-NE and about 12–14 m/s, respectively.

Atmospheric pressures on these days were lower than those of previous and subsequent days except the case of 18 December. Since the dune formed on 19 December differed from other dunes in its direction, this exceptional case is excluded. It can be concluded that a dune might be formed under the condition with a weak wind after a relatively strong wind associated with a cyclon. Such a relation between the formation of a dune and the approach of a cyclon has been anticipated by WATANABE and YOSHIMURA (1972).

An windy days of 3, 12, 18 and 27 December, there were so heavily blowing

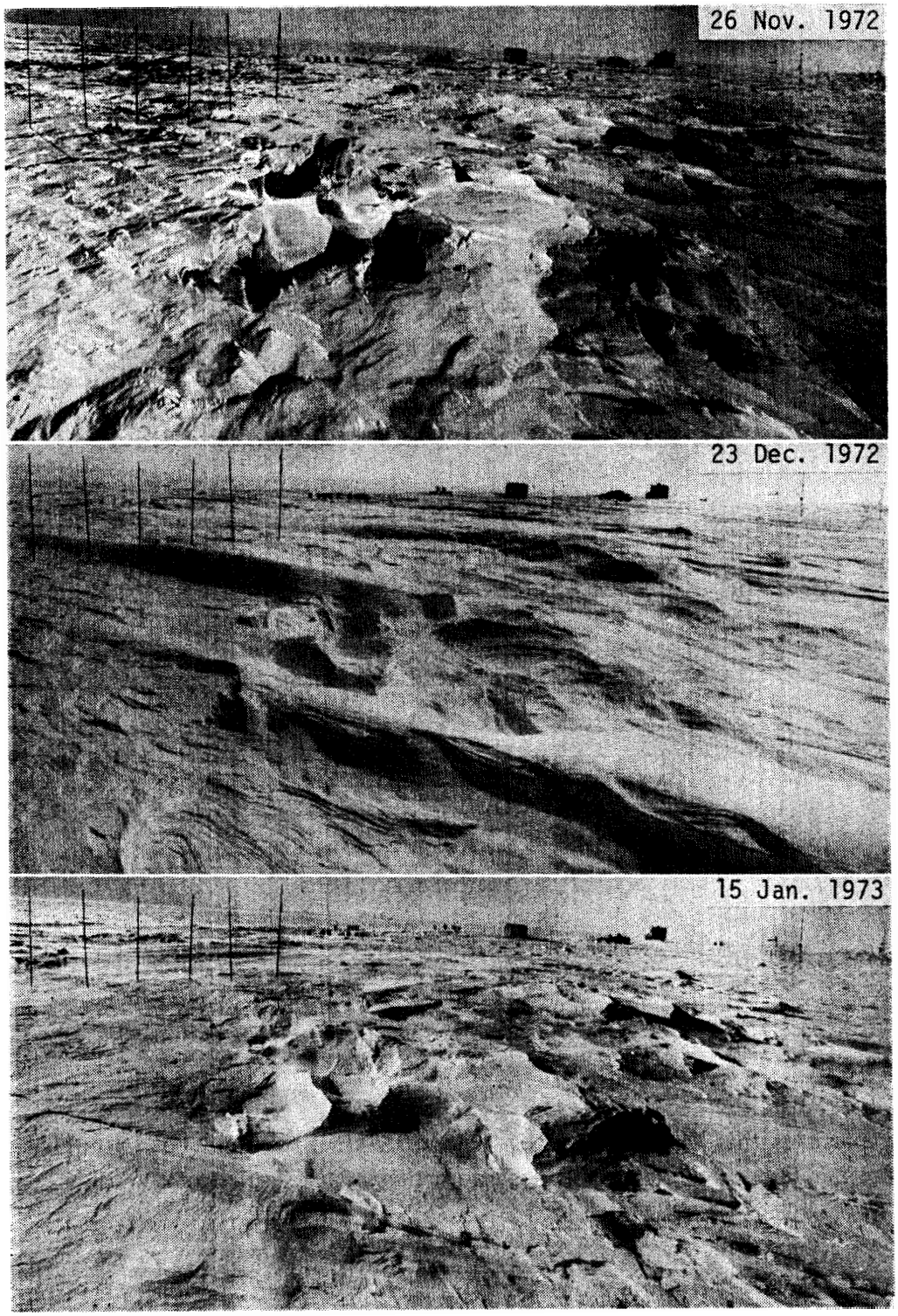

Fig. 5. Sequential variations of surface micro-relief near the stake line at Mizuho Camp.

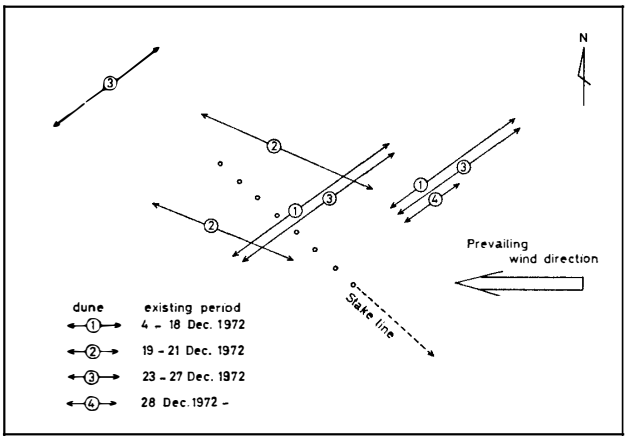

Fig. 6. Sequential variations of surface micro-relief shematically shown by movement of dunes near the stake line at Mizuho Camp.

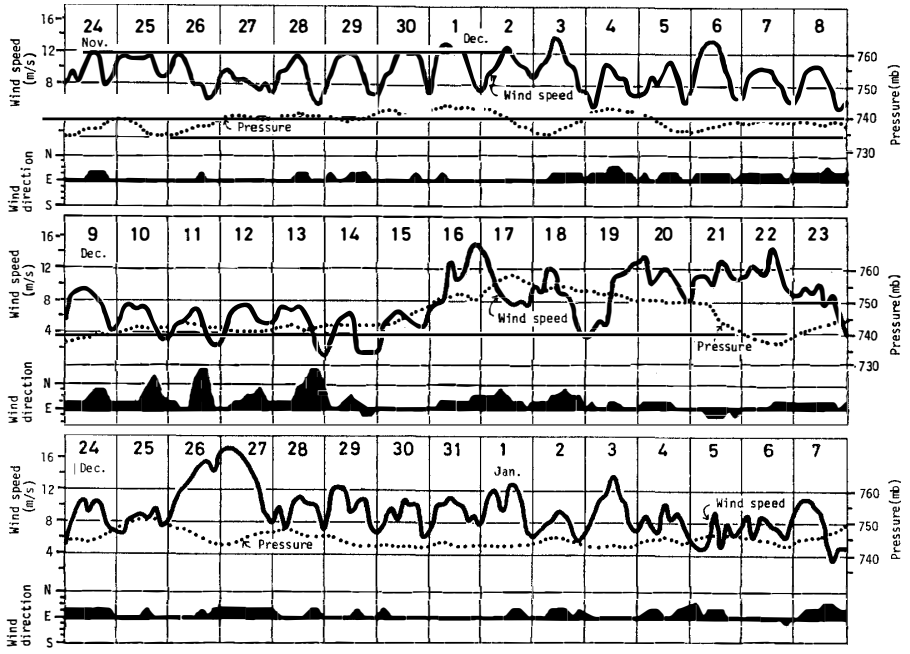

Fig. 7. Meteorological data at Mizuho Camp.

snow particles that the visibility was below 0.2 km. It would be reasonable then to consider that snow deposition occurs on these days despite of the low visibility.

4. Considerations

The deposition-erosion process at the surface depends on the meteorological and geographical conditions, and it varies the surface condition and yields a surface snow layer. At H180 where the balance was positive all over, annual

layers were formed with a certain thickness. On the contrary, at S122 and Mizuho Camp, annual layers were formed patchily on the surface, whereas layers formed before the previous year were exposed elsewhere. The surface of S122 rose by approximately 30 cm of snow for nearly three years, the annual net balance averaging 10 cm of snow. At Mizuho Camp, since the formation of an annual layer was restricted in a very small area, it is not possible to say that the whole surface rose. Besides, even if an annual layer is formed for a certain period, it disappears probably in a later period because of erosion of the surface. Such a variation can be considered on the basis of observations which revealed that the surface rose by 50–60 cm of snow in part of the stake line at Mizuho Camp and fell by about 50 cm of snow in another part for a period of nearly three years. Therefore, the surface in the vicinity of Mizuho Camp can be considered to be in an equilibrium state due to the deposition-erosion process at the surface. The measurement of balance is relatively easy and exact in the area of H180. But in the area where annual layers are formed patchily like at S122 and Mizuho Camp, the values of balance gained by the stakes method and snow stratigraphic analyses are largely scattered. It is difficult, therefore, to calculate the exact balance in such areas. This difficulty can be overcome by clarification of the formation process of an annual layer and the variation in surface condition through observations by means of stake lines and stake farms.

On the basis of observations of stake lines and stake farms, at least three types of deposition can be defined in the observed stations, as shown schematically in Fig. 8.

Types I, II and III are considered to be representative of annual layers at H180, S122 and Mizuho Camp, respectively. It has been considered that in the Antarctic ice sheet type I has taken place widely, and types II and III rarely

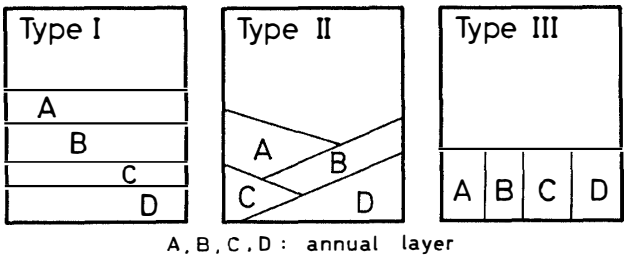

Fig. 8. Three types of annual layer formation process.

Type I: An annual layer is formed every year, but the thickness varies from year to year.

Type II: An annual layer is formed partially, making the surface rise as a whole with lapse of years.

Type III: The formation of an annual layer is localized at the surface in a state of equilibrium in the deposition-erosion processes.

only in special area. According to the result of measurements, however, type II seems to be more probable than III.

Further observations are called for to relate climatic and topographic condition to these types.

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