OBSERVATIONS OF SUN CRUST FORMATION

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ABSTRACT

The mechanism of sun crust formation was investigated through field observations. During the observations, sun crust formed 12 times. The sun crust is a thin ice layer made of ice particles. With the sun crust formation, the local temperature beneath it rose and internal melting occurred. This led to the formation of cavities under the sun crust. The energy balance calculation of the sun crust revealed that the shortwave radiation absorbed was balanced with the total of net longwave radiative flux, latent heat flux, and sensible heat flux. Further down the snow pack, shortwave radiation penetrated through the surface layer, was absorbed and internal melting occurred. The sources of H_2O for sun crust formation were investigated through the fluctuations of oxygen-18 concentration of the sun crust. The isotopic composition changed with sun crust formation: δ value of sun crust had a tendency to increase (heavier water) with time, and was larger (heavier water) than that of the snows beneath it.

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INTRODUCTION

Sun crust, an unusual metamorphism of snow, is a thin grazed ice layer found at the surface of snow pack on sunny day in winter. It is a very interesting snow surface feature. However, it is difficult to observe its formation because it is found only a few times in one winter season in Hokkaido, Japan.

The authors investigated the mechanism of sun crust formation through field observations and laboratory experiments (Ozeki and Akitaya, 1992). The observations found that the sun crust structure and the suitable energy balance condition for sun crust formation. These results were verified by laboratory experiments. However, they were revealed from only one time observation of sun crust, and the source of H_2O for the sun crust layer was not known. This paper aims to investigate the energy balance and the change of $\delta^{18}O$ in sun crust formation through field observations.

OBSERVATIONAL SITES AND INSTRUMENTATION

The mechanism of sun crust formation was investigated through field observations. Field observations were carried out for four winter seasons (1991, 1992, 1993, 1994) at Moshiri, central part of Hokkaido, and Toikanbetsu, northern part of Hokkaido. The site of Moshiri is located in the lowest part of the land basin at an altitude of 285m a.s.l. in the Bifukazawa River Watershed, which is surrounded by mountain ridges with an altitude difference of about 250m (Figure 1). Two meteorological stations were set up for four seasons: A at the center of the basin; B at the highest part of the surrounding mountains. An additional meteorological station was set up in 1994: C at the 200m south from the station B. The surface condition of each station was composed of thick, flat and smooth snow cover. The observed parameters and the instrumentation used are summarized in Table 1. These field observations were made by automatic and manual measurements. In addition to these measurements, sampling of crust layer and 1 cm snow layer beneath it were carried out when sun crust was forming.

The site of Toikanbetsu is located on the ridge at an altitude of 240m a.s.l. in the Teshio Experimental Forest of Hokkaido University (Figure 2). Snow sampling and analyses of polarized picture of thin section were carried out for two seasons (1993, 1994).

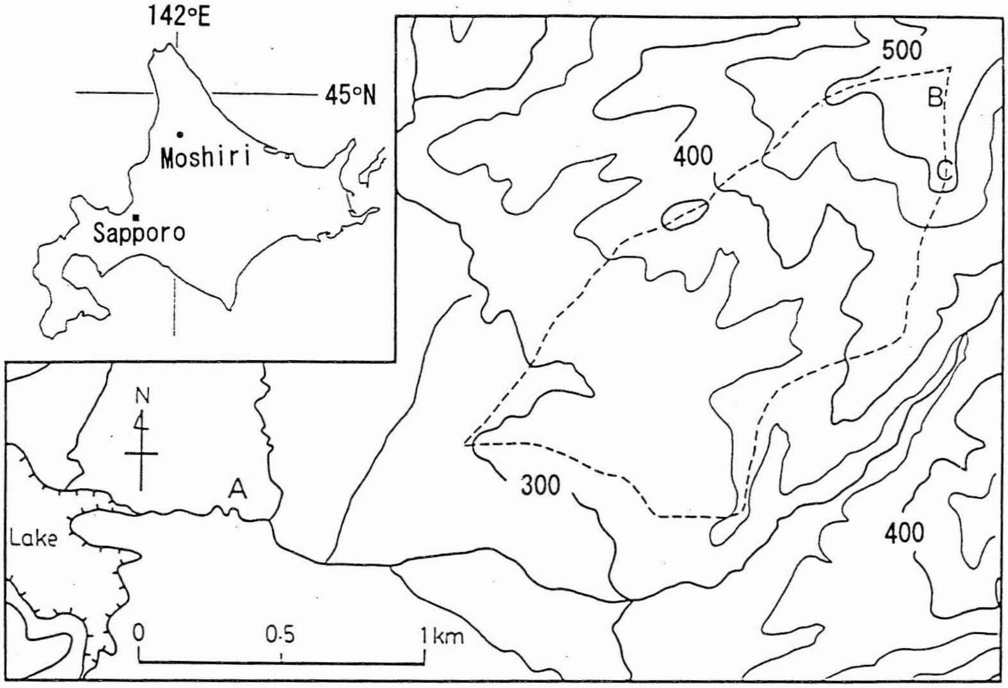

Fig. 1. Location map of 3 meteorological stations in Moshiri.

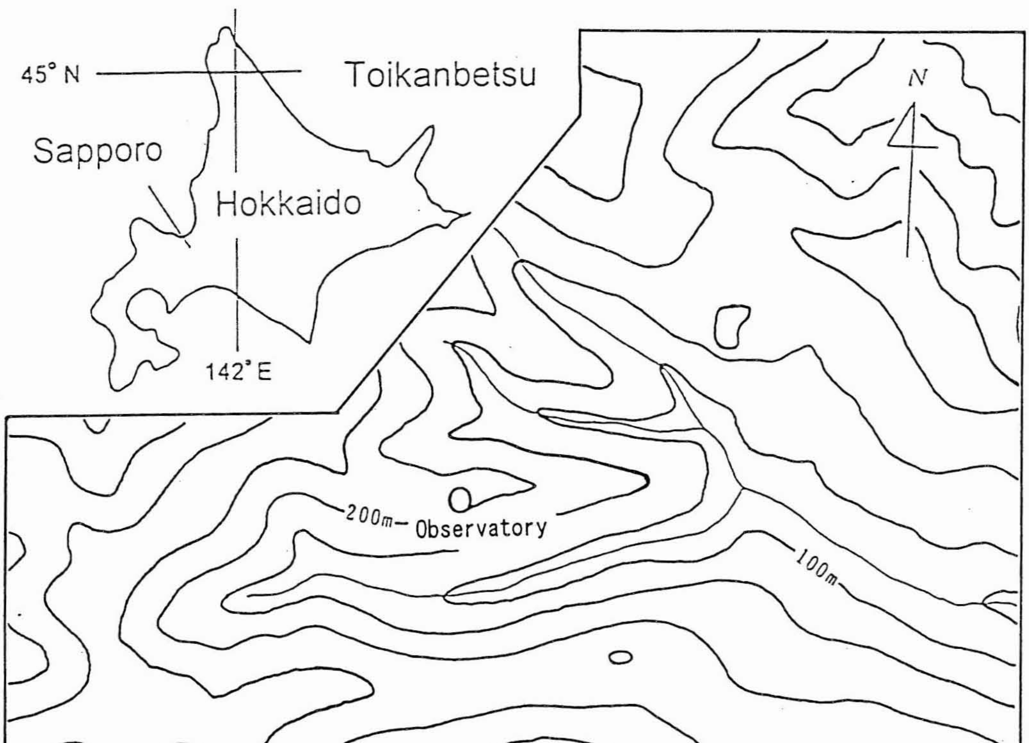

Fig. 2. Location map of an observatory in Toikanbetsu.

Table 1. Observational Items and Instruments

Items	Instruments	stations
1. Continuous measurements		
Dry-bulb temperature	forced ventilated resistance thermometers	A, B, C
Wet-bulb temperature	forced ventilated resistance thermometers	A
Surface temperature	an infrared thermometer	A, B
Humidity	static electric capacitance type hygrometer	B, C
Wind speed	a three -cup anemometer	A, B, C
All-wave net radiation	a net pyrradiometer	A, B
Incoming and outgoing of Shortwave radiation	pyranometer	A, B
Air pressure	a cylindrical resonator type barometer	A
2. Manual measurements		
Liquid water contents	a calorimetric snow-water content meter	A, B, C
Snow density	a snow sampler	A, B, C

ESTIMATION OF HEAT FLUX

Sensible heat flux and latent heat flux are calculated at each station according to a bulk method (Takeuchi and Kondo, 1981). An equation of the bulk method for sensible heat flux Q_H is the following:

$$Q_H = \rho_a C_p h V_1 (T_1 - T_0), \qquad (1)$$

where h is the bulk coefficient, T_1 and T_0 the air temperature at a height of 1 m and snow surface temperature, V_1 the wind speed at a height of 1 m, ρ_a the air density, C_p the specific heat capacity of air at constant pressure. Latent heat flux Q_E is given by

$$Q_E = L \rho_a h V_1 (q_1 - q_0), \qquad (2)$$

where L is the latent heat of ice on evaporation, q_1 and q_0 the specific humidity at a height of 1 m and snow surface. The following value for the bulk coefficient h (Ishikawa and Kodama, 1994) is used in this study:

$$h = 2.3 \times 10^{-3}. \quad (3)$$

The amount of net longwave radiation is calculated from the observed incoming and outgoing solar radiation and net radiation.

OBSERVATIONAL RESULTS

Energy Balance

During the observations, sun crust formed 12 times. A cross section of the sun crust is shown in Figure 3. The sun crust was a thin ice layer made of ice particles with the thickness of 1 to 2 mm, and internal melting formed cavities under it. The thickness decreased as the ice layer extended laterally.

The weather conditions during sun crust formation were fine weather, air temperature nearly 0 ℃, wind speed about 1 to 5 m/s, humidity about 30 to 60 % at a height of 1 m. In 11 of the 12 times of sun crust formation, the surface snow type before the formation was granular snow. In only one case did the sun crust form after new snow had metamorphosed into granular snow. The average density of 3 cm layer from the surface was 4.2×10^2 kg/m^3 and the average water content was 12.6 % (Table 2).

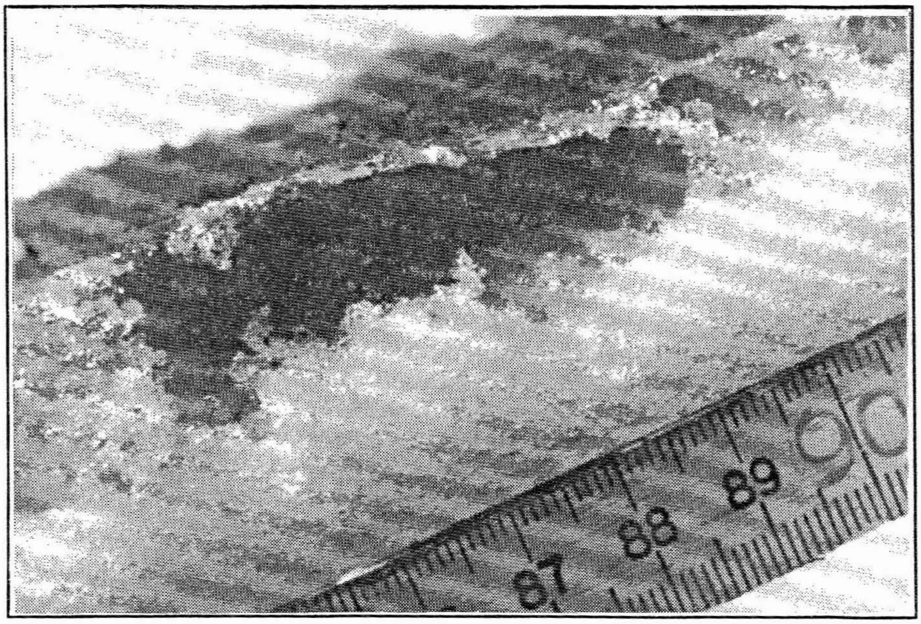

Fig. 3. Vertical cross section of the sun crust.

Table 2. Density and liquid water content of outermost snow layer prior to sun crust formation

	density kg/m³	liquid water content %
average	4.2×10^2	12.6
max	4.8×10^2	19.0
min	3.7×10^2	4.9

The components of heat balance at snow surface are calculated during formation of sun crust. Figure 4 shows the time series of shortwave and longwave radiative flux, sensible and latent heat flux during sun crust formation at the station A on Apr. 6, 1994. In Figure 4, the ordinate shows the amount of heat flux going into the snow layer. The sun crust was forming for a few hours near noon. During the sun crust formation, absorbed shortwave radiation exceeds 300 W/m² and net longwave radiative flux was about -50 W/m² which cools the snow surface. Additionally, sensible heat is transported from air to snow surface and oppositely latent heat from snow surface to air, and those two values are nearly equal.

During sun crust formation, the thin layer near surface was not melting and the layer beneath it was melting. In order to verify it, the amount of

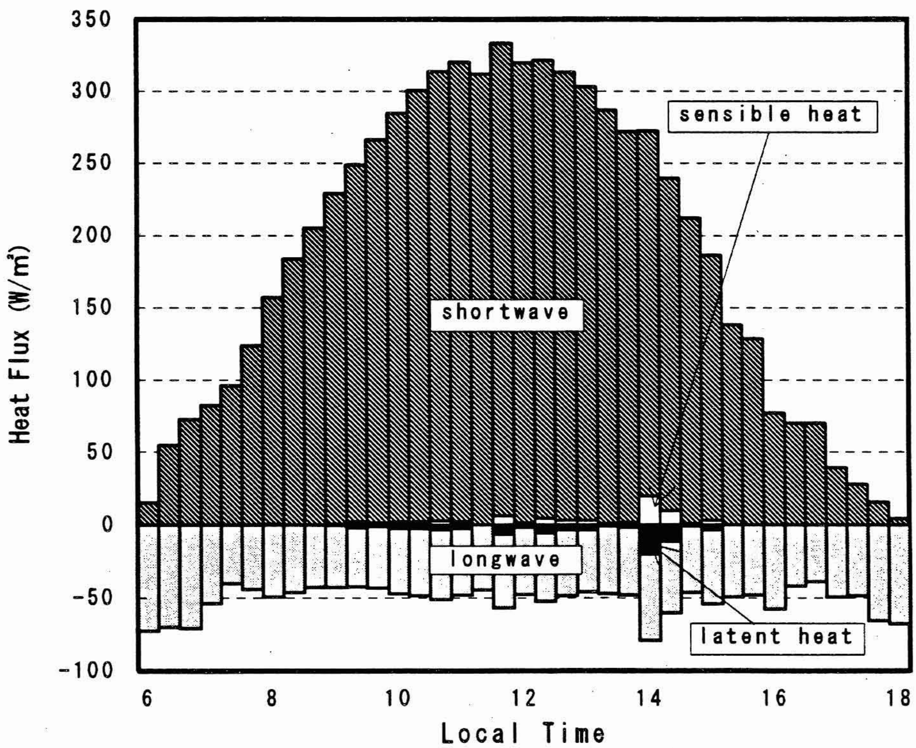

Fig. 4. Time series of heat balance components at station A on Apr. 6, 1994.

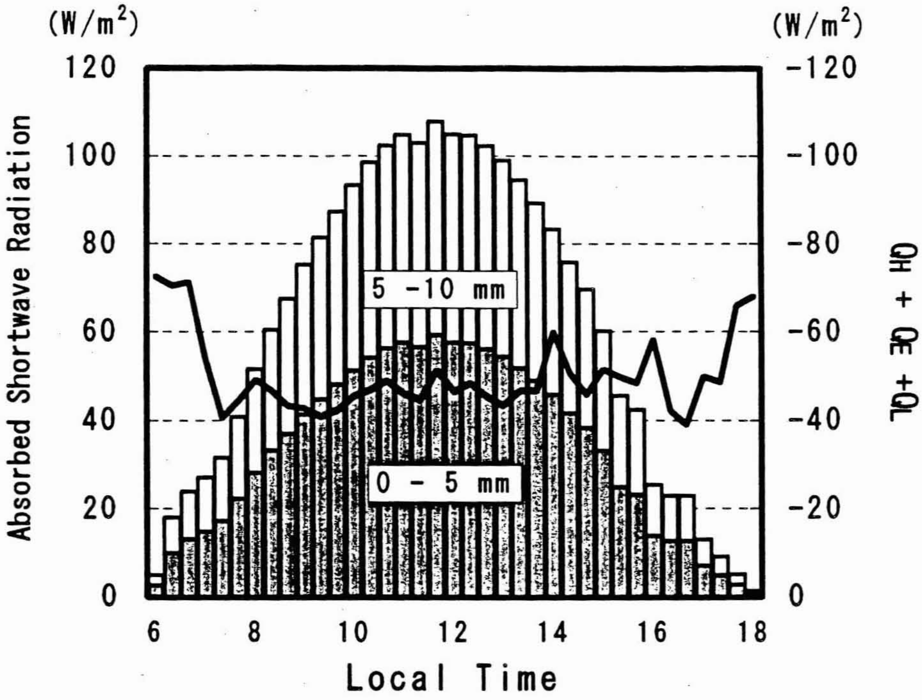

Fig. 5. Comparison of the absorbed shortwave radiation in the layers of 0-5 mm and 5-10 mm (boxes) and the total of sensible heat Q_H, latent heat Q_E, longwave radiation Q_L (solid line) at station A on Apr. 6, 1994.

shortwave radiation absorbed by the snow layers is calculated and compared with the result of heat budget at the surface. Shortwave radiation I attenuate in snow covers as following:

$$I = (1 - r)\, I_0 \exp(\alpha Z), \qquad (4)$$

where I_0 is the incident shortwave radiative flux, r the albedo of the snow cover, α the attenuation coefficient and Z the depth. The attenuation coefficient is assumed to be -0.4 cm^{-1}, which was obtained by Fukami and Kojima (1980). Figure 5 shows a case at the station A on Apr. 6, 1994. The boxes in the figure show the amount of absorbed shortwave radiative flux in each layer. The solid line in the figure shows the amount of the total heat flux except net shortwave radiative flux at the surface (i.e. longwave radiative flux, sensible and latent heat fluxes). The total heat flux is acting to cool the surface and balanced with the amount of shortwave radiation absorbed in the layer from surface to a few mm in depth during the sun crust formation. As a result, near surface thin layer is not melting and the layer beneath it is melting.

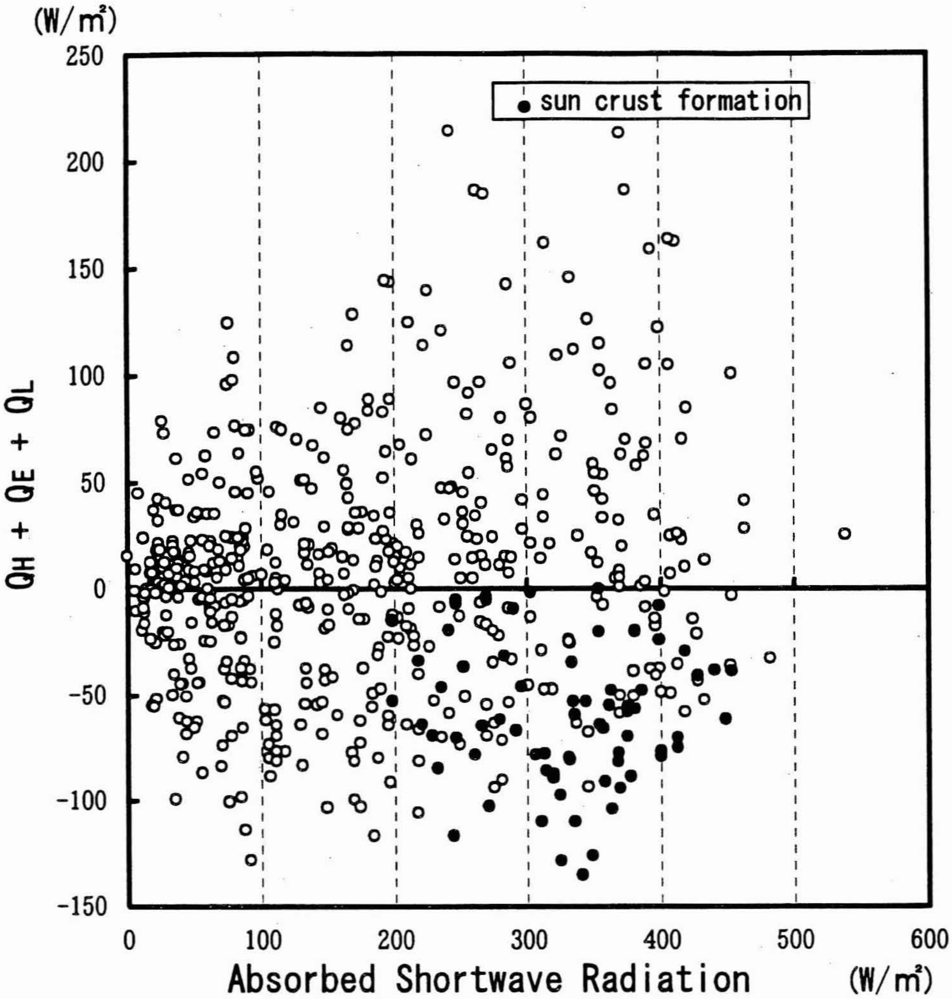

Fig. 6. Comparison of the absorbed shortwave radiation and the total of sensible heat Q_H, latent heat Q_E, longwave radiation Q_L through the observations. ●: during sun crust formation, ○: others.

Comparison of absorbed shortwave radiation and the total of net longwave radiative flux, sensible and latent heat flux is shown in Figure 6. The circles indicate daytime data averaged every 1 hour through the observations and solid ones are for the data in sun crust formation. The solid circles are distributed among 0 and -140 W/m2 of the total heat flux except for shortwave radiative flux. It indicates the surface is surely cooling. On the other hand, the absorption of shortwave radiation exceeds 200 W/m2 during sun crust formation.

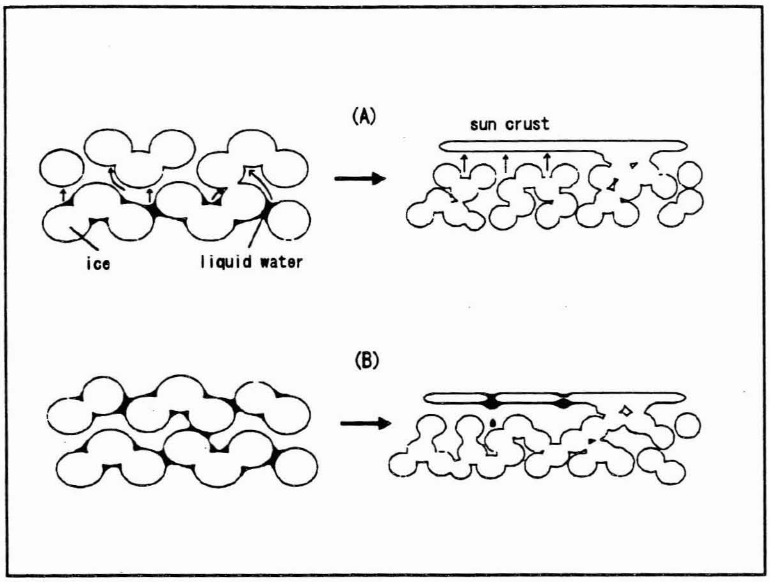

Fig. 7. Hypotheses for the sources of H_2O of the sun crust layer. (A): condensation of water vapor, (B): refreezing of melt water.

change of $\delta^{18}O$

The sources of H_2O for formation of sun crust were investigated through the fluctuations of oxygen-18 concentration of the sun crust. Surface snow (average density 4.2×10^2 kg/m^3: see Table 2) metamorphosed into an ice layer in sun crust formation. Two hypotheses are made for the sources of H_2O of the ice layer. One is condensation of water vapor. Vapor pressure gradient transport water vapor from lower melting layer to crust layer cooled by the heat loss at surface (Figure 7a). Second is refreezing of liquid water in the crust layer: the crust layer becomes dense as the thickness decreased, and the heat loss by longwave radiation refreezes some liquid water in it (Figure 7b).

Concentration of a heavy stable isotope oxygen-18 change with phase change (evaporation or condensation) and depends on the temperature of formation (Dansgaard and others, 1973). Isotopic composition of solid and liquid portion of wet snow changes during grain coarsening: $\delta^{18}O$ of ice becomes larger than those for water (Nakawo and others, 1993). It was anticipated that isotopic compositions would change with sun crust formation. The oxygen isotopic composition has been expressed in terms of $\delta^{18}O$ as:

$$\delta^{18}O = (R - R_{SMOW}) / R_{SMOW} \times 1000 \ (‰) \qquad (5)$$

where R is the isotopic ratio ($H_2{}^{18}O/H_2{}^{16}O$) of sample and R_{SMOW} is that of Standard Mean Ocean Water.

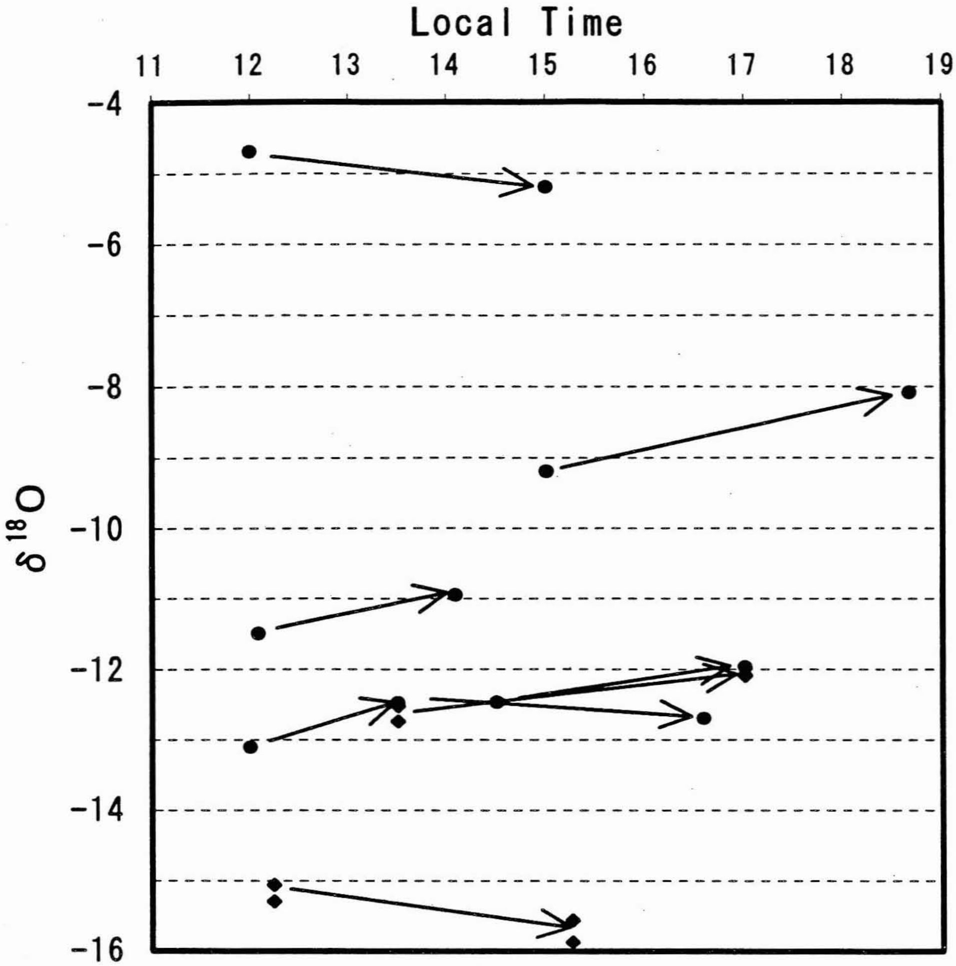

Fig. 8. Changes with time of $\delta^{18}O$ in the sun crust

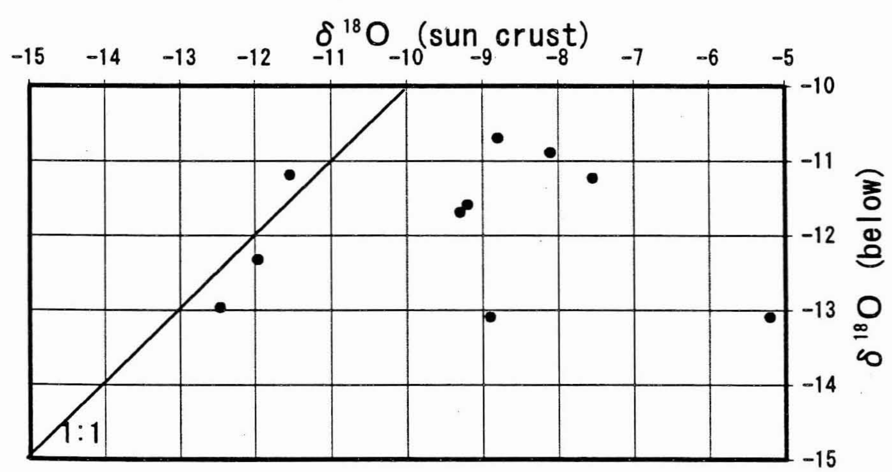

Fig. 9. Comparison of $\delta^{18}O$ in the sun crust and the snow layer below it.

The changes of $\delta^{18}O$ in sun crust with time are shown in figure 8. The values had a tendency to become larger with time, though there are a few cases the values become smaller. Comparison of the oxygen-18 content of the sun crust and the snow layer beneath it is shown in Figure 9. The $\delta^{18}O$ of the snow layer is distributed between -10.7 ‰ and -13.6 ‰. These are similar to the value of whole snow layer at Moshiri, -12.2 ‰. Isotopic compositions changed with sun crust formation. The $\delta^{18}O$ of sun crust is distributed between -4.7 ‰ and -12.5 ‰ and became larger than those of the snow beneath it. If the main source of H_2O was the condensation of water vapor from the lighter snow beneath it, the values would become smaller. $\delta^{18}O$ of the sun crust layer changed during refreezing of liquid water by heat loss at the upper surface, forming heavier ice . It is not sufficient to explain the heavier sun crust layer: the dropping of liquid water was often observed during sun crust formation, therefore, it also suggests that the lighter residual liquid water drops out from the sun crust layer, making the layer heavier.

CONCLUSION

The mechanism of sun crust formation was investigated through field observations. During the observations, sun crust formed 12 times. The weather conditions during sun crust formation were fine weather, air temperature nearly 0 ℃, wind speed about 1 to 5 m/s, humidity about 30 to 60 % at a height of 1 m. The sun crust is a thin ice layer made of ice particles. With sun crust formation, the local temperature beneath it rose and internal melting occurred. As a result, the cavities formed under it. The energy balance condition for sun crust formation was revealed from the energy balance calculation of the surface layer. Longwave radiative flux and latent heat flux cooled the snow surface. Beneath the surface, shortwave radiation penetrated through the surface layer, was absorbed and internal melting occurred.

The sources of H_2O for formation of sun crust were investigated by comparing the oxygen-18 content of sun crust and the snow layer beneath it. Surface snow (average density 4.2×10^2 kg/m^3) metamorphosed into an ice layer with sun crust formation. Isotopic compositions changed with sun crust formation. δ values of sun crust were becoming heavier with time. As a result, δ values of sun crust became larger than those of the snow beneath it.

Acknowledgments
The authors are grateful to the staff of the Uryu Experimental Forests, Teshio Experimental Forests of Hokkaido University and the members of snow damage science and snow hydrology sections of the Institute of Low Temperature Science, Hokkaido University, for their logistic support, and Dr. N. Ishikawa, Dr. Y. Kodama and Dr. R. Naruse for their useful comments on this investigation.

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