AN INVESTIGATION OF SUN CRUST FORMATION USING FIELD DATA AND LABORATORY EXPERIMENTS

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ABSTRACT

Sun crust formation mechanism is investigated through field observations as well as laboratory experiments. From the field observations, the structure of the sun crust is observed. 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. As a result, the cavities under the sun crust were formed. The energy balance calculation of the sun crust revealed that the shortwave radiation absorbed is balanced with the total of net longwave radiative flux, latent heat flux, and sensible heat flux. At the further down the snow pack, the shortwave radiation penetrated through the surface layer was absorbed and the internal melting occurred. The field observations are verified by the laboratory experiment using various snow types. As a result, sun crust was formed from both compact snow and granular snow, however, when the snow surface became rough due to the quick melting, the sun crust was not formed even under the suitable energy balance condition for the sun crust formation.

INTRODUCTION

Sun crust, a thin grazed ice layer found at the surface of snow pack on sunny day in winter, is a very interesting snow surface feature. Among the metamorphisms of snow particles, the sun crust formation occurs very quickly changing from a snow layer to a thin ice film. The formation of sun crust creates a suitable circumstance for quick depth hoar growth. It is due to, during nighttime, the large temperature gradient existed between the radiatively cooling sun crust surface and the relatively warm snow layer by the latent heat release on the refreezing of the meltwater. The formation of depth hoar at the near-surface decrease the stability of the snow pack when newly fallen snow accumulated on it, and causes the surface layer avalanche. Therefore, it is important to study the sun crust in the viewpoint of disaster prevention. However, there are few studies on the formation of sun crust. In this paper, the sun crust formation mechanism is investigated through field observations as well as laboratory experiments.

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OBSERVATION

Observational site and instrumentation

The observations were made during snowy seasons from 1990 to 1991. Observational site was set at the Uryu Experimental Forest of Hokkaido University in Moshiri (Fig.1) located in the northern part of Hokkaido. The experimental forest is in a land basin, surrounded by mountains with an altitudinal difference of about 250 m between the mountaintop and the bottom of the basin.

Two meteorological stations were set up: A at the highest part of the surrounding mountains; B at the center of the flat part of the basin. The both sites are located on the flat plain. Followings are the observed items and used instruments at each station :

A) At the higher station

Air temperature	Ventilated resistance thermometer
Wind speed	Three–cup anemometer
Humidity	Static electric capacitance type hygrometer
Net radiation	Funk–type net radiometer

B) At the lower station

Air temperature	Ventilated resistance thermometer
Wind speed	Ultrasonic anemometer
Humidity	Static electric capacitance type hygrometer
Net radiation	Funk–type net radiometer
Incoming and outgoing solar radiation	Pyranometer

At each station latent heat flux and sensible heat flux were calculated according to a bulk method. Sensible heat flux S is given by

$$S = Ka \cdot (T_1 - T_0) \cdot Ws \qquad (1)$$

where Ka is the bulk coefficient of sensible heat, T_1 and T_0 the air temperature at the height of 1 m and snow surface temperature, Ws the wind speed at the height of 1 m. Latent heat flux E is given by

$$E = l \cdot Ke \cdot (e_1 - e_0) \cdot Ws \qquad (2)$$

where l is the latent heat of ice on evaporation, Ke the bulk coefficient of latent heat, e_1 and e_0 the water vapor pressures at the height of 1 m and snow surface. The following values for the coefficients Ka and Ke (Ishikawa and others, 1982) were used in this study:

$$Ka = 0.26 \qquad (ly \cdot hr^{-1} \cdot (m \cdot s^{-1})^{-1} \cdot {}^{\circ}C^{-1})$$

$$Ke = 0.69 \cdot 10^{-3} \qquad (ly \cdot hr^{-1} \cdot (m \cdot s^{-1})^{-1} \cdot mb^{-1})$$

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

Observational results

The Sun crust was formed some time between 11:30 to 13:00 on Apr. 19, 1991 at the station A. A schematic cross section of the sun crust is shown in Fig.2. The weather was sunny, the temperature was about 3 to 4 °C, the wind speed was about 4 to 5 m/s, and the humidity was about 60 %. The snow type of the surface before the sun crust formation was granular snow, the density of snow layer from the surface to the depth of 3 cm was 441 kg/m^3, and water content was 4.9 %. The sun crust was a thin ice layer with the thickness of 1 to 2 mm, and the cavities under the sun crust were formed by the internal melting, which was evident from the existence of liquid water beneath the sun crust and the snow surrounding the cavities.

The components of heat balance at the snow surface was calculated during the sun crust formation. The sensible and latent heat fluxes were obtained from eq.(1) and eq.(2) assuming that the surface temperature was 0 °C and the surface water vapor pressure was 6.11 mb. Fig.3 shows the time variations of net radiation, sensible heat flux, latent heat flux and the sum of the heat fluxes (solid line) from 9:00 to 19:00 on Apr. 19, 1991. The sensible and latent heat fluxes from 9:00 to 11:00 were not obtained because of the lack of wind speed data. In Fig.3, the ordinate shows the amount of heat flux going into the snow layer, and the arrow indicates the period the sun crust was forming. During the sun crust formation, the sensible heat was transported from air to snow surface and oppositely the latent heat from snow surface to air, and the both values were nearly equal.

During the formation of sun crust, the near surface thin layer was not melting and the layer beneath it was melting. In order to verify it, the amount of shortwave radiation absorption by snow layer was calculated and compared with the result of the heat budget at the surface. The solid line in Fig.4 shows the amount of 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. The boxes in Fig.4 show the amount of absorbed shortwave radiative flux in the each layer indicated in the figure. The absorption coefficient was assumed to be $-0.4\ cm^{-1}$, which was obtained by Fukami and Kojima (1980). Fig.4a and b show the cases at the station A and B, respectively. At the station A, the total of net longwave radiative flux, sensible and latent heat fluxes (solid line in Fig.4a) was balanced with the amount of the shortwave radiation absorbed in the layer from surface to 3mm in depth before and after the sun crust formation, and during the sun crust formation, the total heat flux decreased to balance with the amount of the shortwave radiation absorbed from surface to 2mm in depth. Since the thickness of the sun crust layer was up to 2mm, it indicates the shortwave radiation was absorbed and consumed for the internal melting at the layer beneath the sun crust. As a result, the cavities under the sun crust were formed.

At the station B, sun crust was not formed on Apr. 19, 1991. As shown in Fig.4b, the amount of the absorption of shortwave radiation at the station B was larger than at the station A, and the total of longwave radiative flux, sensible and latent heat fluxes at the station B (solid line) was nearly equal to 0 kW/m^2 or below. It indicates, at the station B, the surface layer was warmed not only by the absorption of shortwave radiation but also by the total of heat flux. As a result, snow surface was melted and sun crust was not formed.

LABORATORY EXPERIMENT

Instrumentation

In order to verify the results of the field observations, the experiment in cold laboratory was held using various snow types. The apparatus used for the laboratory experiment is shown in Fig.5. A snow block with a dimension, approximately 45cm x 50cm x 16cm, was covered with an insulator except upper side. Dual Photoreflector Lamps (500 W, brightness temperature 5500 K) were used to reproduce solar radiation with a tracing paper to scatter the light. In order to enhance the sensible and latent heat transports to/from the snow surface, the whole apparatus was housed in the small size wind tunnel (approximately 58cm x 72cm x 30cm) with a fan. The negative heat source for the snow surface was the sensible and latent heat transfers, not the radiative cooling, which was the main heat sink in the field. The air temperature in the cold laboratory, which was measured by thermocouple thermometers, was about –5 °C. Pyranometers (KOITO, IKS–35) were used to measure amounts of incoming and outgoing short wave radiation. Humidity was measured by the hygrometer at the height of 2 cm from the snow surface.

Experimental results

Experiments were done 11 times by changing the snow types (Table 1) and density. The snow density was 400 to 430 kg/m^3 from Run 1 to Run 8 and 350 to 370 kg/m^3 from Run 9 to Run 11. A black fine agent (toner powder for a copy machine) was spread partially on the snow surface or inside the snow layer to increase internal melting.

Sun crust was formed 4 runs (Run 6,9,10,11). The sun crust formed by those experiments (Fig.6) was a thin ice layer made of ice particles, which was consistent with the observed sun crust in the field (Fig.2). The sun crust was formed with and without a black agent, however, the sun crust grew faster for the case with black agents than the case without it because of the more intense internal melting. It was also made clear from Run 6 and 11 that the sun crust was formed through wet snow metamorphism, because from those runs the texture was changed from the fine texture of compact snow into the coarse texture which was similar to the texture of granular snow. It was also verified by the fact that water was retained beneath of the reproduced sun crust.

Whenever the snow surface became rough due to the quick melting, sun crust was not formed (Runs 1 to 5, 7, 8). It seemed that the snow particles were not connected each other when the surface became rough. Furthermore, the concave area of the snow surface, where turbulent transfer was weak, was melted by shortwave radiation more than the convex area. As a result , sun crust was not formed when the surface became rough even under the suitable energy balance condition for the sun crust formation.

CONCLUSION

The sun crust formation mechanism was clarified through field observations as well as laboratory experiments. The weather conditions during the sun crust formation on Apr. 19, 1991 were: fine weather, air temperature nearly to 0 °C, wind speed about 4 to 5 m/s, humidity about 60 %. The sun crust was a thin ice layer made of ice particles. With the sun crust formation, the local temperature beneath it rose and internal melting occurred. As a result, the cavities under the sun crust were formed. The sun crust was formed from both compact snow and granular snow, however, when the snow surface became rough due to quick melting, the sun crust was not formed. From the energy balance calculation of the surface layer, energy balance condition for sun crust formation was revealed that the total of longwave radiative flux, sensible heat flux and latent heat flux was balanced with the shortwave radiation absorbed in the sun crust. At the further down the snow pack, shortwave radiation penetrated through the sun crust was absorbed and the internal melting occurred.

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REFERENCE

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Table 1 Snow type of the experiments.

Run	Snow type	Black agents	Result
1	granular snow	——	none
2	granular snow	——	none
3	granular snow	surface	none
4	granular snow	surface	none
5	granular snow	surface	none
6	conpact snow	inside	crust
7	granular snow	surface	none
8	granular snow	surface	none
9	granular snow	surface	crust
10	granular snow	inside	crust
11	conpact snow	inside	crust

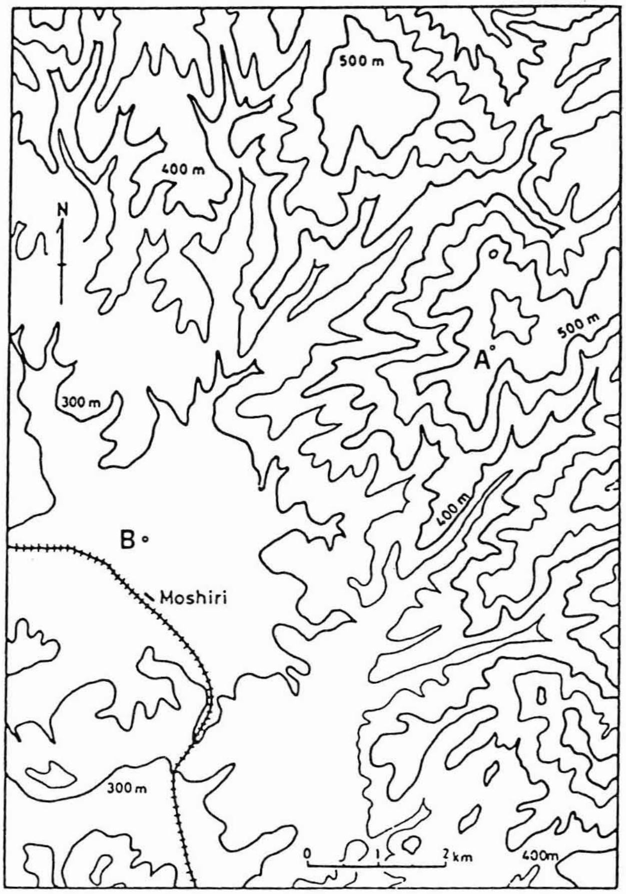

Fig.1 Location map of two heat balance stations in Moshiri.
A:higher station B:lower station

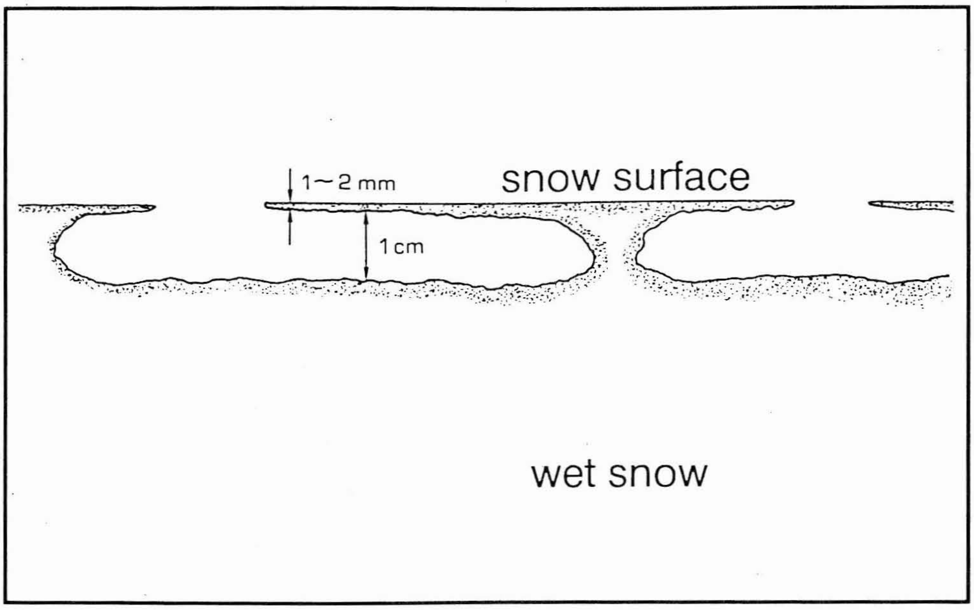

Fig.2 Vertical cross section of the sun crust.

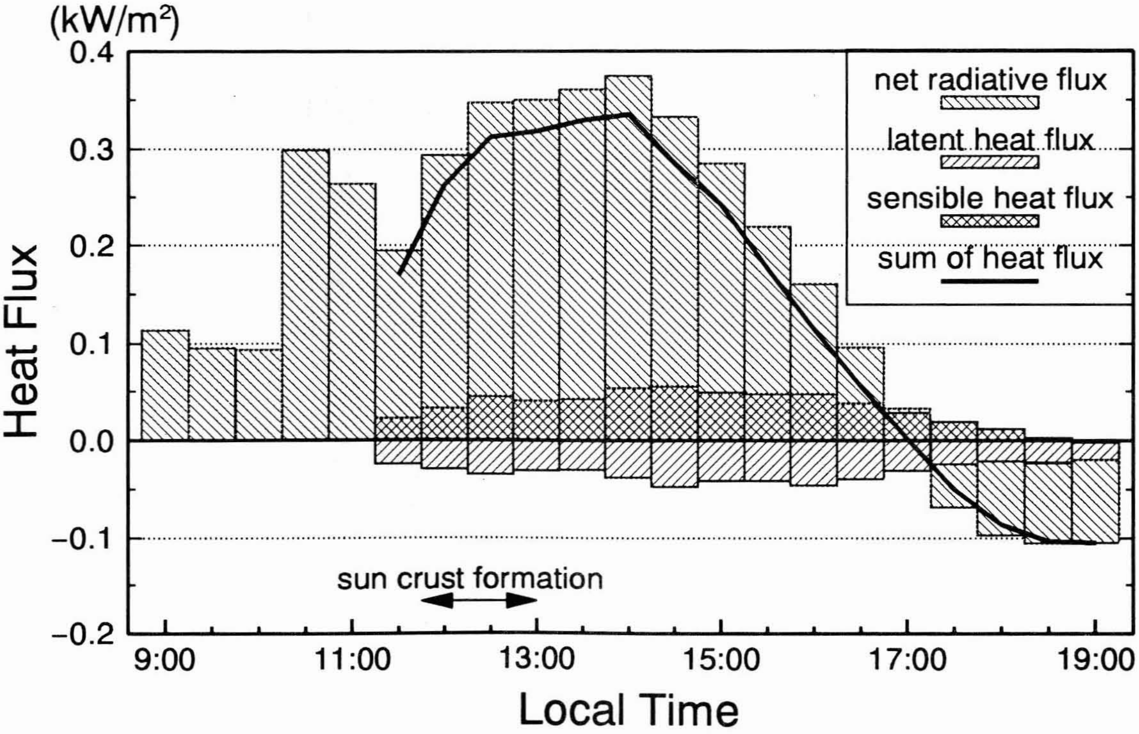

Fig.3 Time variation of heat balance compornents at the station A.

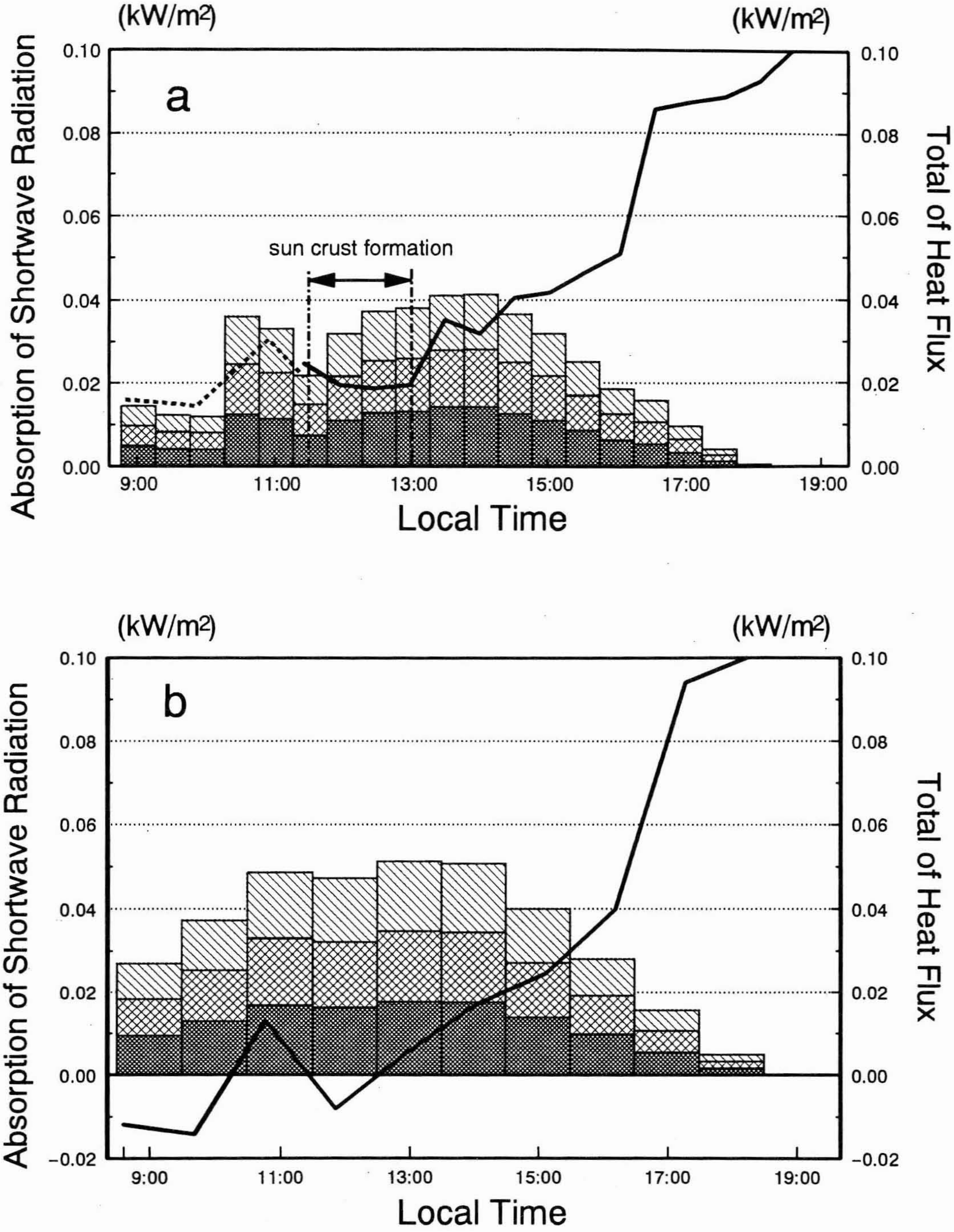

Fig.4 Comparison of absorption with the total of heat flux at two stations.
a: The station A b: The station B
Absorption of short wave radiation at ▒ 0～1 mm, ▩ 1～2 mm, ▧ 2～3 mm
Total of heat flux at the surface :
—— **sum of long wave radiative flux, sensible flux and latent heat flux**
······· **long wave radiative flux**

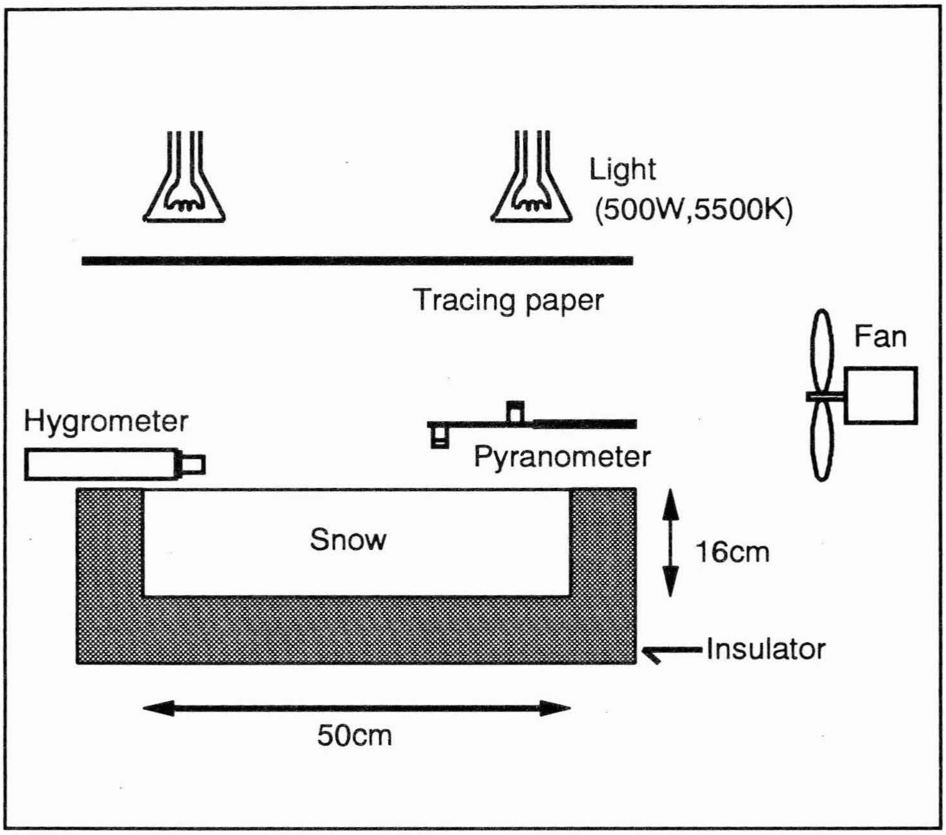

Fig.5 Schematic diagram of the apparatus.

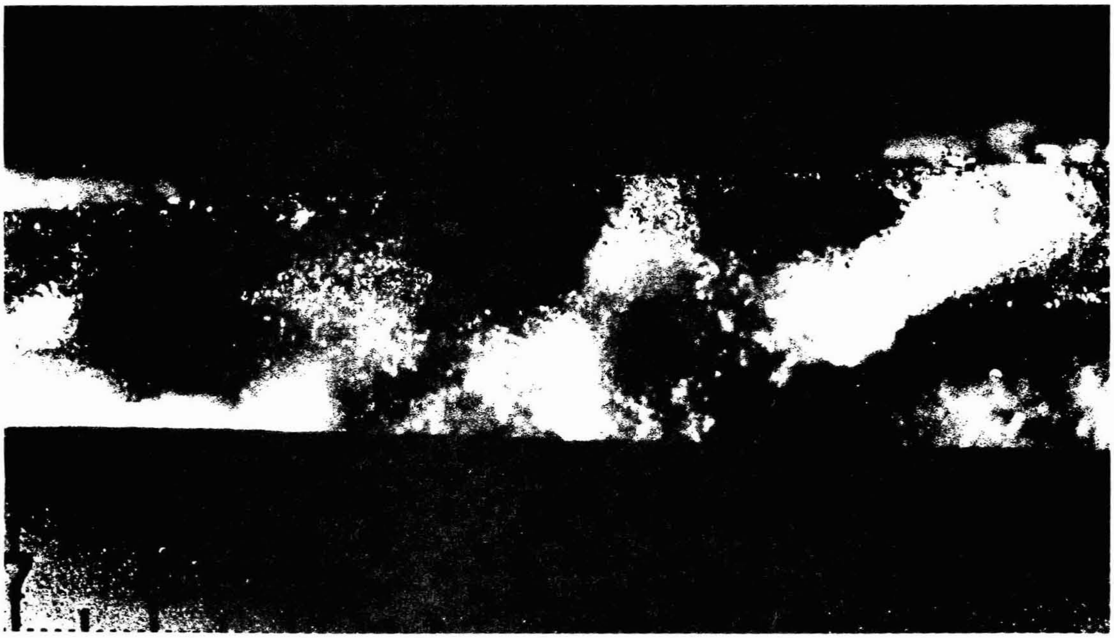

Fig.6 Vertical cross section of the reproduced sun crust.