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Comparison of meteorological features in the debris-free and debris-covered areas at Khumbu Glacier, Nepal Himalayas, in the premonsoon season, 1999

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Abstract

Meteorological observations were carried out in the debris-free and debris-covered areas of Khumbu Glacier, Nepal Himalayas from May 22 to June 1, 1999. Comparisons of meteorological features in the both areas were made. There was little difference of the net radiation between the both areas. The distinct valley wind could be recognized. The air temperature in the debris-covered area was higher than that in the debris-free area. The difference became small in the daytime because the valley wind increased in the daytime and could diffuse the heat.

1. Introduction

The most part of the ablation area of large glaciers in Himalayas is covered with supraglacial debris (Moribayashi and Higuchi, 1977; Fujii and Higuchi, 1977). It is important, therefore, to understand the thermal effect of debris layer on meteorology and ablation rate in debris-covered area. Many meteorological observations were carried out and ablation characteristics under debris layer were studied, for example Inoue and Yoshida (1980), Nakawo and Takahashi (1982) and Sakai *et al.* (1998). However, no simultaneous observations of meteorology in both the debris-covered and the debris-free areas on the same glacier have been made prior to the present study. This paper presents the meteorological features observed in the two areas of Khumbu Glacier, Nepal Himalayas. Ablation, heat balance characteristics and positive degree-day factors are reported by Kayastha *et al.* (2000) and Takeuchi *et al.* (2000).

2. Observation methods

Observations were carried out around the Everest Base Camp (27°59′N, 86°51′E, 5350 m a.s.l.) of Khumbu Glacier, which flows from the basin surrounded by Mt. Sagarmatha (Everest, 8850 m) and Lhotse (8511 m). It is one of the largest glaciers in Khumbu region, with a length of about 17 km and an area of about 17.5 km^2 (Watanabe *et al.*, 1980). The observation period was from May 22 to June 1, 1999 just before the monsoon season.

Three observation sites B, D and M were established as shown in Fig. 1. Heat balance observations were made at the debris-free (B) and debris-covered (D) areas, respectively. Site M, where air temperature was measured, was the subsidiary observation site placed on the lateral moraine close to the glacier margin. The distance between sites B and D is about 200 m apart, and M is 1.7 km apart from B. The altitude of sites B, D and M is 5352 m, 5330 m and 5312 m, respectively. The differences in altitude are small.

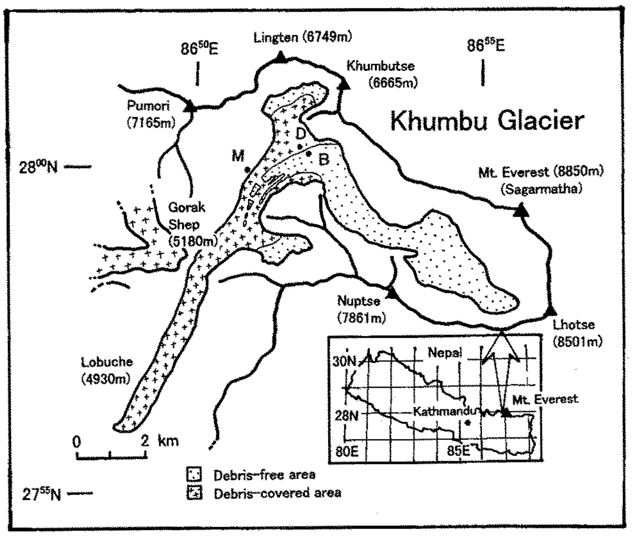

Fig. 1. Map of the Khumbu Glacier, Nepal Himalayas and observation sites. B: the observation site on the debris-free bare ice. D: the observation site in the debris-covered area. M: the observation site on the lateral moraine.

Meteorological elements and instruments are summarized in Table 1. The sensors of wet and dry-bulb temperatures were inserted in double vinyl chloride pipes for insulating solar radiation and ventilated by micro-fans with a solar battery during daytime at each observation site. Most of data were continuously recorded with portable data loggers. Maintenance of all instruments at sites B and D was made every day. In the debris-free area, ablation was measured once a day with seven stakes. Albedo of the ice surface at each stake was measured twice during the observation period at about 11:00-12:00 on fine days. In the debris-covered area, ablation under debris layer was measured four times a day (8:00, 11:00, 14:00 and 17:00) at artificially prepared sites with thickness of the debris layer of 2, 5, 10, 20, 30

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Table 1. Meteorological elements and instruments at sites B and D.
Site B: debris-free area. Site D: debris-covered area.

Elements	Site		Instruments	Recording interval
	B	D		
Air temperature (dry-bulb)	○	○	Thermistor thermometer	30 min.
(1 m high) (wet-bulb)	○	○	Thermistor thermometer	30 min.
Wind speed (1 m, 0.5 m high)	○	○	Three-cup anemometer	30 min.
Surface temperature	–	○	Infrared thermometer	30 min.
Global radiation	–	○	Pyranometer	30 min.
All wave net radiation	○	–	Net radiometer	30 min.
Ablation amount	○	○	Ablation stakes	Once a day (B) Four times a day (D)
Albedo	○	○	Albedometer	Twice during the period (B) Four times a day (D)

and 40 cm, respectively. The surface temperature and albedo of the debris layer were also measured at those times manually. The surface temperature were continuously measured at a point with 10 cm debris layer, the thickness of which is nearly equal to the mean thickness of the debris layer around site D. More detail methods of measurement at artificially prepared debris layer are reported in Kayastha *et al.* (2000).

3. Comparison of meteorological parameters between the debris-free and debris-covered areas.

3.1. Radiation

Albedos measured at seven stakes in the debris-free area were shown in Fig. 2a. The values decreased on May 30 as compared with those on May 22 at all stake sites. From this data, the daily albedo of site B, where the meteorological measurements were made, was obtained by interpolating the measured values linearly. On the debris layer, albedo was measured every day. The mean albedo during the period was 0.21. The result measured on 10 cm debris layer at 11:00 are shown in Fig. 2b.

The radiative balance equation on the ice or debris surfaces can be written as follows:

$$SR+RR+AR+TR=NR, \qquad (1)$$

where positive indicates toward the surface. SR is the solar radiation, RR the reflected short-wave radiation, AR the atmospheric long-wave radiation, TR the terrestrial long-wave radiation and NR the net radiation. SR on the debris-covered ice and NR on the debris-free ice were measured directly. SR is considered to be the same at the both surfaces. RR was obtained from SR and albedo, namely,

$$RR=-\alpha SR, \qquad (2)$$

where α is the albedo of the bare ice or the debris layer. TR was obtained by Stefan-Boltzmann's law, assuming the surfaces as black body. AR on the bare ice can be calculated by equation (1) and it can be the same value on the debris layer. NR on the debris layer was obtained by equation (1).

The variation of solar radiation during the observation period is shown in Fig. 3. It exceeded about 1200 Wm^{-2} around noon on fine days. The mean daily variation of the four components of radiation and the net radiation were compared between bare ice and 10 cm debris layer in Fig. 4. These are mean value of five fine days (May 22, 25, 26, 30 and 31). The absolute value of RR was larger on the bare ice because of a little higher albedo. On the other hand, that of TR was larger on the debris layer, because of the higher surface temperature. As the result, the net radiations in the both areas were almost same as shown in Fig. 4(c).

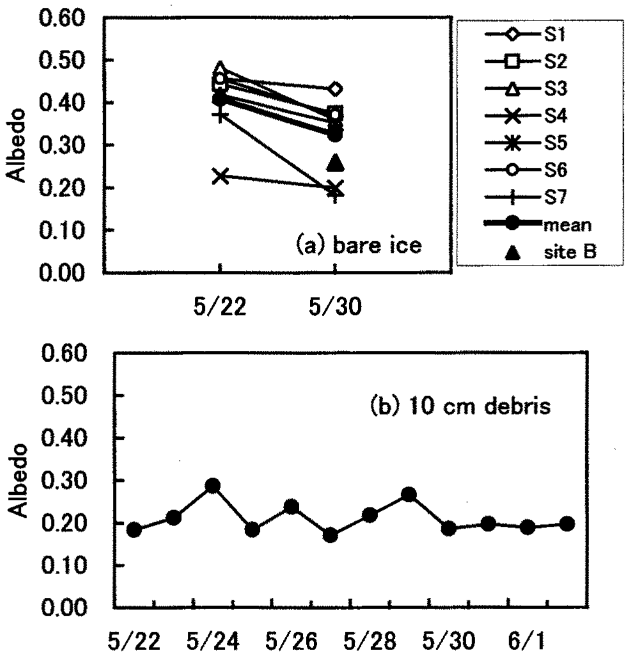

Fig. 2. Albedo of the bare ice (a) and the 10 cm debris layer (b).

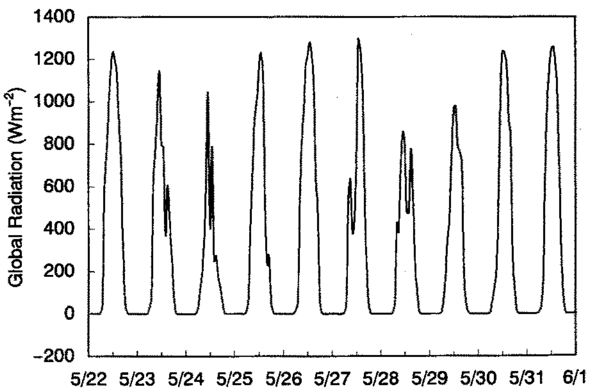

Fig. 3. Variation of solar radiation during the observation period.

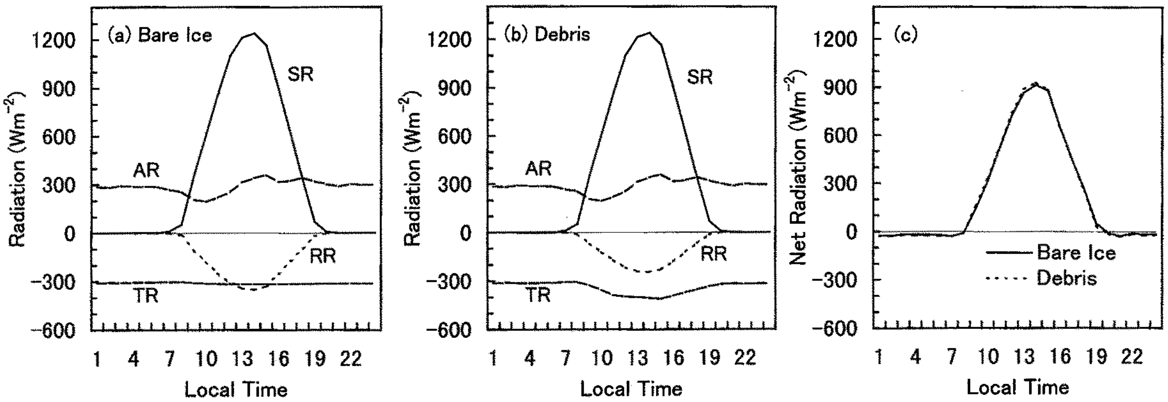

Fig. 4. The mean daily vatiation of the four components of radiation on the bare ice (a) and on the 10 cm debris layer (b), and the net radiation of the both areas (c).

3.2. Wind speed and direction

The variations of wind speed in the debris-free and the debris-covered areas are shown in Fig. 5. The wind speed was small generally and even the maximum value during the period was about 2 ms^{-1} . It was rather large in the debris-covered area than in the debris-free area. The reason can be considered that many ice pinnacles in the debris-free area decreased the wind speed. Systematic daily fluctuation of wind speed can be recognized in the both areas, namely it became larger in the daytime and very small in the nighttime. Especially in the debris-free area, it was nearly zero in the nighttime. The wind direction concentrated from south to southwest, which is from the downstream area of the valley, by the frequency of about 60% (Fig. 6). The wind direction from west to north-east did not occur during the observation period. Namely, a glacier wind which blows from the upglacier to the downglacier was not observed. This should be caused that the Khumbu Glacier is surrounded by higher ridges except the south-west direction as seen in Fig. 1. The prevailing wind is considered to be a valley wind reported from earlier (Inoue, 1976). It blows from lower to upper along the valley due to the rising of warmed air in the daytime, which causes the daily fluctuation in wind speed.

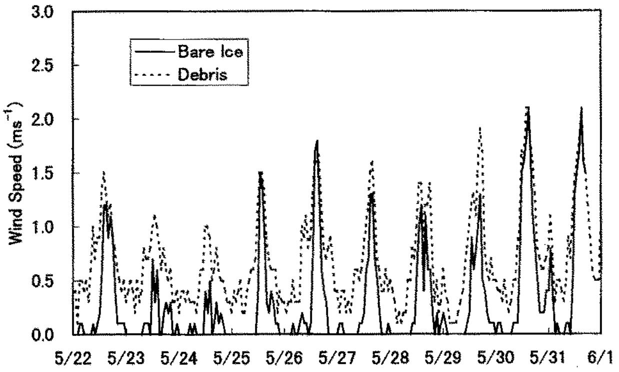

Fig. 5. Variations of wind speed in the debris-free and debris-covered areas.

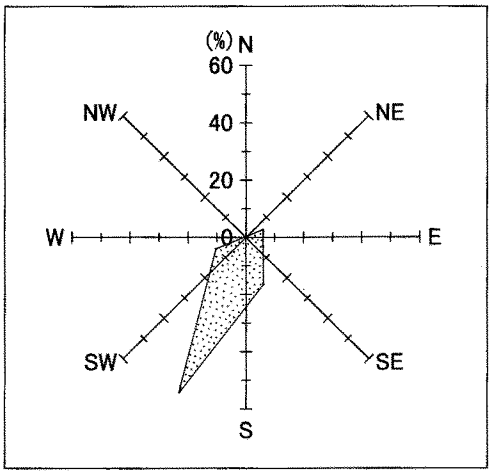

Fig. 6. Frequency of wind direction.

3.3. Air temperature

The variations of air temperature in the debris-free area (B), the debris-covered area (D) and on the moraine (M) are shown in Fig. 7. The daily maximum air temperatures of the three sites were 3.9, 4.8 and 7.6℃ in average during the period. It was the highest at site M and the lowest at site B. This should be caused by the differences in surface temperature of the sites. The surface temperature of the debris-free ice was 0℃ because of melting during daytime. In the debris-covered area, the surface temperature depends on the debris thickness. Most of the energy absorbed on the thin debris surface during daytime conduct to ice and melt it. Then, surface temperature of debris layer may be lower than that on the moraine, where there is no glacier ice below. On the other hand in the nighttime, the daily minimum air temperatures of the site B, D and M were -1.9, -0.2 and -1.5℃ in average and it was higher at site D than that at M. The air temperature decreased more slowly at D compared with at B and M. This tendency can be seen every day during the period.

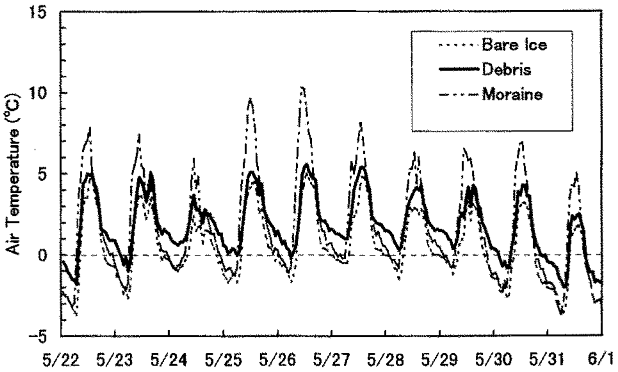

Fig. 7. Variations of air temperature in the debris-free, debris-covered areas and on the moraine.

The variations of air and surface temperatures in the debris-covered area are shown in Fig. 8. The surface temperature became 15 to 20℃ around the noon and decreased rapidly in the afternoon with decrease of solar radiation, but it decrease slowly after sunset. The air temperature also decreased slowly after sunset and was very similar to the surface temperature.

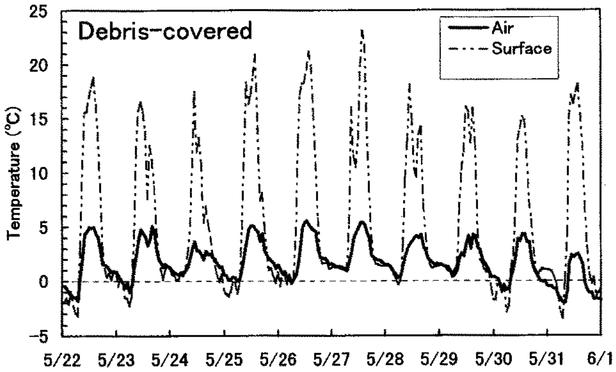

Fig. 8. Variation of air and surface temperatures on the debris-covered ice.

The difference of surface temperature between debris-free and debris-covered areas was larger in daytime but the difference of air temperature between them was larger in nighttime than daytime (Fig. 7). This conflicting phenomenon is considered to be due to the daily fluctuation of wind speed. Namely, the difference of air temperature was decreased by the valley wind during daytime.

The higher air temperature in the debris-covered area during nighttime should be due to the released heat from the warmed debris surface (Takeuchi *et al.*, 2000). Namely, heat stored in the debris layer increases in the daytime and decreases at night. Since the melting under the debris during nighttime was little for any debris thickness, it is likely that most stored heat cause the slow decrease of debris surface temperature and the higher air temperature in the debris-covered area during nighttime.

4. Summary

Comparisons of meteorological features in the debris-free and the debris-covered areas at the Khumbu Glacier were made. Results are summarized as follows:

1) There was little difference of the net radiation between the both areas.
2) The distinct valley wind could be recognized.
3) The air temperature in the debris-covered area was higher than that in the debris-free area due to the higher surface temperature of debris. The difference of air temperature became smaller in the daytime. The valley wind which becomes large in the daytime could cause the smaller temperature difference by diffusing the heat.

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