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Influence of surface debris on summer ablation in Unteraar- and Lauteraargletscher, Switzerland

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Abstract

In order to evaluate the influence of surface debris on summer ablation on a glacier, surface ablation and air temperature were measured from May to September in 2001 on Unteraar- and Lauteraargletscher. The positive degree-day factor obtained for a debris-covered surface was 2.98 mm w.e. K^{-1} day^{-1}, smaller than those obtained for debris free surfaces, 4.45–9.81 mm w.e. K^{-1} day^{-1}. The factors were utilized to compute daily ablation in each altitudinal range using the positive degree-day method. Results of the computation show that the debris layer significantly reduces the total ablation in July and August after the glacier surface changed its state from snow to debris cover at the lower reach. Thus, it is concluded that the debris-covered surface substantially contributes to the decrease in ablation during the mid summer season. The total ablation from May to August would be larger by 32% if the glacier surface had been assumed to be entirely debris free.

1. Introduction

Glaciers are often covered by debris in their ablation areas. Rocks and sediment entrained into ice in the accumulation area are transferred to the lower reach of the glacier, then melt out on the surface and form a supraglacial debris layer. Because thermal processes on a debris layer are quite different from those on snow or ice, the influence of the layer on ablation is crucial for the glacier mass balance. The evolution of medial moraines or supraglacial lakes, often observed on debris-covered glaciers, are considered to be the results of the thermal regime specific to debris-covered ice surfaces.

Observations and experiments on glaciers in the past agree with that debris layers reduce the ablation of ice beneath, unless the layer is very thin. Mattson *et al.* (1993) showed that ablation under debris is less than that on bare ice when the debris layer is thicker than 30 mm, while it is greater when the layer is thinner. Although the similar dependence of ablation on debris thickness has been observed in other glaciers, the critical thickness varies in each glacier and seemed to be controlled by the thermal properties of the debris (Rana *et al.*, 1998). Nakawo and Young (1981; 1982) proposed and tested a model to estimate ablation under a debris layer from meteorological variables, in which the thermal resistance of debris was taken into account by including debris surface temperature. His model was combined with surface temperature measurements from satellites and used as an efficient tool to evaluate large scale mass balance distribution on a debris-covered glacier (Nakawo *et al.*, 1999).

One of the simplest but sufficiently accurate schemes to estimate ablation on a glacier is the positive degree-day method. It bases on linear correlation between ablation and sum of daily mean temperatures above melting point (PDD) during a period. The factor that links the ablation to PDD is called the positive degree-day factor. Braithwaite (1995) summarized positive degree-day factors reported for ice and snow surfaces on various glaciers. Generally a snow surface has a smaller factor than ice, but the differences among glaciers, or even within a glacier, are often larger and attributed to different meteorological conditions. Kayastha *et al.* (2000a) studied spatial and temporal variations of degree-day factors on a glacier in the Himalayas. They concluded that larger contributions of shortwave radiation to ablation results in a larger degree-day factor. The positive degree-day method has not frequently been implemented to debris-covered surface. In Khumbu Glacier, a debris-covered glacier in Nepal, experimental work was carried out to determine positive degree-day factors for ablation under debris layers with different thicknesses (Kayastha *et al.*, 2000b). The factor obtained for 400-mm thick debris-covered surface was 30% of the value for bare ice.

Previous works described above suggest that thick debris cover on a glacier reduces ablation and takes a key role in the evolution of debris-covered glaciers. However, the total reduction in the amount of ablation in a specific glacier has not been studied so far. The objective of this report is to quantitatively evaluate the total decrease in summer ablation due to debris cover in Unteraargletscher by the positive degree-day method. This attempt may display the importance of debris cover in glacier mass balance and gives an insight to the reaction of debris-covered glaciers to climate changes.

2. Study site

Unteraargletscher is a temperate valley glacier in the Bernese Alps, Switzerland. Together with its tributaries, Lauteraar, Finsteraar and Strahleggglets-cher, it composes a glacier system with a total area of 28 km^2 (Fig. 1). Characteristic feature of the glaciers is a thick debris layer that covers the major part of Unteraargletscher and some parts of Lauteraar and Finsteraargletscher (Fig. 2). On Unteraargletscher, several stripes of medial moraines are formed and their heights measure up to about 50 m. Although large rocks are piled up to several meters on the medial moraine at the confluence area, the thickness of the debris layer varies from 50 to 200 mm in general.

The glacier is frequently surveyed by aerial photogrammetry by Glaciology Section, VAW-ETH, Zurich. The digital elevation map of the glacier surface constructed from a survey in 1999 (personal communication from J. Helbing, 2002) was used in this study and the surface debris distribution determined from aerial photographs by Schuler *et al.* (2002) was superimposed on the map. Figure 3 is the resulting map that shows debris distribution on Unteraar- and Lauteraargletscher. Because of the locations of our field measurement sites, this study focuses on those two glaciers and we defined the boundary between Unteraar- and Finsteraargletscher at the altitude of 2400 m a.s.l.. Fig. 4 is a hypsographical diagram of debris-covered and debris-free surface area. Debris-

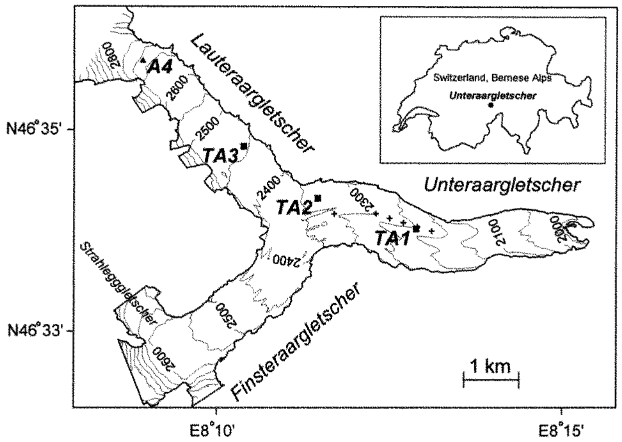

Fig. 1 Map of Unteraar-, Lauteraar-, Finsteraar and Strahlegggletscher. The solid squares are the temperature and ablation measurements sites, and the solid triangle is the ablation measurement site. Plus symbols are the additional ablation measurement sites on the debris covered surface.

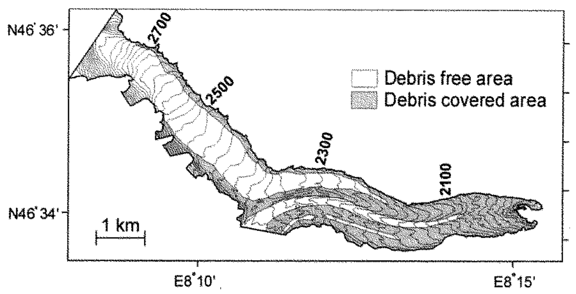

Fig. 3 Map of Unteraar- and Lauteraargletscher with surface topography and debris distribution. Shaded area is covered with a debris layer.

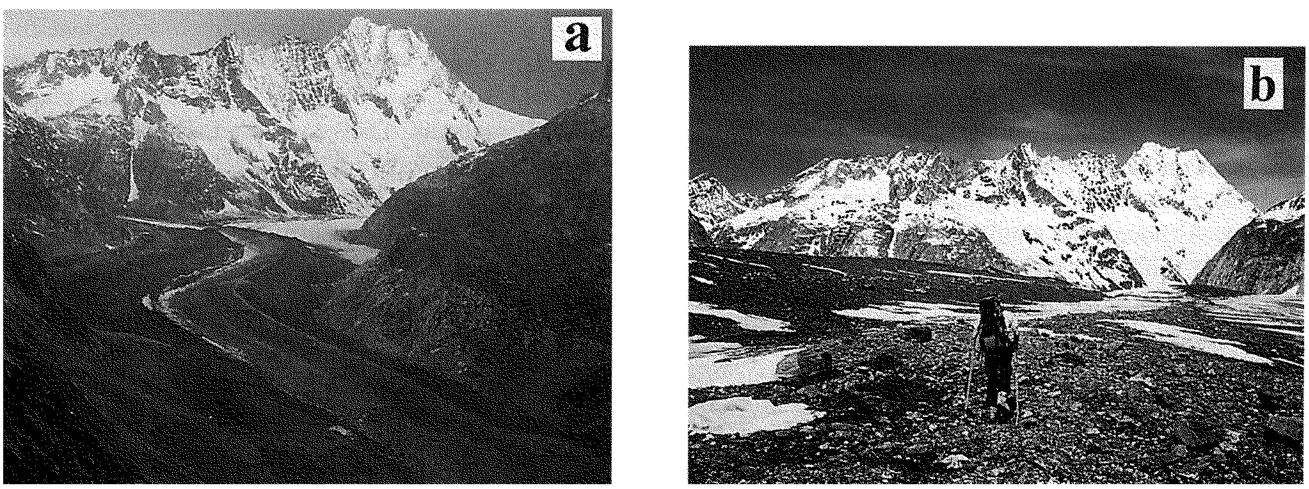

Fig. 2 Photographs showing (a) Unteraargletscher from the lower reach of the valley and (b) the glacier surface condition at about 2300 m a.s.l..

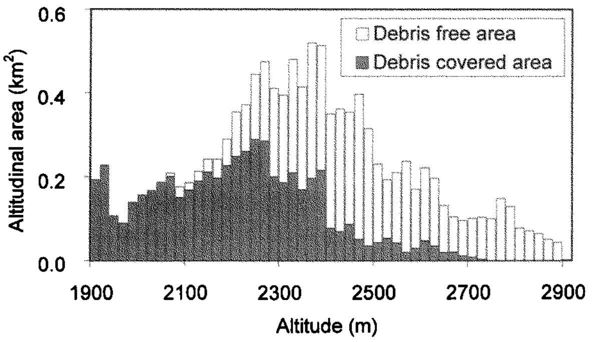

Fig. 4 Hypsometric diagram of Unteraar- and Lauteraargletscher for debris-covered (shaded) and debris-free surface conditions.

covered surface accounts for 47% of the total area and mainly occurs in Unteräargletscher. Apart from the surface area of 11.6 km^2 shown in Fig. 2b, Lauteraargletscher includes hanging glaciers on the steep side walls in the altitude higher than 2900 m a.s.l.. Map issued by Swiss Federal Office of Topography indicates that the total area of such glaciers is more than 5 km^2. Surface conditions and ablation mechanisms, however, are considered to be so complicated that they were excluded from this study.

3. Field observations

3.1. Method

Air temperature was measured every 15 minutes from May 19 to October 2, 2001 on the glaciers at three sites named TA1, TA2 and TA3 (Fig. 1). The altitudes of the sites were 2230, 2330 and 2450 m a.s.l., respectively. TA2 and TA3 are located on debris free surfaces while TA1 is at the ridge of a medial moraine where about a 100-200 mm thick debris layer covers the ice. All three sites were covered with snow when we started the measurements in May, then they turned to ice or debris-covered surface later in the summer. Temperature loggers (Hioki 3633) were installed in 200-mm long, 50-mm diameter plastic pipes fixed on ablation stakes drilled into ice. The pipes were directed along the valley so that the wind helps ventilating the sensors. Occasionally, the heights of the instruments were adjusted to keep them at 1 to 2 m above the glacier surface. To evaluate the validity of the measurements, one of the instruments was installed near the weather station at Lauteraarhut on the left flank of Unteraargletscher and its data were compared with those measured by a ventilated thermistor (Vaisala T107). 16-days measurement in June showed fairly good qualitative agreement in diurnal fluctuations, but suggested that our instrument tend to measure lower daily mean temperature, 0.5 K in average. Since the influence of the simplified instrument on temperature measurement seems to be not identical in each location, I used the data obtained on the glacier without corrections.

Ablation stakes were drilled into the surface at four sites, TA1, TA2, TA3 and A4, then measured from May 19 to October 2 with intervals of 5-28 days. The measurement at the location A4, the altitude of 2670 m a.s.l. which is higher than the equilibrium line altitude in 2001 (Fig. 1), was started on July 3. 6.5-m long, 34-mm diameter aluminium pipes were used as the stakes and installed with a steam drill. Because of surface irregularities, individual measurements may have errors up to ± 10 mm approximately. Measured changes in the surface height were converted to water equivalent ablation by densities of 600 kg m^{-3} for snow and 900 kg m^{-3} for ice.

Transient snow line position was surveyed on the glacier by handy GPS with intervals of a week to a month. Boundary between snow and ice was fairly well determined and error in the snow line altitude was estimated as about ± 20 m.

3.2. Results

Daily mean air temperatures at the three sites throughout the measurement period are shown in Fig. 5. After the start of measurements in May, temperatures were generally positive until the end of August, except for a few cold periods in June. In September, temperatures suddenly dropped and the snow line altitude descended from 2620 to 2400 m a.s.l. during the period from August 27 to September 29.

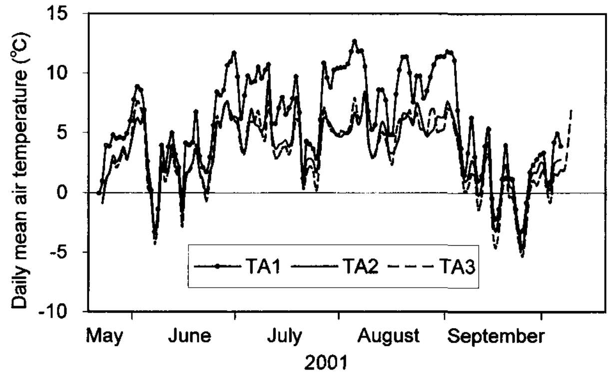

Fig. 5 Daily mean air temperature variations measured on the glacier at TA1 (solid with data points), TA2 (solid), and TA3 (broken).

Temperature at TA1 was generally higher than those at the other two sites and the difference increased in June. Detail examination of subdaily temperature variations implies that the surface condition at TA1 turned from snow to debris on June 7. After the transition, debris covered surface was intensively warmed up in the daytime and caused clear differences in the daily mean temperature against snow and ice surfaces.

The temperature lapse rate on the glacier was calculated from the data sets obtained at TA2 and

TA3, debris free measurements sites, from May to September. In the process of the calculation, the surface transitions from snow to ice at the measurement sites were not considered. A rate $\gamma=2.89\times10^{-3}$ K m^{-1} was obtained and used to estimate a temperature field in the next section both for debris-cover and debris-free surface conditions.

The cold weather in September suggests that ablation decreased and major part of precipitation fell as snow on the glacier during that period. Because snow precipitation might have changed the surface condition in an unpredictable manner, it is difficult to determine the ablation in September. Thus the analysis of ablation in the remainder of this report focuses on the period from May 19 to August 31.

The main objective of the field measurements was to find the positive degree-day factor that relates ablation to PDD measured at each site. The total ablation, A, over a period is given by,

$$A=k\cdot\text{PDD}, \quad (1)$$

where k is the positive degree-day factor and PDD is the sum of daily mean air temperatures above the melting point during the period. Figure 6 shows the plots of cumulative ablation to cumulative PDD at the measurement sites. For A4, air temperature was reconstructed from the data at TA2 and TA3 with the lapse rate obtained above. For TA1, only the measurements after the surface turned from snow to debris covered were plotted. Linearity between the cumulative ablation and cumulative PDD at each site is fairly well, and the changes in the surface conditions from snow to ice at TA2 and TA3 are not distinguishable.

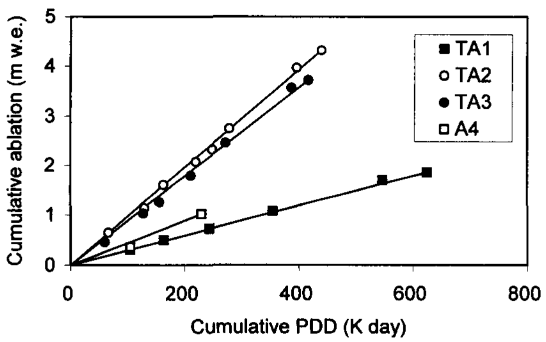

Fig. 6 Cumulative ablation versus cumulative PDD from June 14 to August 28 at TA1 (solid squares), from May 19 to August 28 at TA2 (open circles), from May 19 to August 27 at TA3 (solid circles), and from July 3 to August 27 at TA4 (open squares).

Positive degree-day factors obtained for the sites are given in Table 1. The value on debris-covered surface at TA1 is about 30% of those on snow or ice at TA2 and TA3, which indicates that the insulation due to the debris cover reduced the ablation of ice beneath. At A4, the surface was covered with snow throughout the study period and the factor is much smaller than those at TA2 and TA3. The smaller degree-day factor at A4 cannot be simply attributed to the snow cover in this case because TA2 and TA3 showed much larger values when they were still covered with snow. Plausible interpretation is increase in surface albedo due to fresh snow cover. From May to July, snow precipitation took place from time to time on the glacier. Albedo was expected to be high after the snowfall and such condition may have lasted longer in the upper reach of the glacier. The reduction of energy income through radiation likely kept the degree-day factor at A4 smaller.

As the conditions of the debris layer are not spatially uniform, it is crucial to evaluate the representativity of the degree-day factor obtained at TA1. Beside the frequent measurement at TA1, ablation under the debris layer between June 29 and August 23 was measured at 6 sites shown in Fig. 1. The degree-day factors obtained for those sites are plotted to the altitude in Fig. 7. There is no clear dependence on the altitude and the ablation is presumably controlled by the local conditions such as debris thickness, rock size, surface slope, and so on. Because of the frequent ablation measurement and reliable temperature data, the degree-day factor at TA1 is assumed to represent all debris covered region in the next section.

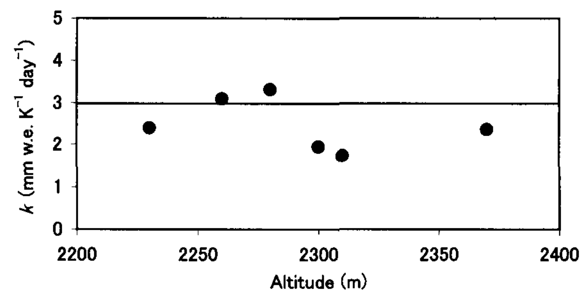

Fig. 7 Positive degree-day factors obtained on debris covered surfaces between June 29 to August 23. Solid line indicates the value obtained at TA1.

Table 1. Positive degree-day factors obtained for the measurement sites

Site	k(mm w.e. K^{-1}day^{-1})	Altitude(m a.s.l.)	Period	Surface condition
TA1	2.98	2230	Jun 14-Aug 28	Debris
TA2	9.81	2330	May 19-Aug 28	Snow → Ice
TA3	8.93	2450	May 19-Aug 27	Snow → Ice
A4	4.45	2670	Jul 3-Aug 27	Snow

4. Ablation calculation

4.1. Method

Positive degree-day factors obtained at TA2, TA3, A4 are interpolated to obtain an altitudinal distribution on snow and ice surfaces between 2230 and 2670 m a.s.l.. The values at TA2 and A4 were given as constants for the regions lower and upper than the above region, and influence of this assumption is less important because the surface area of these regions is limited. For a debris-covered surface, the factor was assumed to be constant and the value obtained for TA1 was used at any altitude.

Daily mean temperature at each altitude was determined from the measured temperature and the lapse rate obtained in the previous section. Temperature at TA2 and TA3 are used for snow and ice surfaces, and that at TA1 is used for the debris covered surface. Before June 7, when all the temperature loggers were above snow surfaces, temperature on a debris-covered surface was estimated by the empirical relationship between the temperatures on the debris covered and debris free surfaces found after June 7.

To specify the surface condition at each altitude on each day, the snow depth distribution at the beginning of the measurements must be prescribed. Snow-ice transition dates at TA1 and TA2, and snow depth measurement at TA3 on June 15 were used to calculate the initial snow depth. The results and the initial snow line altitude were linearly interpolated, and extrapolated to the upper reach of the glacier.

The daily ablation at altitude h on the day t was calculated by,

$$a(h,t)=k_c(h)\,T_c(h,t)\{S_c(h)+S_d(h)\} \quad \text{for} \sum_{t=0}^{t} a(h,t)<d_0(h), \quad (2)$$

$$a(h,t)=k_c(h)\,T_c(h,t)S_c(h)+k_d(h)\,T_d(h,t)S_d(h) \quad \text{for} \sum_{t=0}^{t} a(h,t)\geq d_0(h), \quad (3)$$

where T, k, S, and d_0 are daily mean air temperature, positive degree-day factor, surface area, and initial snow depth with suffixes c for debris free and d for debris covered surfaces. $a(h,t)=0$ when $T(h,t)\leq 0$°C.

4.2. Results

Daily ablation at every 20 m altitudinal range was computed from May 19 to August 31 by Eq. 2 and 3. In Fig. 8, temporal change of snow line altitude in the computation is compared with field data which were measured independently of those used to set the initial snow depths. The good agreement between the computation and the observation indicates that the surface conditions are well reconstructed.

Figure 9 shows altitudinal distributions of ablation on four days in different months but with similar temperature conditions. The ablation was calculated every 20 m with the surface area distribution shown in Fig. 4. Daily mean temperatures averaged between TA2 and TA3 are 6.35, 6.39, 6.58, and 6.13 °C for May 30, June 25, July 22, and August 23, respectively. It is obvious that the ablation was reduced at the altitude of 2100-2300 m a.s.l. from May to June, and at the altitude of 2300-2400 m a.s.l. from June to July. The minor change from July to August is accordant with the facts that the debris layer exists mainly below 2400 m a.s.l. (Fig. 4) and the snow line passed this altitude in July (Fig. 8). Total ablation was reduced by 10% from May to June and 21% from May to August.

To evaluate the total reduction in ablation due to the debris layer during the study period, computation was repeated with an assumption of entirely debris free surface. In this experiment, Eq. 2 was used regardless of the surface condition. Altitudinal distributions of the total ablation from May 19 to August 31 are shown in Fig. 10. They suggest that ablation is reduced substantially in the region lower than 2400 m a.s.l. due to the debris-covered surface condition. The seasonal variations of ablation are shown in Fig. 11. The insulation effect of the debris layer becomes noticeable in late June and takes an important role in July and August during the mid summer. The total computed ablation of the glacier throughout the

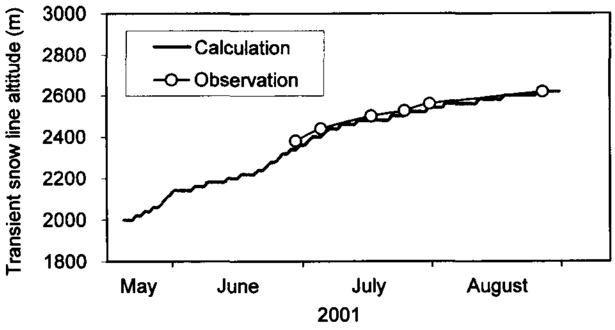

Fig. 8 Observed and calculated transitions of transient snow line altitude.

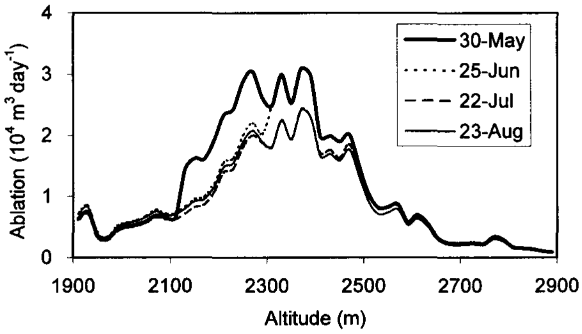

Fig. 9 Altitudinal distributions of daily ablation calculated for May 30 (thick solid), June 25 (dotted), July 22 (broken), and August 23 (solid).

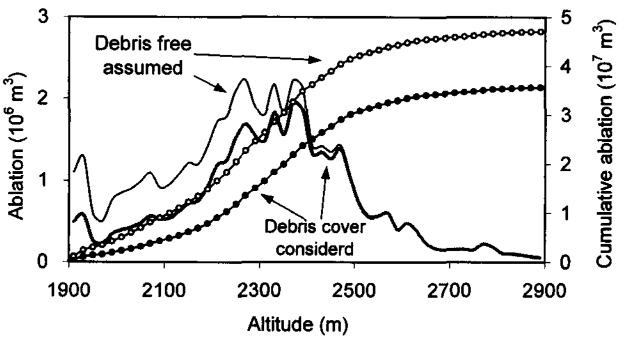

Fig. 10 Altitudinal distribution of total ablation from May 19 to August 31 calculated with the consideration of debris cover (gray line) and with the assumption of entirely debris-free surface (black line). Ablation at each altitude is cumulated and plotted with the solid circles (debris cover considered) and open circles (debris free assumed) for the ordinate in the right.

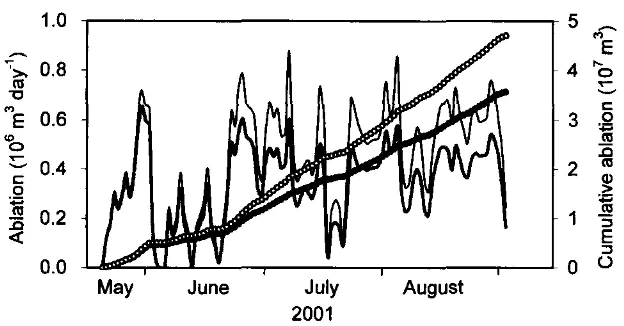

Fig. 11 The results of the same calculation as Fig. 10 but showing their temporal variations.

period is 3.56×10^7 m^3 when the debris is considered while it is 4.70×10^7 m^3 when the surface is assumed entirely debris free. The results predict 32% increase in ablation if Unteraar- and Lauteraargletscher were not covered with debris layer.

5. Discussion

Quantitative analysis of ablation in this study revealed that the surface debris layer is acting as a good insulator on Unteraar- and Lauteraargletscher. Such influence of debris should have taken a key role in the long-term evolution of the glaciers. Unteraargletscher has been continuously retreating since 1871 (Haefeli, 1970) and the current terminus lies at the altitude of 1900 m a.s.l. This altitude was compared with terminus altitudes of the other 116 glaciers in Switzerland that were reported by IAHS (ICSI)-UNEP-UNESCO (1998). 1900 m a.s.l. is much lower than the total mean of 2310 m a.s.l. (σ=320 m) and only 13 glaciers terminate at altitudes lower than the terminus of Unteraargletscher. Terminus altitude of a glacier can be related to the glacier size, but the median altitude of Unteraargletscher (2660 m a.s.l.) is still lower than the mean (2890 m a.s.l., σ=260 m) of the 116 glaciers and it is eighteenth from the lowest. The significantly lower terminus of Unteraargletscher infers that its retreat rate has been reduced by the insulation effect of the surface debris at the lower reach of the glacier.

The positive degree-day factor obtained for debris-covered surface in this study, and the values reported for three glaciers in Himalayas (Kayastha *et al.*, 2000b) are listed in Table 2. It is not straightforward to compare the factors, but the ratio between factors for debris-covered and debris-free surfaces may give an idea to evaluate the effect of debris on each glacier. The smallest fraction on Unteraargletscher indicates greater insulation of debris layer, and this may be attributed to the thicker debris layer. Thermal regime characteristic to each glacier is also very important. One of the examples is greater contribution of net radiation to energy balance on Himalayan glaciers at higher altitude. Under identical air temperature conditions, debris surface temperature may be higher when the local energy balance is dominated by radiation rather than by other components because of its low albedo. If it is assumed that ablation under debris layer is related to debris surface temperature, smaller insulation effect of debris is expected under greater radiation.

Validity of the positive degree-day method was assessed by looking at the snow line altitude in Fig. 8. The limited number of measurement sites, however, introduces errors in the estimations of the positive degree-day factor and temperature distributions. Figure 7 indicates that detail spatial distribution of degree day-factor on the debris-covered surface is required to improve the quality of the calculation. It is also needed to verify the constant lapse rate assumed all over the glacier. Character of the temperature measurement used in this study should be also discus-

Table 2. Positive degree-day factors obtained for various glaciers. k_d and k_c are factors obtained for debris covered and debris free surfaces. Original data in Lirung and Rakhiot Glaciers were recalculated by Kayastha *et al.* (2000b).

	Altitude (m a.s.l.)	Debris thickness (m)	k_d (mm w.e. K^{-1} day^{-1})	k_c (mm w.e. K^{-1} day^{-1})	k_d/k_c	Reference
Unteraargletscher	2230	0.1-0.2	2.98	9.81	0.30	This study
Khumb Glacier	5350	0.1	11.1	16.9	0.66	Kayastha *et al.* (2000b)
Lirung Glacier	4350	0.1	5.5	6.6	0.83	Rana *et al.* (1998)
Rakhiot Glacier	3350	0.1	3.5	6.6	0.53	Mattson and Gardner (1989)

sed. According to Ohmura (2001), the close relationship between air temperature and ablation is based on the major contribution of longwave atmospheric radiation to surface ablation. It implies that the location of temperature measurement for the positive degree-day method should be determined considering the details in the processes of energy transfer on each individual glacier. Thus, further study on the energy balance over debris is needed for better implementation of positive degree-day method to debris-covered glaciers.

6. Conclusion

The influence of a surface debris layer on summer ablation in Unteraar- and Lauteraargletscher was studied by field measurements and positive degree-day method. The obtained positive degree-day factors showed insulation effect of the debris layer which is more efficient than those reported in Himalayan glaciers. The reconstruction of summer ablation in 2001 indicated that ablation is reduced substantially due to the debris layer at the region lower than 2400 m a.s.l.. The reduction was enhanced as the snow line altitude ascends the glacier in July and August during the intensive ablation season in the Swiss Alps. It is predicted that total summer ablation would increase by 32% if the glacier were entirely debris free. Debris on Unteraargletscher seems to be responsible for its low terminus altitude which is lower than most of other glaciers in Switzerland.

Acknowledgments

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