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"Aeolian Dust Experiment on Climate Impact"

Impact of Dust on Glacier Mass Balance of the Tibetan Plateau

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Model calculations revealed the impact of dust deposition on glacier mass balance. A change in albedo from dust will affect the glacier mass balance even under the same meteorological conditions. Calculations of seasonal dependence of mass balance revealed that dust deposition during melting season would cause a higher negative mass loss from a glacier. Because a higher contribution of meltwater from glaciers will be expected in dryer environments, it would be meaningful to understand how and when the dust is transported and supplied to glaciers which provide water for arid terrain.

Key Words: Glaicer, Mass balance, Dust, Albedo, Tibet

1. Introduction

Glaciers located around the Asian highlands play an important role in the water cycle of arid/semi-arid regions. The contribution of meltwater from the glaciers was estimated to account for about half of the river water in the west Kunlun Mountains on the southern periphery of the Takulamakan Desert (Ujihashi *et al.*, 1998). Melt conditions of glaciers, therefore, will strongly affect the wetness of arid terrain through replenishing the water supply.

Glacier mass balance consists of addition and loss of ice mass, which are called accumulation and ablation, respectively. Accumulation corresponds to the solid phase of precipitation, which is affected by amount of precipitation and the air temperature when precipitation occurs. Ablation, on the other hand, consists of runoff and evaporation from glaciers, which result from the heat balance on a glacier. The volume and extent of a glacier result from a balance of accumulation and ablation. The mass balance of a glacier, therefore, is considered to be one of the most significant indicators of climate. Studies on glacier mass balance in the Asian highlands, however, are very limited due to the difficult access compared to the European and Arctic regions.

Knowledge about glaciers on the northern periphery of the Tibetan Plateau, which is considered an especially arid environment, is quite limited except for a few observational studies (Ageta *et al.*, 1989; Takahashi *et al.*, 1989). In the 1990s, intensive observations of glacier mass balance and its role in the water cycle on the semi-arid central Tibetan Plateau were carried out, revealing some features of glacier mass balance (Ageta *et al.*, 1994; Seko *et al.*, 1994; Fujita *et al.*, 1996, 2000). A numerical study based on the observational results revealed that the glacier mass balance would change with great sensitivity according to changes in albedo and air temperature rather than other meteorological parameters such as precipitation, wind speed and humidity (Fujita and Ageta, 2000). They pointed out that strong solar radiation was the main heat source of energy flux, and that its absorption would effectively change the glacier melt. In fact, a drastic melt was observed from May to June in spring 1995, which is considered to have been caused by low surface albedo due to dust deposition even under low-air-temperature conditions (Fujita *et al.*, 2000). It is expected, therefore, that the intensity of dust deposition will change water circulation through a change in mass balance even if no change in air temperature occurs. Using a numerical model, this paper discusses how the lowering of albedo by dust deposition will affect glacier mass balance and melting.

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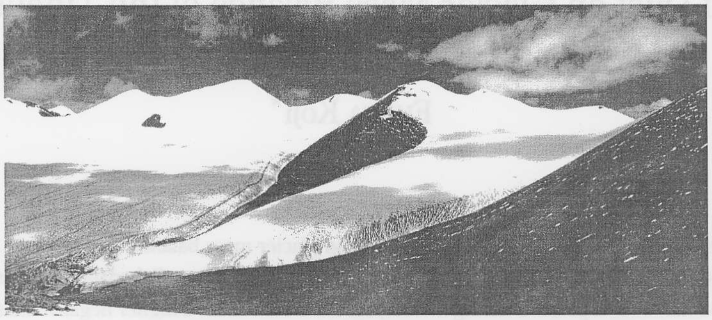

Fig. 1. Photograph of Xiao Dongkemadi Glacier in Tanggula Mountains.

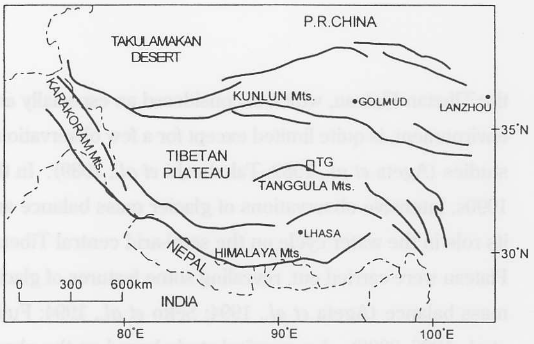

Fig. 2. Location map of Tanggula Mountains (TG).

2. Location and Climate of Study Site

Observational studies have been carried out at the Xiao Dongkemadi Glacier (Fig. 1) in the Tanggula Mountains on the central Tibetan Plateau (Fig. 2). Terminus and top altitudes, length and area of the glacier are 5380 and 5926 m above sea level (a.s.l.), 2.8 km and 1.77 km^2, respectively. The average surface inclination is about 10°, facing south, and there are few crevasses and no icefall.

Figure 3 and Table 1 show the meteorological conditions, observed at 5600 m a.s.l. on/around the glacier for the simulated period from October 1992 to October 1993 (Fujita and Ageta, 2000). The mean annual air temperature at 5600 m a.s.l. is about -10°, with an annual range exceeding 20℃. Daily mean air temperatures are above 0℃ for only 30 days a year, mainly in August. Most precipitation is supplied during the summer melting season by the Indian monsoon, and the annual amount was 670 mm water equivalent (w.e.) in 1992/93. The average short-wave radiation flux from June to August 1993 was 280 W m^{-2}, which is stronger than that of almost all mid-latitude glaciers (Ohmura *et al.*, 1992). Observations and features of the glacier mass balance were described by Seko *et al.* (1994), Ageta and Fujita (1996) and Fujita *et al.* (1996, 2000).

3. Surface Albedo in the Model

Fujita and Ageta (2000) discussed the characteristics and sensitivities of the glacier mass balance using an energy-balance numerical model consisting of heat and mass balances. Although its details were described by Fujita and Ageta (2000), it should be noted that surface albedo is evaluated according to surface conditions which vary with altitude, time and climate change. Surface albedo is estimated from surface snow density considering the multiple reflections in a surface snow layer and assuming that such a layer consists of an ice plate and an air layer in the vertical dimension (Yamazaki *et al.*, 1993). The thickness of the ice plate is empirically calculated from surface snow density. The existence of water is also considered in the model. A model of snow densification due to viscous compression (Motoyama, 1990) was adopted for the estimation of surface density. A compactive viscosity factor is estimated by an empirical formula with respect to snow density. The strain-rate-stress relation for a layer is calculated when the density of a snow layer at a given depth and the overburden load on that layer are known. The relations between surface density and estimated albedo for dry and wet snow are shown in Fig. 4. Although albedo of ice is possibly less than 0.1 in this scheme, the minimum albedo of bare ice is assumed to be fixed at 0.48

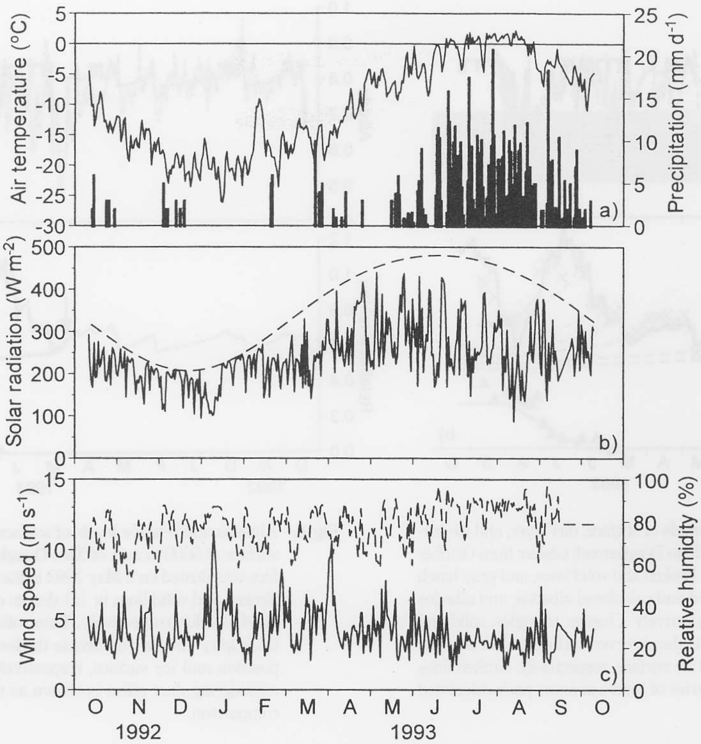

Fig. 3. Daily mean values of air temperature (a: solid line), precipitation va: solid bar), downward solar radiation (b: solid line), short-wave radiation at the top of atmosphere vb: broken line), wind speed (c: solid line) and relative humidity (c: broken line) at 5600 m a.s.l. of Xiao Dongkemadi Glacier from 10 October 1992 to 9 October 1993.

Table 1. Annual average/total variables at 5600 m a.s.l. of Xiao Dongkemadi Glacier as input in the calculation for one year from 10 October 1992. Differences in variables to change the annual mass balance by -100 mm w.e. are also shown as sensitivity.

	Average/total value	Sensitivity
Air temperature (℃)	-10.27	+0.20
Precipitation (mm w.e.)	672	-73
Solar radiation (W m^{-2})	237	+39
Rlative humidity (%)	77.9	+4.8
Wind speed (m s^{-1})	4.1	-2.8

based on the observed data (Seko *et al.*, 1994). The effects of dust deposition and condensation on the surface due to ablation were not taken into account in their study.

Calculations were done to verify the model in the first step. Meteorological parameters shown in Fig. 3 are used as the input data. Figure 5a shows the comparison between observed and calculated albedos at 5600 m a.s.l. for the period from October 1992 to October 1993. The calculated albedo represents the observed one well for the whole period with a few exceptions. A drastic decrease in albedo appeared in early May 1993, which is not shown in

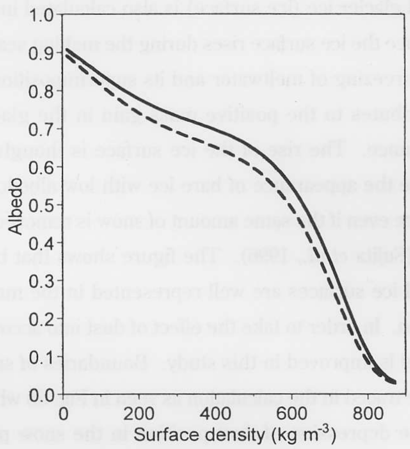

Fig. 4. Relationships between surface density and albedos for dry (solid line) and wet (broken line) snow.

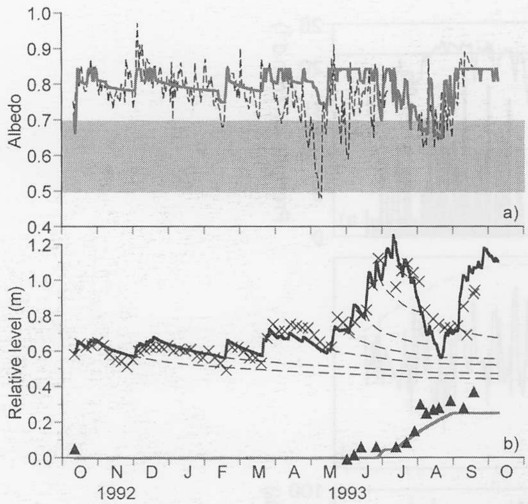

Fig. 5. Albedos and relative levels of surface, dirt layer, and ice surface at 5600 m a.s.l. of Xiao Dongkemadi Glacier from October 1992 to October 1993. Broken and solid lines, and gray hatch in (a) denote observed and calculated albedos, and albedos of dusted surface, respectively. Crosses, triangles, solid and gray lines in (b) denote the observed surface and ice surface, calculated surface and ice surface, respectively. Broken lines denote certain boundaries of layers in snow pack calculated in the model.

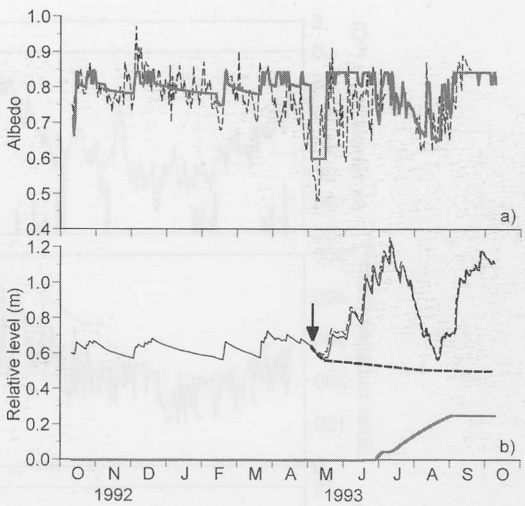

Fig. 6. Albedos and relative levels of surface, dirt layer, and ice surface at 5600 m a.s.l. of Xiao Dongkemadi Glacier. Surface was dusted on 2 May 1993 in the calculation (arrow). Broken and solid lines in (a) denote observed and calculated albedos, respectively. Thin solid, thick broken and thick gray lines in (b) denote the levels of surface, dust position and ice surface, respectively. Surface without considering dust effect is shown as thin broken line for comparison.

the calculated result. Figure 5b shows that the rise and fall of snow surface due to snowfall and melting are well represented by the calculation. In addition to the change in snow surface level, the boundary level between snow layer and glacier ice (ice surface) is also calculated in the model since the ice surface rises during the melting season due to refreezing of meltwater and its superimposition of ice contributes to the positive mass gain in the glacier mass balance. The rise of the ice surface is thought to accelerate the appearance of bare ice with low albedo on the surface even if the same amount of snow is removed by melting (Fujita *et al.*, 1996). The figure shows that both snow and ice surfaces are well represented in the model calculation. In order to take the effect of dust into account, the model is improved in this study. Boundaries of snow layers are traced in the calculation as seen in Fig. 5b which shows the depression of dust position in the snow pack due to the compaction of each successive snow layer. The effect of albedo lowering due to dust will be treated in the next chapter.

4. Impact of Dust on Glacier Mass Balance

In order to evaluate the impact of dust on glacier mass balance, the lowering of albedo is taken into account in this study. Although no observation has been done with respect to the amount of dust and surface albedo, sharp drops in the observed albedo are considered to be caused by dust depositions (Fig. 5a). The albedo of a dusted surface is assumed to be 0.6 in this study since sharp drops of albedo range from 0.5 to 0.7 (Fig. 5a). Figures 6 and 7 show the observed and calculated albedo, snow and ice surfaces and dust position along with the dates of dusting. In Fig. 6, dust was deposited on 2 May 1993, indicating the observed drastic lowering of albedo. Although the calculated surface albedo lowered for a several days, the dust was buried by snow and did not appear on the surface (Fig. 6). This implies that the dust deposition in spring did not affect glacier mass balance so strongly. In contrast, Fig. 7 shows the observed and calculated albedo, snow and ice surfaces and dust position when dust was deposited on 6 June 1993. Dust caused albedo lowering and melting just after its deposition at the surface. Although the dust was

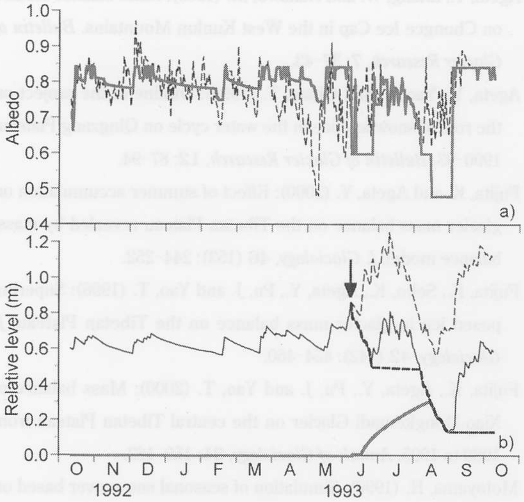

Fig. 7. Albedos and relative levels of surface, dirt layer, and ice surface at 5600 m a.s.l. of Xiao Dongkemadi Glacier. Surface was dusted on 6 June 1993 in the calculation (arrow). Broken and solid lines in (a) denote observed and calculated albedos, respectively. Thin solid, thick broken and thick gray lines in (b) denote the levels of surface, dust position and ice surface, respectively. Surface without considering dust effect is shown as thin broken line for comparison.

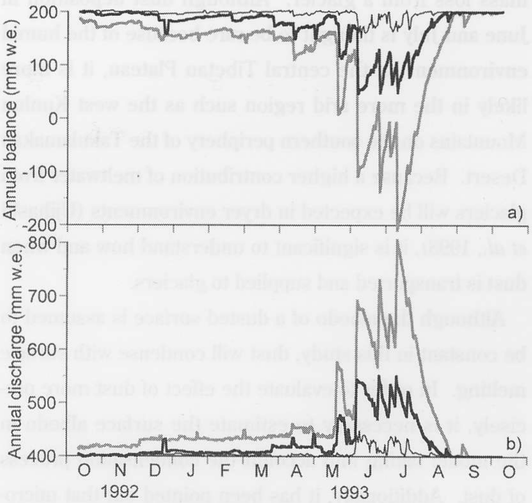

Fig. 8. Seasonal dependence of mass-balance (a) and discharge (b) sensitivities on the changes in dust deposited date and albedo. Horizontal and vertical axes denote the date when dust was deposited, and the areal averaged annual balance (a) and discharge (b) at the end of calculation period (9 October 1993). Thin, thick and gray lines denote the albedos of 0.7, 0.6 and 0.5, respectively.

buried once by snowfall, it appeared again and accelerated the melting which exposed the ice surface with lower albedo.

The seasonal dependence of glacier mass balance was examined by changing the date when dust was deposited. The areal average of glacier mass balance for the whole glacier was calculated considering a specific mass balance and an area of Xiao Dongkemadi Glacier at a given altitude span of 50 m. Calculated annual balance and discharge during 1992/93 was +200 mm and 400 mm w.e. without dust deposition. Figure 8 shows the seasonal dependence of mass balance (a) and discharge (b) on the changes in the dust deposition date and albedo of dusted surface. The abscissa and ordinate are the date when dust was deposited, and the annual balance (a) and discharge (b) at the end of the calculation year (October 1993), respectively. Changes in winter do not seriously affect either the annual balance or discharge, though dust was usually deposited in the winter dry season. On the other hand, the dust depositions in June and July alter the annual balance by >100 mm w.e. in a negative direction and increase the discharge by 40% (albedo=0.6) because solar radiation in this season is intense. Changes in annual balance of -100 mm w.e. will be caused by changes in annual air temperature of +0.2℃ or annual precipitation of -70 mm w.e. (Fujita and Ageta, 2000). It must be emphasized that such a large negative/positive impact on glacier mass-balance /discharge would be caused even if dust was deposited in only one day during June and July. The negative/positive impact on mass-balance/discharge drastically increases associated with the decrease of albedo of dusted surface from 0.7 to 0.5 as shown in Fig. 8. Dust deposition during winter could affect mass-balance and discharge largely if albedo of dusted surface was enough low (in case of 0.5). If material of dust consisted of bright mineral (in case of 0.7), on the contrary, impact of dust could be negligible even though it was deposited in summer.

5. Summary

Model calculations revealed the impact of dust deposition on the glacier mass balance. A change in albedo by dust will affect the glacier mass balance even in the same meteorological conditions. Calculations of the seasonal dependence of mass balance revealed that dust deposition during the melting season would cause a higher negative mass loss from a glacier. Although dust deposition in June and July is thought to be rare because of the humid environment on the central Tibetan Plateau, it is more likely in the more arid region such as the west Kunlun Mountains on the southern periphery of the Takulamakan Desert. Because a higher contribution of meltwater from glaciers will be expected in dryer environments (Ujihashi *et al.*, 1998), it is significant to understand how and when dust is transported and supplied to glaciers.

Although the albedo of a dusted surface is assumed to be constant in this study, dust will condense with surface melting. In order to evaluate the effect of dust more precisely, it is necessary to estimate the surface albedo in the model taking into account the condensation process of dust. Additionally, it has been pointed out that microorganisms living in a glacier produce dark material, thereby decreasing the albedo (Takeuchi *et al.*, 2001). It is also probable that the assumption of ice albedo (0.48 in this study) may affect discharge largely because most of the meltwater is yielded in the ablation area. Further study is required on the relation among quality and amount of dust, and albedo on snow and ice surfaces.

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