Effect of dust event timing on glacier runoff: sensitivity analysis for a Tibetan glacier

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ABSTRACT

The impact of the timing of dust deposition on glacier runoff was evaluated using a glacier mass–balance model with a newly improved scheme to track a dusted layer in a snow layer of a glacier. The lowering of surface albedo due to the dusted layer appearing leads to a drastic increase of glacier runoff even under the same meteorological conditions. Calculations of seasonal sensitivity, the relationship between dusted date and resulting runoff, have shown that dust deposition during a melting season might cause a drastic mass outflow from a glacier through changing the surface albedo during the melting season. **Citation:** Fujita, K. (2007), Effect of dust event timing on glacier runoff: sensitivity analysis for a Tibetan glacier, *Hydrol. Process., 21*, 2892-2896, doi:10.1002/hyp.6504.

KEY WORDS glacier, dust, runoff, model, albedo, Tibet

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INTRODUCTION

Glaciers located around the Asian highlands play an important role in the local water cycle since they provide an abundance of meltwater to the surrounding arid/semi–arid regions. The contribution of glacier meltwater in the west Kunlun Mountains, for instance, accounts for about half of the river water in the Taklimakan Desert (Ujihashi *et al.*, 1998). Fluctuations in glacier runoff and the consequent replenishing the water supply will, therefore, strongly affect human life in arid terrain.

Knowledge of 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; Kang, 2000). In the 1990s, intensive observations of glaciers, meteorology, permafrost, and river runoff at the Da and Xiao (large and small in Chinese) Dongkemadi Glaciers in the Tanggula Mountains of the central Tibetan Plateau were carried out (33°04'N, 92°04'E), revealing the current status of the water cycle system comprised of glaciers, permafrost and precipitation (Koike *et al.*, 1994; Ohta *et al.*, 1994; Seko *et al.*, 1994; Ueno *et al.*, 1994; Ageta and Fujita, 1996; Fujita *et al.*, 1996; 2000; Ageta *et al.*, 1997; Fujita and Ageta, 2000). Fujita *et al.* (2006) discuss the characteristics and sensitivities of glacier runoff using an energy–balance numerical model that includes heat and mass balances on the glacier and runoff from the glacier. They described the detailed schemes and verified the model. Their sensitivity test reveals that the glacier runoff under the summer monsoon, when most precipitation occurrs in summer, has a high sensitivity to changes in air temperature compared with the other variables. The same investigators pointed out that warmer temperatures during the summer melting season would change snowfall into rainfall, and the decrease in fresh snow could reduce the surface albedo of glacier, which would lead to lesser accumulation and greater ablation of the glacier. They conclude that changes in air temperature strongly affect glacier runoff through changing surface albedo. In other words, this implies that glacier runoff is highly sensitive to changes in albedo itself. In fact, a drastic melt observed from May to June in the spring of 1995 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 a dust event will alter water circulation through a change in mass balance even if no change in air temperature occurs. This paper describes the basic treatment of surface albedo in the model of Fujita *et al.* (2006), proposing a new scheme for tracking the dust layer in snow layer and sensitivity of the glacier runoff to the timing of dust deposition.

SURFACE ALBEDO IN MODEL

The albedo of a dusted snow surface has been well studied, since it has been well recognized that changes in albedo by dust and aerosol would strongly affect the water cycles through changes in snow melting (e.g. Warren and Wiscombe, 1980; Conway *et al.*, 1996; Aoki *et al.*, 2003). However, Fujita *et al.* (2006) calculated the surface albedo from the surface snow density using a practical method, since the surface conditions vary with altitude and time, as well as with the sensitivity test. They evaluated the surface albedo α from the surface snow density, taking account of multiple reflections in the 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):

$$\alpha = r_I + \frac{(1 - r_I)^2 \tau}{1 - r_I \tau} \tag{1}$$

where

$$\tau = \frac{(1-T_I) - \sqrt{(1-T_I)^2 - R_I^{\ 2}}}{R_I}$$

$$T_I = \frac{(1-r_I)^2 \exp(-k_I l_I)}{1-r_I^{\ 2} \exp(-2k_I l_I)}$$

$$R_I = r_I + \frac{(1-r_I)^2 r_I \exp(-2k_I l_I)}{1-r_I^{\ 2} \exp(-2k_I l_I)}$$

where r_I is the reflectivity of ice (0.018) and k_I is the absorption coefficient of ice (assumed to be 10 m^{-1}). The thickness of the ice layer l_I is obtained as

$$l_I = \frac{2}{\rho_I S} \tag{2}$$

where ρ_I is the density of ice and S (m^2 kg^{-1}) is the specific surface area (the area of the surface of ice particles in a unit volume of snow). The specific surface area is obtained by the following experimental equation (Narita, 1971):

$$\log_{10} S = -15.32 \times 10^{-9} \rho^3 + 16.65 \times 10^{-6} \rho^2 - 7.30 \times 10^{-3} \rho + 2.23 \tag{3}$$

And we finally obtain the surface albedo from the surface snow density ρ. The influence of water, which reduces the albedo, is taken into account by changing the specific surface area for wet snow as $S_w = 0.6S$.

It is necessary to evaluate the temporal change in snow density for the estimation of surface albedo. We adopted the model of snow densification due to viscous compression by Motoyama (1990) for our estimation of surface density. A compactive viscosity factor η is estimated using an empirical formula for snow density:

$$\eta = \eta_0 \exp(K\rho) \tag{4}$$

where both η_0 and K are constant (16 kg day m^2 and 0.021 m^3 kg^{-1} after Motoyama (1990)). The strain–rate–stress relation for a layer is calculated based on the density of a snow layer at a given depth and the overburden load W on that layer as

$$\frac{1}{\rho}\frac{d\rho}{dt} = \frac{W}{\eta} \tag{5}$$

The influence of water, which enhances snow compaction, is taken into account by changing the compactive viscosity factor for wet snow as $\eta_w = 0.5\eta$. Figure 1 shows the relations between surface density and estimated albedo for dry and wet snow. Although the albedo of ice is possibly less than 0.1 in this scheme, the minimum albedo of bare ice is assumed to be 0.48 based on the observations of Seko *et al.* (1994). According to this treatment, therefore, albedo will decrease temporally by condensation and wetting of surface snow, whereas only fresh snow will increase the surface albedo. In addition, melting of surface snow will cause a drastic decrease of albedo by removal of the upper snow layer and exposing the denser snow underneath. In terms of altitude, the precipitation phase (snow or rain) and melting will affect albedo through changing the snow density at the surface. The effects of a dusted surface were not taken into account in the model of Fujita *et al.* (2006).

The model was verified with observed glacier mass balance and runoff (Fujita *et al.*, 2006). Figure 2a shows changes in the surface level that vary with snowfall and melting, and the boundary level between the snow layer and glacier ice (ice surface) that varies with the superimposition of refrozen water. We obtained surface and ice levels by an automatic snow depth gauge and manual stake and pit observations. A rise of the ice surface would accelerate the appearance time of bare ice with a low albedo on the surface even if the same amount of snow were removed by melting (Fujita *et al.*, 1996). The figure shows that both snow and ice surfaces are well represented in the model calculation. Figure 2b shows both observed and calculated albedo at 5600 m a.s.l. The calculated albedo corresponds well to the observed albedo for the whole period with only a few exceptions. For instance, the drastic decrease in the albedo that appeared in early May 1993 is not included in the calculated results. Figure 2a and b suggests that the model results are plausible at a given altitude, and Figure 2c confirms that the calculation for the whole glacier area accurately represents the observed glacier runoff. These results are referred to as 'control' results hereafter. In this study, the model has been improved to take into account the effect of a dust layer. The boundaries of snow layers traced in the calculation seen in Figure 2a show the depression of boundaries in the snowpack due to compaction. The effect of lowering albedo will be treated in the next section.

EFFECT OF DUST EVENT TIMING

Sharp drops in the observed albedo are probably caused by dust depositions (Figure 2b), though no relationship between the amount of dust and the surface albedo has actually been measured. In our calculation, the surface albedo will decrease to 0.6 if 'dusted surface' appears at the surface, since sharp drops in the albedo range from 0.5 to 0.7 (Figure 2a). Figures 3 and 4 show that the calculated examples change the dusting date, whereas the other input variables are not different from the control run. Figure 3 depicts dust deposited on 2 May 1993, representing an observed drastic lowering of the albedo. Although the calculated surface albedo declined for several days, the dust was buried by snow and did not reappear on the surface (Figure 3a and b). Glacier runoff will change slightly in the early melting season since the melt amount increases at the lower elevation (Figure 3c). The total amount of glacier runoff for the whole melting season increased by 4% over the control runoff, suggesting that the dust deposition in spring did not significantly affect the glacier runoff. In contrast, the calculated albedo and the snow and ice surfaces showed drastic differences from those in the control run when dust was deposited on 6 June 1993 (Figure 4). A drastic surface lowering from melting often occurs just after dust deposition. Although the dust is initially buried by snowfall, it reappears and accelerates the melting, thus exposing the ice surface with a lower albedo (Figure 4a and b). The resulting glacier runoff exceeds that of the control run throughout the whole melting season (Figure 4c). The total glacier runoff increases by 29% over the control run. However, no change is found in the upper limits of runoff production between the control run and the test run. This implies that the dust event causes no areal extent of melting, but rather an intensive melting in the ablation zone by accelerating removal of snow layer on glacier ice.

The 'seasonal sensitivity' of glacier runoff was examined by changing the dusted date and the albedo of the dusted surface (Figure 5a). The abscissa and ordinate are the date when dust was deposited, and the calculated total glacier runoff (a) and summer mean albedo (b) respectively. Summer mean albedo is obtained by averaging the surface albedo with weighted–area distribution for the period from June to August. Changes in winter do not seriously affect the total glacier runoff, though dust is usually deposited in the winter dry season. On the other hand, the dust depositions in June and July increased the glacier runoff by 40% (in the case of a 0.6 albedo) due to the intense solar radiation during this season. A 10% increase in glacier runoff will be caused by a change of +0.1 °C in annual air temperature or –108 mm water equivalent in annual precipitation (Fujita *et al.*, 2006). It is important to note that such a large impact on glacier runoff might be caused even if dust were deposited for only 1 day. The impact on glacier runoff increases drastically in association with a decrease in the albedo of the dusted surface from 0.7 to 0.5, as shown in Figure 5a. Dust deposition during winter will significantly affect glacier runoff provided that the albedo of the dusted surface is low enough (in the case of a 0.5 albedo). On the contrary, if the dust consists of bright minerals (in the case of a 0.7 albedo), the impact of dust will be negligible even though it was deposited in summer. Temporal changes in summer mean albedo, which are well consistent with total glacier runoff (Figure 6, $r = -0.95$ to -0.97, with a 99% significance level), suggest that dust events indeed affect glacier runoff by changing the surface albedo of the glacier.

CONCLUDING REMARKS

The model calculations, including the scheme for tracking a dusted surface, revealed that a lowering of the albedo by a dusted surface would increase glacier runoff even under the same meteorological conditions. Calculations of seasonal sensitivity revealed that dust depositions during the melting season might cause a drastic mass outflow from the glacier if the dust fell in June and July. Although dust deposition in those two months is thought to be rare because of the humid environment on the central Tibetan Plateau, it is more likely in an arid region such as the west Kunlun Mountains on the southern periphery of the Taklimakan Desert. Sakai *et al.* (2006) reported a strong dust storm event in July 2004 at the July 1st Glacier in the Qilian Mountains on the northern periphery of the Tibetan Plateau. Since meltwater from glaciers contributes significantly to river runoff in dry environments (Ujihashi *et al.*, 1998), it is important to understand how and when dust is transported and deposited on glaciers.

Although the assumption of a constant albedo for a dusted surface is unrealistic, the present study proposed the importance of timing of a dust event on the glacier runoff. For instance, intensive melting caused by the dusted surface will change albedo by flushing smaller size particles and leaving only larger size particles. For more accurate estimation, therefore, a more realistic model is required to estimate the albedo of the dusted surface, which will vary with time after deposition (Conway *et al.*, 1996) and with the course of melting. Additionally, it has been pointed out that microorganisms living in a glacier produce dark material that decreases the surface albedo (Takeuchi *et al.*, 2001). It is also probable that the assumption of ice albedo (0.48 in this study) may affect glacier runoff largely because the ablation area provides most of the melt water. Further study is required on the relation between the quality and the amount of dust, and between the albedo on snow and ice surfaces.

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Figure 1. Albedos of dry (solid line) and wet (broken line) snow versus surface snow density.

Figure 2. (a) Relative levels of surface (solid line), dirt layers (broken lines), and snow-ice interface (gray line) at 5600 m a.s.l. of Xiao Dongkemadi Glacier. Observed surface (gray circles) and snow-ice interface (black circles) are compared with those calculated. (b) Observed (broken line) and calculated (gray line) albedos at the same elevation. (c) Calculated runoff (gray line) accurately represents the estimated runoff (solid line) from observation. A more detailed description is shown in Fujita *et al.* (2006)

Figure 3. (a) Relative levels of surface (solid line), dusted layer (thick broken line), and snow-ice interface (gray line) at 5600 m a.s.l. of Xiao Dongkemadi Glacier when surface was dusted on 2 May in the calculation (arrow). Surface level of the control run is shown as a thin broken line for comparison. (b) Observed and calculated albedos(broken and gray lines in denote respectively). (c) Calculated runoff (solid line) differs slightly from the control result (broken line).

Figure 4. (a) Relative levels of surface (solid line), dusted layer (thick broken line), and snow-ice interface (gray line) at 5600 m a.s.l. of Xiao Dongkemadi Glacier when surface was dusted on 6 June in the calculation (arrow). Surface level of the control run is shown as a thin broken line for comparison. (b) Observed and calculated albedos(broken and gray lines in denote respectively). (c) Calculated runoff (solid line) differs obviously from the control result (broken line).

Figure 5. Seasonal sensitivities of (a) glacier runoff on the changes in dusted date and albedo and (b) summer mean albedo of the glacier. Horizontal and vertical axes denote the dusted date and total glacier runoff (a) and summer mean albedo (b) respectively. Thick, thin, and gray lines denote albedos of dusted surface as 0.7, 0.6 and 0.5 respectively. Runoff amount and summer mean albedo of the control calculation (61.3×10^5 m^3 and 0.762 respectively) are shown as straight broken lines.

Figure 6. Summer mean albedo versus runoff depth. Black and gray dots result from dusted surface with albedo of 0.6 and 0.7 respectively. The result for albedo of 0.5 is not shown.

Figure 1. Fujita

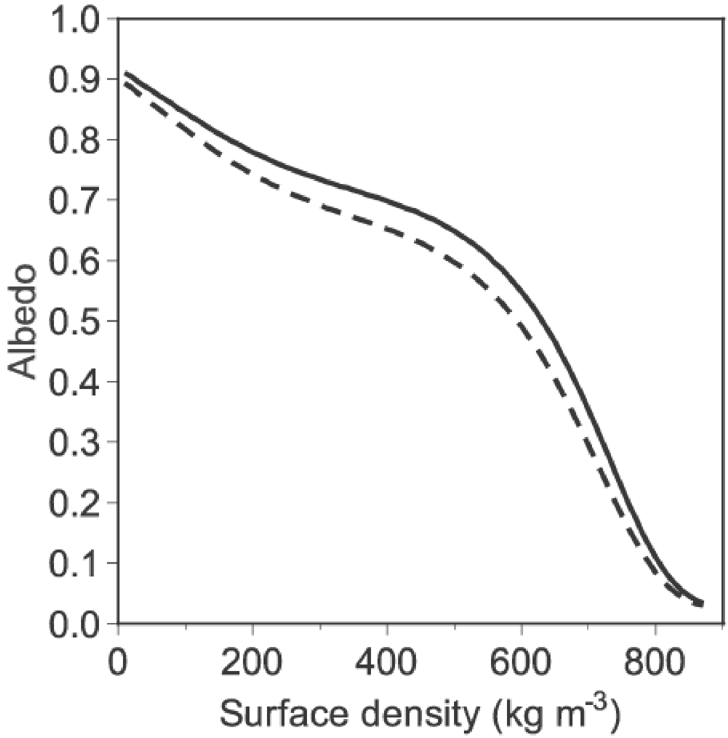
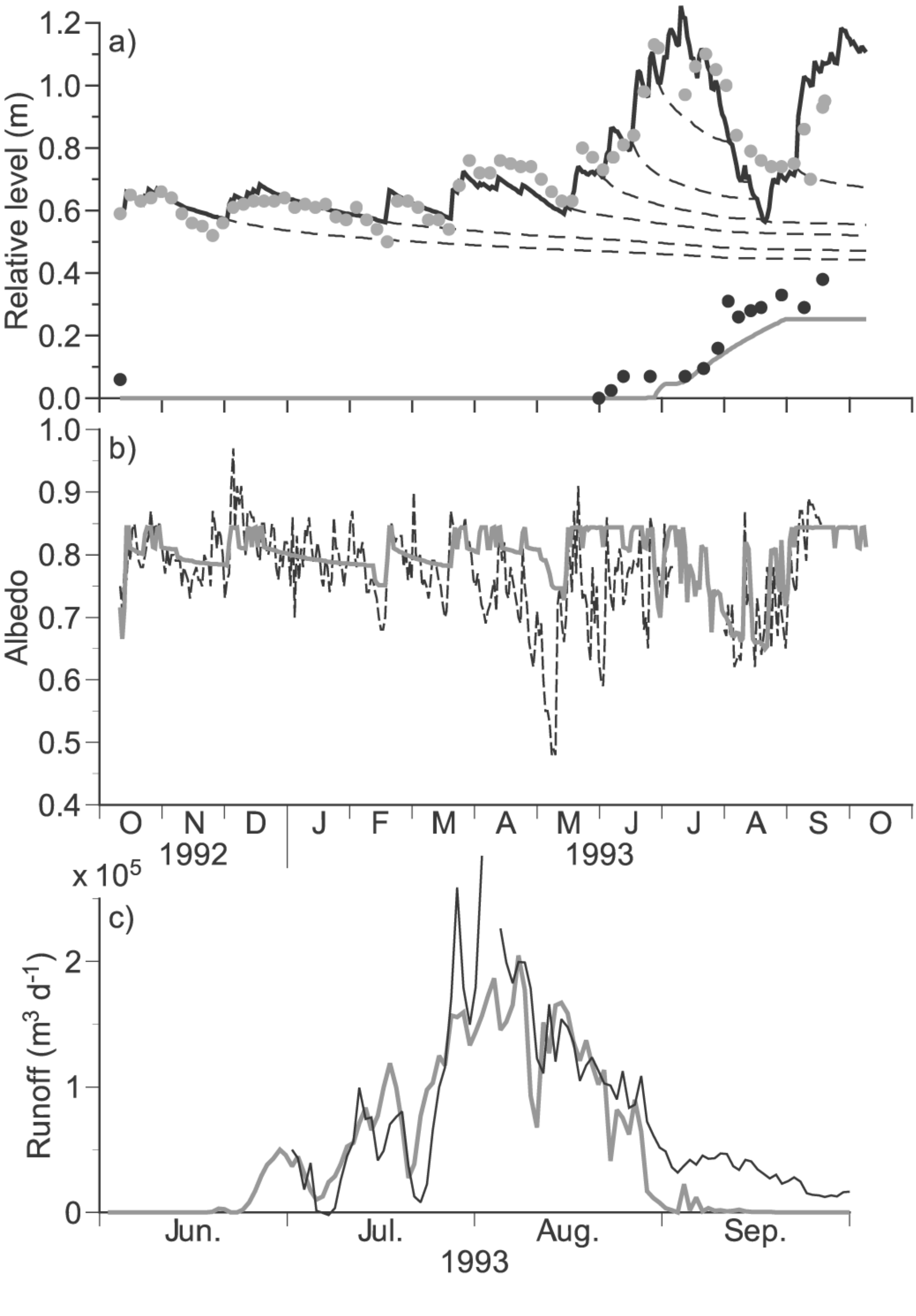
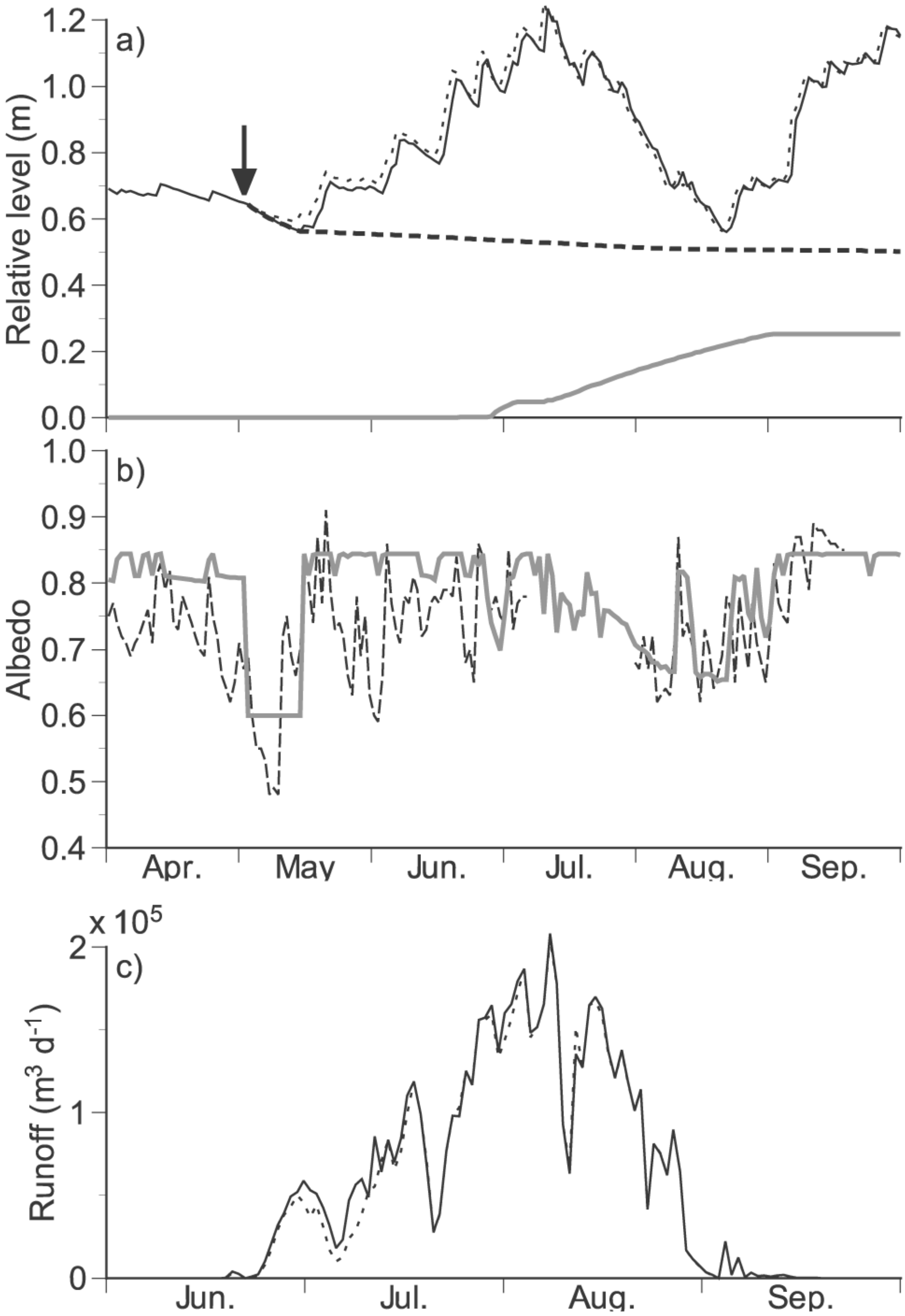


Figure 2. Fujita





a)
b)
c)
Relative level (m)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Albedo
1.0
0.9
0.8
0.7
0.6
0.5
0.4
Apr.
May
Jun.
Jul.
Aug.
Sep.
x 10^5
Runoff (m^3 d^-1)
2
1
0
Jun.
Jul.
Aug.
Sep.

Figure 4. Fujita

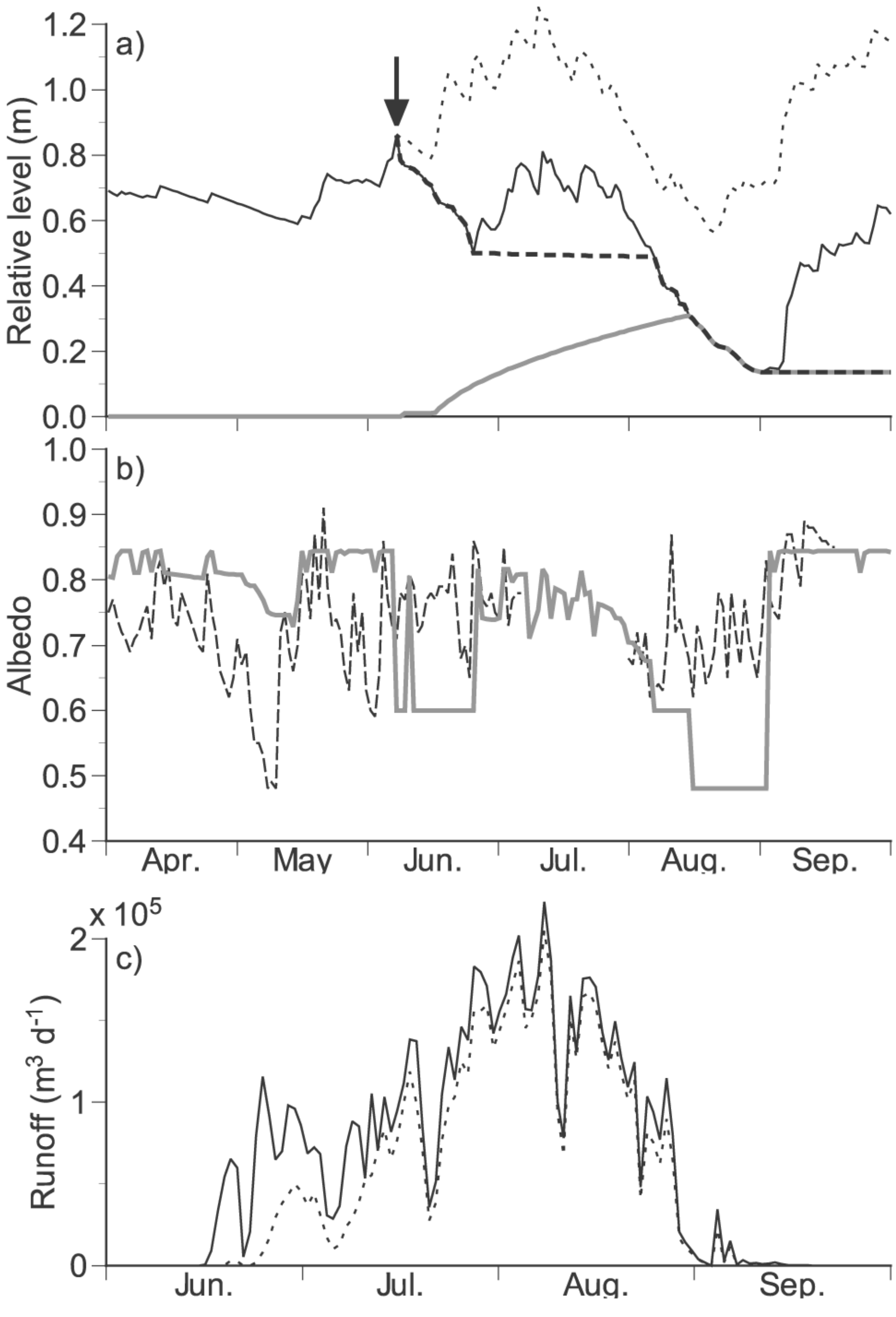


Figure 5. Fujita

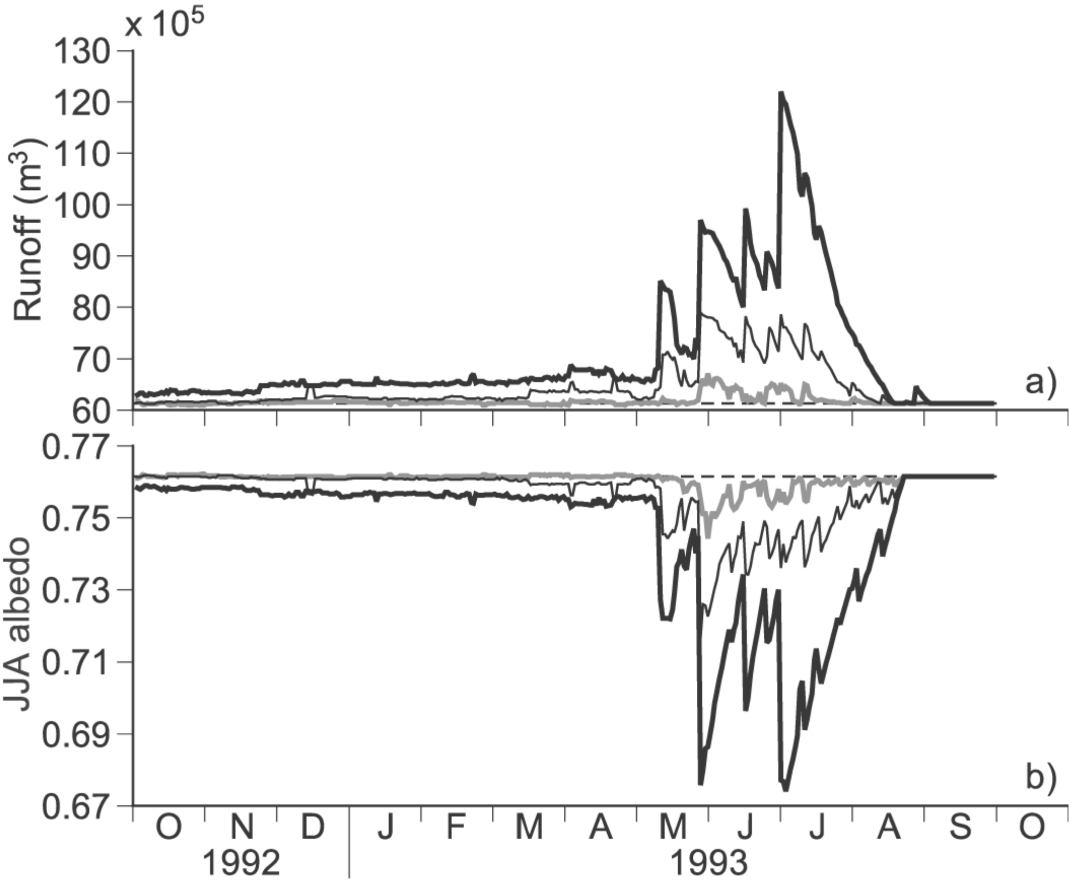


Figure 6. Fujita