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Modeling Glacier Behavior under Different Precipitation Seasonalities

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Abstract

To understand the dependence of glacial features on precipitation, glacier behavior was simulated under different precipitation conditions using a glacier fluctuation model that combined a mass-balance model with a glacier flow model. The results reveal a strong dependence of glacier behavior on precipitation conditions. Glacier volume changes in accordance with both precipitation seasonality and annual precipitation amount. Glacier volume also fluctuates in response to changes in precipitation seasonality even if no change in annual precipitation amount occurs, because of changes in glacier albedo and the volume that is able to accumulate. Furthermore, the accumulation area ratio (AAR) depends not only on the annual precipitation amount, but also on precipitation seasonality. These relationships should be considered when the AAR method is used to reconstruct the past equilibrium line of glaciers. Glacier reactions to temperature change become more sensitive as the amount of annual precipitation increases. Response time is different for each glacier type defined by precipitation seasonality: the winter-precipitation-seasonality type had the longest response time, and the summer-precipitation-seasonality type had the shortest. The difference in the response time of glacier types is larger under arid conditions and smaller under humid conditions. The simulation results in this study underscore the importance of including glacier response to precipitation conditions when estimating glacier reactions to climate change.

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Introduction

Valley glaciers respond rapidly to climate change and are thus important indicators of global warming (Oerlemans and Fortuin, 1992; Oerlemans, 1994). A recent increase in the rate of glacier melting is thought to have contributed significantly to global sea-level rise (Meier, 1984; Dyurgerov and Meier, 1997; Gregory and Oerlemans, 1998; Raper and Braithwaite, 2006). Understanding glacier sensitivity to climate change is critical to predicting glacier behavior (e.g., Jóhannesson, 1997; Oerlemans, 1997; Zuo and Oerlemans, 1997; Schneeberger et al., 2001) and to accurately estimating the amount of global meltwater that will be produced and the extent of sea-level rise that will result from future climate change (e.g., Oerlemans et al., 1998). Information on glacier behavior is also useful for understanding the record of past glacial coverage (e.g., Anderson and Mackintosh, 2006; Yamaguchi et al., 2008). Most studies have treated glaciers as simple systems in which accumulation is controlled by temperature alone, with no strong precipitation seasonality (here referred to as a ''no-seasonality-type glacier''). Such work (e.g., Dyurgerov and Meier, 2000; Dyurgerov, 2003) has addressed the behaviors of mountain glaciers using detailed measurements from certain areas only (e.g., Scandinavia, the Alps, and mountains in the U.S.A., Canada, and former Soviet Union). Information on glacier behavior in other important areas (e.g., High Asia, Andes) is lacking. These latter areas may have different climate conditions from the better-studied areas and hence their glaciers may not be dominated by the no-seasonality-type. In fact, Fujita (2008a) suggested that the world's glaciers could be of various types, including both no-seasonality-type and other glacier types that are subject to strong precipitation seasonality, in which mass balance is controlled by seasonality in temperature and precipitation. Fujita (2008b) showed that the mass balance of glaciers with summer-precipitation-seasonality (sum-type glacier), such as those in the Himalayas, responds more sensitively to climate change than does that of glaciers with winter-precipitation-seasonality (win-type glacier). Determining how precipitation conditions (both annual amount and seasonal distribution) affect glacier behavior may be helpful in understanding glacier regimes in areas with sparse measurements. Indeed, Fujita and Nuimura (2011) noted that glaciers in the Nepal Himalaya showed spatially heterogeneous wastage resulting from geographically variable precipitation conditions. The timing and amount of precipitation are clearly fundamental to realistic estimations of global glacier melt.

Naito et al. (2001) used a glacier fluctuation model that combined a mass-balance model and a glacier dynamics model to compare the responses of sum-type and win-type glaciers in the Himalayas of Nepal to climate change. The altitudinal distribution of mass balance was calculated using an empirical mass-balance equation based on measurements (Ageta, 1983; Ageta and Kadota, 1992), and simulations were conducted under only one annual precipitation condition (1600 mm a^{-1}). Their results indicated that sum-type glaciers respond more quickly to temperature and precipitation changes than do win-type glaciers. Although their results were very helpful for understanding the different responses of sum-type and win-type glaciers to climate changes, an empirical equation was used to estimate mass balance, and thus it is unclear whether their results can be applied to glacier behaviors in other regions. In the present study, glacier behaviors are simulated using different precipitation seasonalities and also several annual precipitation amounts in a glacier fluctuation model. The results are discussed

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with a focus on the dependence of glacier behavior on precipitation conditions.

Glacier Fluctuation Model

The glacier fluctuation model developed by Yamaguchi et al. (2008) is revised in this study. The one-dimensional model has 50-m grid resolution, and the flowline is along the x-axis. The transverse cross section S at all grid points is assumed to be rectangular, with valley width W_s set at 500 m. The dynamic behavior of the glacier is described in terms of changes in ice thickness H, which are calculated from the mass continuity equation. Given that the glacier is assumed to be composed of ice of uniform density (ρ_i), the conservation equation for the ice volume is

$$\frac{\partial S}{\partial t} = -\frac{\partial}{\partial x}(US) + B_n W_s, \quad (1)$$

where U is the depth-averaged ice velocity at x, S is the area of the cross section, and B_n is the net balance on the glacier surface. Melting of ice at the bottom is ignored. In general, the surface ice velocity U_s is the sum of the internal ice deformation U_d and the basal motion U_b. Parameterization of U_b is still controversial because U_b is one of the most poorly understood aspects of glacier dynamics. For these reasons, U_b is omitted in this study, to simplify the model. Therefore

$$U = U_d = f_1 \frac{2A}{n+1}(-f_2 \rho g \sin\beta)^n H^{n+1}, \quad (2)$$

where β and g are the surface slope and acceleration due to gravity, respectively, and A and n are parameters of the flow law of ice. In this study, A is given the value of 1.6×10^{-15} s^{-1} kPa^{-3} at ice temperature of -5 °C (Paterson, 1994), and n is 3. The ratio of the average speed through the ice thickness (f_1) is set at 0.8. The value of the so-called shape factor accounting for lateral drag (f_2) is estimated using the following regression equation for rectangular cross sections, as shown by Naito et al. (2001) based on the work of Nye (1965):

$$f_2 = 1 - \frac{0.30\frac{W_s}{2H} + 0.58\frac{W_s}{2H}}{2}. \quad (3)$$

To solve Equation (1), surface mass balance should be calculated using a mass-balance model. This study uses the energy/mass-balance model developed by Fujita and Ageta (2000) and revised by Fujita (2007, 2008a, 2008b). This model calculates the daily energy balance at the glacier surface using the energy budget approach. The energy balance includes radiation balance, sensible and latent turbulent heat fluxes, heat conduction into the glacier, and mass balance consisting of snow accumulation, melting, refreezing, and evaporation, as follows:

$$\max[Q_M, 0] = (1 - a_l)R_S + R_L - \min[\sigma T_S^4; 315.6] + Q_S + E_V l_e + Q_G. \quad (4)$$

Energy for melting (Q_M) is obtained if the right-hand side of the equation is larger than zero. Absorbed shortwave radiation is calculated from surface albedo (a_l) and downward shortwave radiation (R_S). Downward longwave radiation (R_L) is calculated from air temperature, relative humidity, and the ratio of downward shortwave radiation to that at the top of atmosphere using an empirical scheme (Kondo, 1994). Upward longwave radiation is obtained by the Stefan-Boltzmann constant (σ) and surface temperature in Kelvin (T_S) assuming a blackbody for the snow/ice surface. A melting surface ($T_S = 0$ °C) releases upward longwave radiation of 315.6 (W m^{-2}). Sensible (Q_S) and latent ($E_v l_e$) turbulent heat fluxes are obtained by bulk methods, and l_e is the latent heat for evaporation of water or ice, which is determined from the surface temperature. Heat conducted into the glacier ice (Q_G) is obtained by calculating the temperature profile of the snow layer and/or glacier ice. Absorption of shortwave radiation in snow and ice, which increases their temperature, is accounted for in the model. All energy components are positive when fluxes are directed downward. Mass balance (B) at any location on the glacier is calculated as

$$B = Ca - \frac{Q_M}{l_m} + E_V + R_F \quad (5)$$

Solid precipitation (Ca, positive sign), which is determined as a function of air temperature, is equivalent to accumulation over the glacier. Mass is removed from the glacier as meltwater (Q_M/l_m, positive sign) and evaporation (E_V, negative sign). Sublimation evaporation (ice to vapor), sublimation condensation (vapor to ice), and condensation (vapor to water) are calculated as different expressions of evaporation. Positive and negative signs of E_v correspond to condensation and evaporation, respectively. Phases against vapor, water, or ice are distinguished by positive or negative surface temperature; l_m is the latent heat for melting ice. A part of the meltwater is fixed to the glacier by refreezing (R_F, positive sign) if the glacier ice is cold enough (Fujita et al., 1996). The refreezing amount is calculated in the model by considering the conductive heat into glacier ice and the presence of water at the interface between the snow layer and glacier ice. Refreezing during both winter and other shorter cooling events is also calculated. Transformation from snow to glacier ice is mainly caused by the refreezing of percolated meltwater rather than by snow compaction. Special attention is paid to the treatment of the surface albedo (α_l), which varies enormously in space and time even on a single glacier (albedo declines down-glacier and during the course of the melt season). The model empirically calculates albedo according to the surface density, which changes with snow compaction. Detailed descriptions of the model schemes have been provided by Fujita and Ageta (2000), Fujita et al. (2007), and Fujita (2007).

Simulation Conditions

To evaluate the influence of precipitation characteristics on glacier behavior, idealized meteorological input data were used to calculate glacier mass balance (Fig. 1). Air temperature and solar radiation (assumed for the northern hemisphere, 30°N; 4000 m a.s.l.) had clear seasonality. Seasonal precipitation patterns were set with the peaks at the end of January (win-type), the end of August (sum-type), the middle of April (spr-type), the middle of October (atm-type), and with no peak (no-seasonality-type). Multiplying the precipitation ratio by the annual precipitation gave the amount of daily precipitation. Annual precipitation amount fluctuated from 500 to 6000 mm a^{-1} (500, 1000, 1500, 2000, 2500, 3000, 4000, 5000, and 6000 mm a^{-1}). The purpose of this study was to understand the behavior of normal glaciers in which the dominant ablation process is melting; glaciers in extremely dry

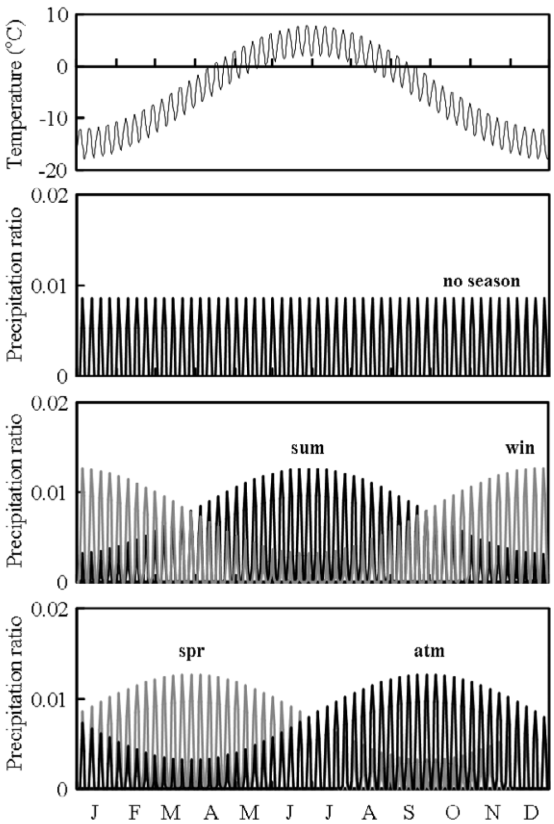

FIGURE 1. Meteorological conditions for calculation of mass balance under several precipitation conditions. The precipitation ratio is daily precipitation divided by annual precipitation. No season: no-seasonality-type glacier, atm: autumn-type glacier, win: winter-type glacier, spr: spring-type glacier, sum: summer-type glacier.

climates in which the main process of glacier ablation is sublimation (Fujita et al., 2011) were not considered. Other meteorological variables were set as simple annual and weekly period patterns to represent both seasonality and synoptic climate. Because the combination of weekly peaks in precipitation and air temperature significantly affects calculations of mass balance, the seasonal peak of precipitation was changed ±3 days from the primary settings, and the 7-day averages of the output were used for mass balance input thereafter. Weekly patterns of relative humidity and transmissivity were also linked to precipitation (e.g., high humidity and low transmissivity with the precipitation peak, and vice versa). Such relations are also observationally supported (e.g. Matsuda et al., 2006; Sakai et al., 2009). Calculations were performed for the annual cycle from October to September. Initial temperature within the glacier ice was set at the annual mean air temperature from the surface to 60 m depth, at 0.5 m depth intervals. A 7-year iterative calculation was made to allow the ice temperature to equilibrate, and the warming (cooling) tests were begun in the 11th year. The altitudinal dependence of mass balance was introduced by changing the annual mean air temperature by 6.0 °C km^{-1} at increments of 50 m from 0 to 6000 m a.s.l.

Because the aim of this study was to examine the influence of precipitation conditions on glacier behavior, simple geographical conditions were assumed for all precipitation conditions: a mountain with a constant grade of 0.1 and a peak bedrock altitude of 6000 m a.s.l. The glacier form was calculated using Equation (1) with the calculated mass balance for each day.

Dependence of Steady-State Glacier Regimes on Precipitation Conditions

EQUILIBRIUM LINE ALTITUDE AND VOLUME

Starting from an initial ice-free condition, the model was run until it reached a steady state for each glacier type. A steady state was defined as the glacier form in a state in which its volume does not change over a long time span (5000 years in this study) under constant climate conditions. Figure 2, part a, shows the equilibrium line altitude (ELA) calculated from the distribution of mass balance and steady-state glacier volume for a no-seasonality-type glacier under each annual precipitation amount. To clarify the influence of precipitation seasonality on glacier behavior, simulation results for a no-seasonality-type glacier are compared with those for glaciers having precipitation seasonality. The ELA for a no-seasonality-type glacier decreases from 4800 to 3800 m with increased

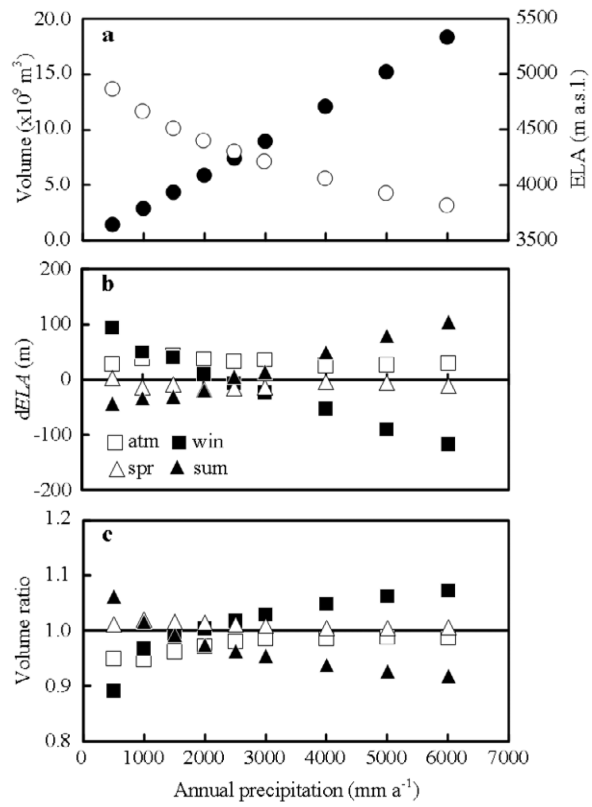

FIGURE 2. Calculated steady-state for each glacier type for several annual precipitation values. (a) ELA and glacier volume of a no-seasonality-type glacier, with several annual precipitation values. (b) Differences in ELA between no-seasonality-type and other glaciers (*dELA*), with several precipitation values. *dELA* represents the ELA of a particular glacier type minus that of a no-seasonality-type glacier. (c) Ratio of volume between a no-seasonality-type glacier and other seasonality-type glaciers (V_{ratio}), with several precipitation values. V_{ratio} is calculated as the volume of a given seasonality-type glacier divided by that of a no-seasonality-type glacier. atm: atm-type glacier, win: win-type glacier, spr: spr-type glacier, sum: sum-type glacier.

annual precipitation, and the glacier volume changes from 1.4×10^9 to 1.8×10^{10} m^3 with the lower ELA.

Figure 2, part b, shows ELA variations under several precipitation conditions; the values were standardized by subtracting the ELA of the no-seasonality-type glacier from that of each seasonality-type glacier (*dELA*) for each annual precipitation amount. This figure presents the seasonality types as two groups. In the group composed of sum- and win-type glaciers, the relationship between their ELA and that of the no-seasonality-type glacier depends on the annual precipitation amount. The sum-type glacier has a lower ELA than the no-seasonality-type glacier under arid conditions, but the ELA of the sum-type glacier becomes higher than that of the no-seasonality-type glacier under more humid conditions. Such dependence also appears in the win-type ELA, although its fluctuation trend is opposite that of the sum-type. On the other hand, for the group composed of spr- and atm-type glaciers, the relationship between each ELA and that of the no-seasonality-type glacier does not change with the annual precipitation amount. The ELA of the spr-type glacier is always lower than that of the no-seasonality-type glacier, whereas the ELA of the atm-type glacier maintains a higher value than that of the no-seasonality-type glacier under all annual precipitation amounts. Differences in the volume accumulated do not explain all of the behavior variation in ELAs because both spr- and atm-type glaciers have the same accumulation amount under the same annual precipitation setting relative to air temperature. Under arid conditions, snow accumulation during the melt season makes the surface albedo higher and decreases the ablation amount dramatically. Therefore, the sum-type glacier has a lower ELA than the other glacier types. Although the no-seasonality-type glacier receives precipitation in summer, the albedo change effect resulting from snow accumulation is limited because the amount of precipitation in summer is very small. The spr-type glacier does not receive precipitation in summer, but spring snowfall should permit maintenance of a higher albedo in early summer and decrease the amount of ablation that takes place. Because autumn and winter snowfalls do not affect albedo in summer, atm- and win-type glaciers have higher ELAs than glaciers in arid conditions. In more humid settings, increased annual precipitation volume in sum-, spr-, and no-seasonality-type glaciers does not cause lowered ELAs because the temperature at the ELA is warmer when the ELA is lower, and the warmer temperature forces precipitation to fall as rain. In contrast, increased precipitation directly affects winter accumulation amount in the win-type glacier (Fujita, 2008b).

To examine the dependence of glacier mass balance on precipitation seasonality and amount, the altitudinal distribution of net balance (B_n) of each glacier type under an arid condition (500 mm a^{-1}) and a humid condition (6000 mm a^{-1}) were compared as shown in Figure 3, parts a and b. In this figure, the values (dB_n) were standardized by subtracting the B_n of the no-seasonality-type glacier from that of each seasonality-type glacier for each altitude. The values of dB_n for all glacier types in both conditions are almost 0 at the higher altitude, where the temperature is lower. These results indicate that precipitation seasonality does not affect glacier mass balance at the lower temperature. In the arid condition, dB_n of the sum-type glacier shows positive value around the ELA, and the sign of dB_n of the sum-type glacier then changes from positive to negative because B_n of the sum-type glacier decreases more

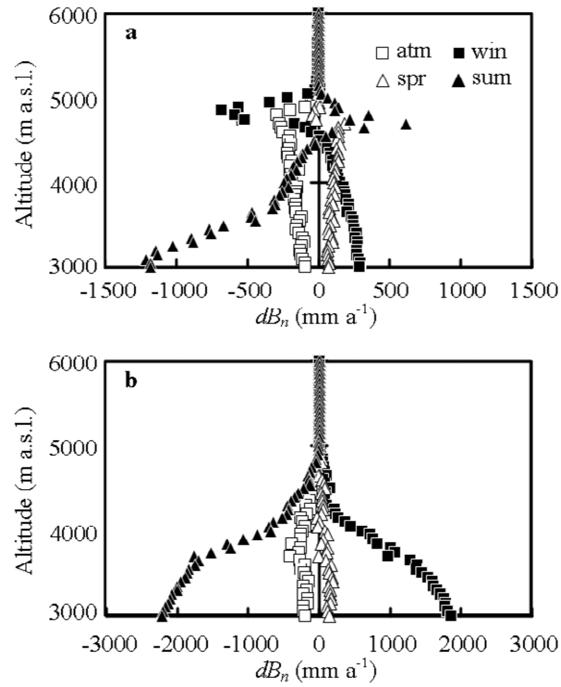

FIGURE 3. Net balance distributions of glaciers having precipitation seasonality compared with that of a glacier having no precipitation seasonality (no-seasonality-type glacier). dB_n indicates the net balance of each glacier minus that of the no-seasonality-type glacier at each altitude. (a) Arid condition (annual precipitation is 500 mm a^{-1}). (b) Humid condition (annual precipitation is 6000 mm a^{-1}). atm: atm-type glacier, win: win-type glacier, spr: spr-type glacier, sum: sum-type glacier.

rapidly than B_n of the no-seasonality-type glacier with altitude decrease in the ablation area. On the other hand, dB_n of the win-type glacier changes from a negative to a positive sign around the ELA. The sign of dB_n of the spr- and atm-type glaciers basically does not change, but the peaks of dB_n for both types appear around the ELA. These results imply that the effect of snowfall-induced albedo increase on glacier mass balance is strongest around the ELA. Under humid conditions, dB_n for all glacier types does not change sign even around the ELA. This result implies that the effect of snowfall-induced albedo increase on glacier mass balance is not the dominant factor in glacier mass balance under humid conditions. This dependence of the albedo effect on precipitation amount causes the change in the behavior of *dELA* at sum- and win-type glaciers. These results show the complex behavior of the ELA, which strongly depends on both annual precipitation amount and precipitation seasonality through the effects of albedo variation and accumulation volume. Any discussion of glacier characteristics that is based only on annual precipitation and annual mean air temperature at the ELA (e.g., Ohmura et al., 1992) is probably incomplete because of the strong dependence of the ELA on precipitation seasonality. Moreover, the behavior of ELAs based on measurements of no-seasonality-type glaciers is not directly applicable to other types of glaciers.

Figure 2, part c, compares glacier volume and precipitation conditions. The volumes for each seasonal type of glacier were standardized by dividing by the volume of the no-seasonality-type glacier at each annual precipitation amount (V_{ratio}). Fluctuations of

V_{ratio} for each glacier type resemble those of the *dELA* and reveal two types of glaciers: one is a win- and sum-type glacier, and the other is an atm- and spr-type glacier. These results suggest that the development of large glaciers is strongly dependent on precipitation conditions. For example, glaciers in arid conditions (e.g., Tibet, the Andes) may become large if the annual precipitation maximum is in summer, whereas glaciers in humid conditions (e.g., Alaska, Patagonia) can develop the largest volume when the annual precipitation maximum is in winter. As shown in Figure 2, part c, glacier volume strongly depends not only on annual precipitation amount but also on precipitation seasonality. Glaciers should react to annual precipitation seasonality change even if the annual precipitation amount does not change. Comparison of glacier reaction to precipitation seasonality (i.e., changes in the timing of maximum precipitation) shows that the range of volume change versus precipitation seasonality change increases with increased annual precipitation amount for all glacier types because the volume differences among the different glacier types increase with annual precipitation increase (Fig. 2). Although glacier types behave differently under each precipitation condition at a decadal scale, the simulation results of glacier response to changes in precipitation seasonality indicate that all glacier types change rapidly until about 400 years after the seasonality change, after which the volume change ratio is reduced. A steady state is reached under the new precipitation conditions after approximately 1000 years. This demonstrates that interpretations of observed glacier retreat or advance data should include not only the effects of temperature and/or annual precipitation fluctuation, but also any change in precipitation seasonality.

ANNUAL MASS TURNOVER

Annual mass turnover (α) is a characteristic parameter of glaciers (Meier, 1984). The original definition of α is as follows:

$$\alpha = \frac{(|b_w| + |b_s|)}{2}, \tag{6}$$

where b_w is the specific winter mass balance, and b_s is the specific summer mass balance. As noted by Dyurgerov and Meier (1999), the differences between annual snow/ice accumulation (c_t) and b_w, and between annual ablation (a_t) and b_s are substantial under some climate conditions. This study compares glaciers under various seasonal precipitation patterns, with glaciers experiencing accumulation in various seasons. This requires a new definition of annual mass turnover (α):

$$\alpha = \frac{(|c_t| + |a_t|)}{2}, \tag{6}$$

where c_t and a_t are the values calculated for steady-state conditions.

Figure 4, part a, shows the values of α for each glacier type. The values of α for all glaciers increase with increased annual precipitation. The ratio (R_p), obtained by dividing α by each annual precipitation amount, seems to be independent of annual precipitation amount, and there is a linear relation between α and annual precipitation amount (Fig. 4, part a). The value of R_p is largest (0.88) for win-type glaciers and smallest (0.65) for sum-type glaciers. Given the definition of α [Equation (7)], R_p shows how the percentage of annual precipitation is used for accumulation, which

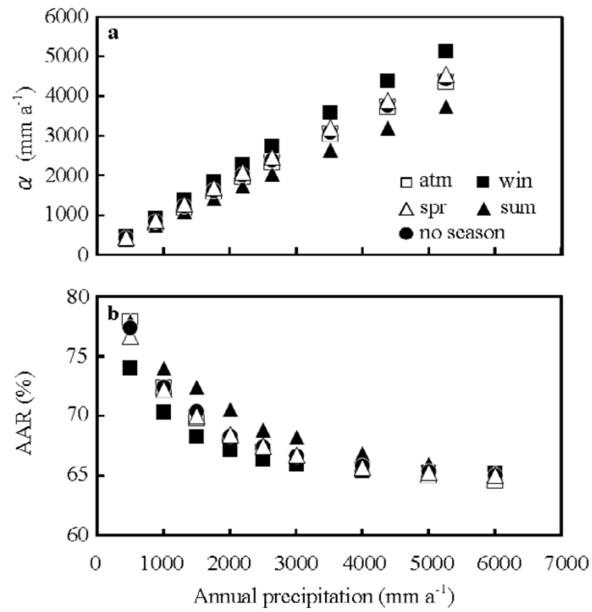

FIGURE 4. Glacier regimes for each precipitation condition. (a) Comparison of annual mass turnover (α) for each precipitation condition. (b) Comparison of accumulation area ratio (AAR) for each precipitation condition. sum: sum-type glacier, atm: atm-type glacier, spr: spr-type glacier, win: win-type glacier, no season: no-seasonality-type glacier.

is averaged over the glacier surface, because $|c_t|$ should be equal to $|a_t|$ under steady-state conditions. Viewed from this perspective, a constant value of R_p indicates that the percentage of total annual precipitation that accumulates, averaged over the glacier surface, is independent of the annual precipitation amount even though the values of R_p depend on the season in which the precipitation is delivered.

Under identical annual precipitation amounts, win-type glaciers always have the largest values, sum-type glaciers have the smallest values, and the other three glacier types (atm-, spr-, and no-seasonality-type glaciers) generally have the same values. The value of a_t for win-type glaciers should be largest because the surface in the middle and lower parts of a win-type glacier has lower albedo during the melt season due to the absence of snowfall. The c_t of win-type glaciers is highest because the full annual precipitation amount is delivered as snow in the middle and upper parts of the glaciers. In contrast, at least some of the annual precipitation delivered to other glacier types falls as rain, which cannot contribute to accumulation. This factor should dominate the mass balance of sum-type glaciers, which always have the smallest value of α.

ACCUMULATION AREA RATIO

The accumulation area ratio (AAR), which is calculated by dividing the accumulation area by the total glacier area (Meier and Post, 1962; Meierding, 1982; Hawkins, 1985), is a way to depict glacier attributes. Dyurgerov (2003) indicated that the AAR has large spatial variability, from 40% to 70%, based on a large data set, and also implied that a single, fixed AAR value should not be applied to different regions. The AAR depends on precipitation conditions (Fig. 4, part b), such that AAR decreases from 78% to

65% with increased annual precipitation amount. Furthermore, the AAR also differs with precipitation seasonality. The AAR of sum-type glaciers is largest, and the AAR of win-type glaciers is smallest under the same annual precipitation amount. The difference between AARs under the same annual precipitation amount is large in an arid setting, but decreases when annual precipitation increases. The different trends in AAR fluctuation versus change in the annual precipitation amount should cause contradictory results, with the win-type glaciers having larger volumes than the sum- or no-seasonality-type glaciers, even though the win-type glaciers have higher ELA than the latter glacier types when annual precipitation is 2000 mm a^{-1} (Fig. 2, parts b and c). These results imply that the glacier type with the lowest ELA does not necessarily have the largest volume under the same annual precipitation amount.

The AAR method has been used to reconstruct past ELAs and environmental conditions (e.g., Aoki, 2000; Ono et al., 2005). Given that the AAR depends on the annual precipitation conditions (Fig. 4, part b), reconstructing past ELAs using the AAR method and calculated results for win- and sum-type glaciers can reveal the influence of fluctuating AARs due to different precipitation conditions. First, the influence of AAR dependence on the annual precipitation amount is estimated. The AAR values of sum- and win-type glaciers with precipitation of 500 mm a^{-1} are 78% and 74%, respectively, whereas they are 65% (sum-type) and 65% (win-type) for precipitation of 6000 mm a^{-1}. The differences in AAR with 500 mm a^{-1} and 6000 mm a^{-1} conditions are 12% for the sum-type glacier and 9% for the win-type glacier. Thus, if the ELA of a glacier at 500 mm a^{-1} of precipitation is reconstructed using AAR values of 6000 mm a^{-1} of precipitation, the reconstructed ELA will be 4985 m a.s.l. for sum-type and 5058 m a.s.l. for win-type glaciers. However, their true ELAs, as determined from the altitudinal distribution of mass balance, are 4825 m (sum-type) and 4960 m a.s.l. (win-type). Therefore, the reconstructed ELA of a sum-type glacier, without considering dependence on annual precipitation amount, is approximately 160 m higher than its true ELA, and that of a win-type glacier is approximately 98 m higher than its true ELA. The AAR changes sensitively in an arid condition (Fig. 4, part b), and thus it is important to consider the dependence of AAR on annual precipitation amount when reconstructing the ELA of a glacier located in an arid condition using the AAR method.

The influence of AAR dependence on precipitation seasonality can be examined. The difference in AAR (*dAAR*), defined as the AAR of sum-type glaciers minus that of win-type glaciers (which is considered the largest error caused by precipitation seasonality at each precipitation amount), is largest (4.1%) with annual precipitation of 1500 mm a^{-1} and almost 0% with precipitation of 6000 mm a^{-1} (Fig. 5). Assuming a steady-state sum-type glacier, there should be differences between the true ELA and the reconstructed ELA using the AAR of a win-type glacier because of the dependence of AAR on precipitation seasonality. To address errors that result from precipitation seasonality, the term $dELA_{reconst}$ is introduced, which is the true ELA of a sum-type glacier minus the reconstructed ELA using the AAR of a win-type glacier (Fig. 5). The maximum error resulting from precipitation seasonality is 89 m at a precipitation amount of 2000 mm a^{-1}. The error becomes approximately 0 m at 6000 mm a^{-1} of precipitation.

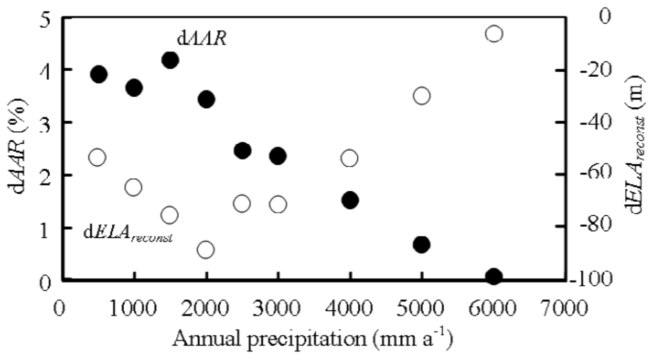

FIGURE 5. Differences in AAR and reconstructed ELA between sum- and win-type glaciers. dAAR **indicates the sum-type AAR minus the win-type AAR.** ***dELA$_{reconst}$*** **represents the reconstructed ELA for a sum-type glacier using the sum-type AAR minus the reconstructed ELA of the sum-type glacier using the win-type AAR.**

These results indicate that the influence of annual precipitation characteristics, such as the amount and seasonality of precipitation, should be considered when the AAR method is applied to reconstruct the past ELA of a glacier, especially in an arid condition.

Dependence of Glacier Response to Temperature Change on Precipitation Conditions

To understand qualitatively the time-scales of glacier fluctuation, Oerlemans (1998) proposed the following time scale:

Volume response time (τ_{rV}): The climatic state is changed stepwise from C_1 to C_2. The corresponding changes in equilibrium glacier volume are V_1 and V_2. The response time is now the time a glacier needs to attain a volume of $V_2 - (V_2 - V_1)/e$.

Here, e is Napier's number. Using this volume response time (τ_{rV}), glacier response under different precipitation conditions can be considered in the context of temperature changes.

Figure 6, part a, shows changes in $\tau_{rV\pm 1K}$ for a no-seasonality-type glacier relative to temperature change ($\pm$1 K). The values of $\tau_{rV\pm 1K}$ decrease with increased annual precipitation amount, but the gradients of $\tau_{rV\pm 1K}$ against change in annual precipitation amount ($d\tau_{rV\pm 1K}/dp$) express a different trend relative to temperature change. The $d\tau_{rV\text{-}1K}/dp$ sensitively decreases with increased annual precipitation amount in arid conditions; the $d\tau_{rV+1K}/dp$ shows only small changes, although it decreases slightly with increased annual precipitation in arid conditions. In contrast, the values of $d\tau_{rV\pm 1K}/dp$ become smaller in humid conditions. The difference between $\tau_{rV\pm 1K}$ decreases with increased annual precipitation amount, but τ_{rV+1K} is always smaller than $\tau_{rV\text{-}1K}$ under the same annual precipitation amount. These results indicate that a no-seasonality-type glacier responds more rapidly to temperature rise than to temperature fall, even if the temperature fluctuation is of the same magnitude. This trend is especially pronounced for glaciers in arid conditions.

Figure 6, parts b and c, shows variations in $\tau_{rV\pm 1K}$ at each seasonality-type glacier. The values in Figure 6, parts b and c, were standardized by subtracting the $\tau_{rV\pm 1K}$ of the no-seasonality-type glacier from that of each seasonality-type glacier for each annual precipitation amount ($d\tau_{rV\pm 1\mathrm{K}}$). The $d\tau_{rV+1K}$ at win-type glaciers is positive under all precipitation amounts, whereas that for sum-

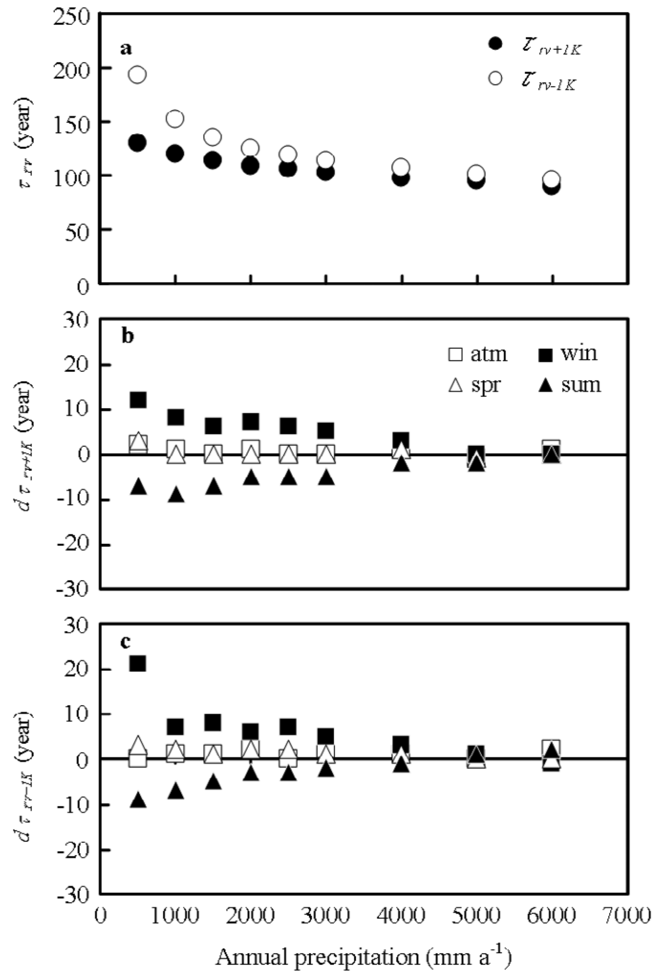

FIGURE 6. Volume response time versus temperature change of ±1 K for each precipitation condition. (a) Volume response times of +1 K (τ_{rV+1K}) and −1 K (τ_{rV-1K}) of the no-seasonality-type glacier, with several annual precipitation values. (b, c) Differences in $\tau_{rV\pm1K}$ between the no-seasonality-type glacier and other-seasonality-type glaciers ($d\tau_{rV\pm1K}$), with several precipitation values. $d\tau_{rV\pm1K}$ represents the $\tau_{rV\pm1K}$ of a seasonality-type glacier minus that of a no-seasonality-type glacier. atm: atm-type glacier, win: win-type glacier, spr: spr-type glacier, sum: sum-type glacier.

type glaciers is negative. The maximum $d\tau_{rV+1K}$ for sum-type glaciers is at −9 years with 1000 mm a^{-1}, and that for win-type glacier is at 12 years with 500 mm a^{-1} of precipitation. In contrast, the $d\tau_{rV+1K}$ values for atm- and spr-type glaciers are almost 0, which indicates that the τ_{rV+1K} values of atm- and spr-type glaciers are almost the same as the τ_{rV+1K} of a no-seasonality-type glacier with the same precipitation amount. The $d\tau_{rV+1K}$ for all glaciers, including win- and sum-type glaciers, approaches 0 years when the annual precipitation amount increases; in other words, the τ_{rV+1K} for all glacier types approaches the same response time under humid conditions. Although the values of $\tau_{rV\text{-}1K}$ are much larger than those of τ_{rV+1K} under arid conditions, the trend of variation in d$\tau_{rV\text{-}1K}$ seems to be basically similar to that of dτ_{rV+1K}. Values of $\tau_{rV\text{-}1K}$ for the sum-type glacier (win-type glacier) are shortest (longest) under the same annual precipitation amount and the $d\tau_{rV\text{-}1K}$ for all glacier types also approach 0 years with increased annual precipitation amount.

Figure 7 shows mass balance component changes (snowfall amount, ablation amount, and albedo) against temperature change (±1 K) for win- and sum-type glaciers. In Figure 7, parts a and b, the change in snowfall amount with change in temperature (±1 K) is given at each altitude under different annual precipitation volumes: an arid condition with 500 mm a^{-1} (Fig. 7, part a) and a humid condition with 6000 mm a^{-1} (Fig. 7, part b). R_{sf} indicates the snowfall amount at each altitude after a temperature change, divided by the snowfall amount before the temperature change. The response of precipitation phase change (snow or rain) to temperature fluctuation is different for win-type and sum-type glaciers. The large amount of precipitation is delivered to sum-type glaciers in the highest temperature season, and thus small temperature changes strongly affect snowfall amount. Snowfall in win-type glaciers is not strongly affected by temperature change because the precipitation is delivered predominantly in the lowest temperature season. Figure 7, parts c and d, shows the ablation amount change with temperature change (±1 K) at each altitude. d_{ab} presents the value subtracting ablation amount at each altitude before a temperature change from the ablation amount at each altitude after a temperature change; a positive (negative) value indicates increase (decrease) of the ablation amount. Figure 7, parts c and d, shows results for arid (500 mm a^{-1}) and humid (6000 mm a^{-1}) conditions, respectively. Comparing Figure 7, parts c and d, the distribution patterns of d_{ab} is similar: maximum change in ablation amount occurs around the ELA for all glaciers. Examining the change ratio of d_{ab}, d_{ab} under arid conditions changes markedly with altitude change, whereas under humid conditions d_{ab} changes gently with altitude change. Comparing win- and sum-type glaciers, the absolute value of d_{ab} of the sum-type glacier is larger than that of the win-type glacier under both precipitation conditions. Figure 7, parts e and f, shows albedo change with temperature change (±1 K) at each altitude. R_{al} indicates annual mean albedo at each altitude after a temperature change, divided by annual mean albedo before the temperature change. Comparing Figure 7, parts e and f, the change ratio of surface albedo under arid conditions is obviously larger than that under humid conditions in both glacier types. Comparing the win- and sum-type glaciers, the fluctuation in change ratio of the surface albedo of the sum-type glacier is larger than that of the win-type glacier under the same annual precipitation.

The reasons for the significant difference in the responses of the glacier types can be examined using these results. In arid conditions, a change in precipitation phase strongly affects melting by changing the surface albedo, and this albedo change effect is most dominant in the sum-type glacier, for which the snow amount and surface condition sensitively change with temperature fluctuation because of the concentration of precipitation in the highest temperature season. Although this albedo change effect should also appear in other glacier types, such a response is limited because their precipitation peaks do not coincide with the season of highest temperature. However, in humid conditions, change in precipitation phase mostly affects accumulation amount rather than surface albedo (Fujita, 2008b). When win- and atm-glaciers are affected by warming or cooling, neither surface conditions during the summer melting season nor annual accumulation change significantly, and thus changes in melt amount are simpler than in the other glacier-types (no-seasonality-, spr-, and sum-type glaciers), especially in

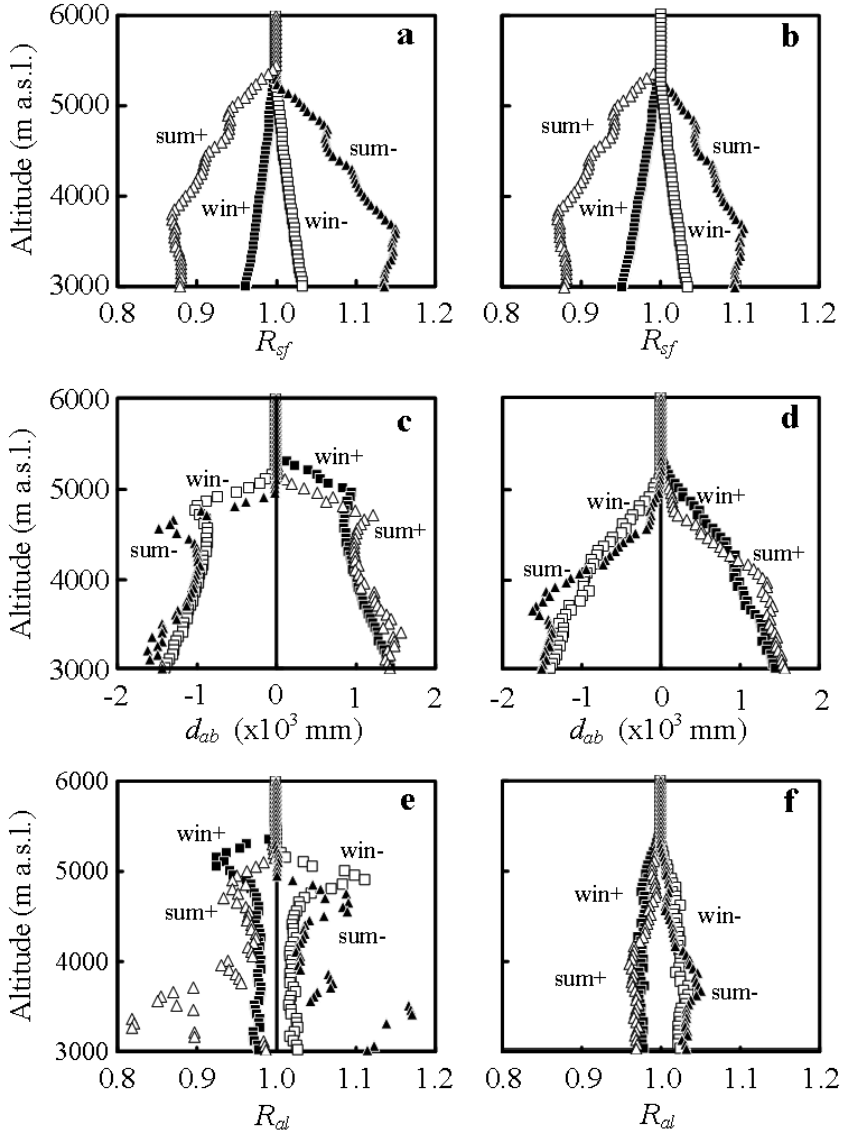

FIGURE 7. Change in mass balance components versus temperature change of ±1 K in win- and sum-type glaciers for an arid condition (500 mm a^{-1}) and a humid condition (6000 mm a^{-1}). (a, b) Snowfall amount change of ±1 K for win- and sum-type glaciers. R_{sf} indicates snowfall amount at each altitude after temperature change, divided by snowfall amount before the temperature change. (c, d) Ablation amount change of ±1 K for win- and sum-type glaciers. d_{ab} indicates the value subtracting ablation amount at each altitude before temperature change from the ablation amount after temperature change. (e, f) Surface albedo change of ±1 K for win- and sum-type glaciers. R_{al} indicates annual mean albedo at each altitude after temperature change divided by annual mean albedo before temperature change. a, c, and e are results for the arid condition (500 mm a^{-1}), and b, d, and f are results for the humid condition (6000 mm a^{-1}). win+: result for win-type glacier with +1 K. win−: result for win-type glacier with −1 K. sum+: result for sum-type glacier with +1 K. sum−: result for sum-type glacier with −1 K.

arid conditions. These differences should be more effective when the glacier advances with temperature decrease (Fig. 6, part c). Since response times to temperature change strongly depend on precipitation conditions (seasonality and/or amount), quantitative discussion may still be precluded, although Oerlemans (2005) reconstructed past fluctuations in air temperature from glacier terminus changes without considering precipitation conditions. Moreover, estimating the behavior of all glaciers in the world relative to climate change based only on the behavior of glaciers that have no precipitation seasonality (no-seasonality-type glaciers) may result in large errors because of the different response times of no-seasonality-type glaciers compared with glaciers with precipitation seasonality, especially in arid conditions. In the relationship between the fluctuation of α (Fig. 4) and that of $\tau_{rV\pm 1K}$ (Fig. 6), $\tau_{rV\pm 1K}$ becomes shorter when α increases with increased annual precipitation amount. Considering the effect of precipitation seasonality, win-type glaciers with the largest value of α always show longer τ_{rV} than those of the other glacier types for the same annual precipitation amount, whereas sum-type glaciers have the shortest value of τ_{rV} even though they have the smallest α. The other two glacier types have roughly the same value of $\tau_{rV\pm 1K}$ as the no-seasonality-type glacier, but spr-type glaciers have larger α than atm- and no-seasonality-type glaciers. The values of $d\tau_{rV}$ for all glacier types decrease with increased annual precipitation amount, and all glaciers have approximately the same response time under humid conditions, although the difference between α values of win- and sum-type glaciers becomes larger with increased annual precipitation amount (Fig. 4). Therefore, a glacier that has a larger α than other glaciers does not necessarily have a shorter τ_{rV} than the other glaciers if they are under different precipitation conditions.

Haeberli and Hoelzle (1995) suggested that the response time of a glacier depends on its surface slope. To assess whether such a relationship might be important to the present study, several simulations were conducted for different bed slope and flow parameters. The results of all simulations show similar dependences of glacier behavior on precipitation conditions: response time of sum-type glaciers is shortest and that of win-type glaciers is longest, although response time becomes longer (shorter) if bed slope decreases (increases) or flow parameters become smaller (larger). Therefore, it seems reasonable to conclude that the relationships between glacier behavior and precipitation conditions, as shown by this study, are common to all glaciers.

Conclusions

Using a glacier fluctuation model that combined a mass-balance model and a glacier flow model, the behaviors of glaciers were simulated under different precipitation conditions. The simulation results indicate that glacier behavior strongly depends on precipitation conditions. To clarify the influence of precipitation seasonality on glacier behavior, the behavior of a glacier having no precipitation seasonality (no-seasonality-type glacier) was compared with the behavior of glaciers having precipitation seasonality. The steady-state volume of the glacier at which precipitation peaks in winter (win-type glacier) is the smallest of all glacier types under arid conditions, but is the largest when the annual precipitation amount increases. This indicates that a glacier's volume will change when precipitation seasonality changes, even if the annual precipitation amount remains the same. Other glacier attributes also depend strongly on precipitation conditions. Annual mass turnover (α) of win-type glaciers is always larger than those of other glacier types under the same annual precipitation. The accumulation area ratio (AAR) increases as annual precipitation decreases, and also depends on precipitation seasonality. The dependence of the AAR on precipitation conditions is quite important in reconstructing ELAs using the AAR method.

Glacier responses under each precipitation condition were also simulated as a function of temperature change (± 1 K). The win-type glacier always shows the longest response time, whereas the glacier at which precipitation peaks in summer (sum-type glacier) has the shortest. The difference in response time between sum- and win-type glaciers becomes largest under the arid condition (precipitation of 500 mm a^{-1}) and then decreases with continued increase in annual precipitation amount, reaching approximately similar values under humid conditions.

The results of this study, although preliminary, show a strong dependence of glacier behavior on precipitation conditions. Many of the large glaciers in the Himalaya region are debris-covered and have shown different behaviors from those of the clean glaciers addressed in this study (Scherler et al., 2011). Further modeling studies should examine the dependence of the mass balance of debris-covered glaciers on precipitation condition.

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