Journal of Earth Science, *Vol. 22*, *No. 4*, *p. 470–481*, *August 2011* *ISSN 1674-487X*
Printed in China
DOI: 10.1007/s12583-011-0201-x

Application of a Degree-Day Model for Determination of Mass Balance of Urumqi Glacier No. 1, Eastern Tianshan, China

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ABSTRACT: In order to verify the feasibility and stability of a degree-day model on simulating the long time series of glacier mass balance, we apply a degree-day model to simulate the mass balance of Urumqi Glacier No. 1 for the period 1987/1988–2007/2008 based on temperature and precipitation data from a nearby climate station. The model is calibrated by simulating point measurements of mass balance, mass balance profiles, and mean specific mass balance during 1987/1988–1996/1997. The optimized parameters are obtained by using a least square method to make the model fit the measured mass balance through the model calibration. The model validation (1997/1998–2007/2008) indicates that the modeled results are in good agreement with the observations. The static mass balance sensitivity of Urumqi Glacier No. 1 is analyzed by computing the mass balance of the glacier for a temperature increase of 1 ℃, with and without a 5% precipitation increase, and the values for the east branch are -0.80 and -0.87 m w.e. $a^{-1}\cdot℃^{-1}$, respectively, and for the west branch, the values are -0.68 and -0.74 m w.e. $a^{-1}\cdot℃^{-1}$, respectively. Moreover, the analysis of the parameter stability indicates that the parameters in the model determined from the current climate condition can be applied in the prediction of the future mass balance changes for the glacier and provide a reference for extending the model to other small glaciers in western China.

KEY WORDS: Urumqi Glacier No. 1, degree-day model, mass balance.

INTRODUCTION

Glaciers represent important water resources, contributing significantly to stream-flow (Hock, 2005), and exert considerable influence on hydrology, especially in mountain areas, by temporarily storing water as snow and ice on many different time scales (Jansson et al., 2003; Braun et al., 2000). The growth and wastage of glaciers are commonly cited indices of global climate change, both directly and for the asso-

This study was jointly supported by the Knowledge Innovation Project of the Chinese Academy of Sciences (No. KZCX2-EW-311), the National Basic Research Program of China (No. 2007CB411501), the National Natural Science Foundation of China (Nos. 1141001040, J0930003/J0109).
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Manuscript received December 30, 2010.
Manuscript accepted April 08, 2011.

ciated impact on global sea-level (Casal et al., 2004). As an important link connecting changes of glaciers with changes in climate (Paterson, 1994), glacier mass balance changes are important (e.g., Arendt et al., 2002), as well as being significant on a local and regional scale for many aspects of water resource management including flood protection, water supply, and operation of hydroelectric facilities (Hock et al., 2005). It is important to assess and predict the response of glacier mass balance to global climate change.

During the past few decades, numerous models have been suggested and implemented to estimate glacier mass balance and meltwater, ranging from energy balance models (e.g., Schneider et al., 2007; Arnold et al., 1996; Brun et al., 1989) to temperature-index models (e.g., Hock, 2003, 1999; Braithwaite, 1995). Among these models, energy balance models require a lot of observational data that in many cases are not available. In contrast, degree-day models have been the most common approach for simulating glacier mass balance and meltwater due to their parsimony in data requirements compared with energy balance models (e.g., Anderson et al., 2006; Raper and Braithwaite, 2006; Zhang et al., 2006; Braithwaite and Zhang, 1999; Jóhannesson, 1997; Jóhannesson et al., 1995). Although they simplify the complex processes that are more properly described by the energy balance of the glacier surface, degree-day models often match the performance of energy balance models on a catchment scale (e.g., Hock, 2005; Rango and Martinec, 1995; WMO, 1986).

There are 46 377 glaciers in China (Shi et al., 2008, 2005). Most of these glaciers are distributed in regions of western China and are a vital source of water for sustainable development of human activities and the ecological environment (Yao et al., 2004). While 77% of glaciers in western China are small glaciers of less than 1 km^2 in area (Shi et al., 2005), there is little research focused on the assessment of changes in mass balance for these small glaciers. For the simulation of glacier mass balance in Northwest China, recently, Zhang et al. (2006) applied a degree-day model to simulate a short time series of mass balance of Keqicar Baqi Glacier. However, in the scenario of concurrent climate change from warm-dry to warm-wet in Northwest China since 1987 (Shi et al., 2003), the results of modeling a long time series of glacier mass balance in Northwest China by using degree-day models are still unknown. In other words, it is necessary to verify the feasibility of applying a degree-day model to simulate a long time series of glacier mass balance.

In this article, we apply a degree-day model to simulate a long time series of mass balance of Urumqi Glacier No. 1 in the eastern Tianshan of Northwest China, although Liu et al. (1998) and Huintjes et al. (2010) applied a degree-day model to study Urumqi Glacier No. 1. However, Liu et al. (1998) focused on the sensitivity of mass balance to climate change during the study period from 1959 to 1993. Huintjes et al. (2010) only studied mass balance of the east branch of Urumqi Glacier No. 1. In this study, we address both branches of Urumqi Glacier No. 1 for the period 1987 to 2008. Moreover, the static mass balance sensitivity of Urumqi Glacier No. 1 is analyzed by computing the mass balance of the glacier for a temperature increase of 1 ℃, with and without a 5% precipitation increase. Urumqi Glacier No. 1 has been monitored since 1959 and has the longest data series in mass balance and other measurements in China. It is one of the reference glaciers in the World Glacier Monitoring Service (WGMS), representing the glaciers in western China. The aim of this study is to verify the feasibility and stability of a degree-day model to simulate a long time series of glacier mass balance under current climate conditions and to provide a reference for predicting the future mass balance changes of Urumqi Glacier No. 1 and extending the degree-day model to other glacier areas in western China, especially in remote high-mountain regions that are not routinely monitored.

STUDY AREA AND DATA COLLECTION

Study Area

Urumqi Glacier No. 1 (43º06'N, 86º49'E) is located at the headwaters of the Urumqi River in the eastern Tianshan of Northwest China (Fig. 1). It is a northeast-facing valley glacier composed of the east and west branches currently covering 1.7 km^2. It flanks Tianger Peak II, the highest peak in the southeastern Tianshan, with an altitude of 4 484 m a.s.l. (Li et al., 2010). Urumqi Glacier No. 1 has been shrinking overall since observations were initiated in 1959. In 1993, the east and west branches of Urumqi Glacier No. 1 separated and became two independent glaciers. Urumqi Glacier No. 1 has both accumulation and ablation in summer, and there is little snowfall in winter. Over 95% of precipitation occurs from April to October, with the maximum precipitation observed in July and August (Li et al., 2008). According to the data from the nearby meteorological station, Daxigou (Fig. 1, see also section on Data Collection), the mean annual air temperature (1959–2008) at the station was -5.1 ℃, with a mean annual precipitation amount of 459 mm. The variations of annual precipitation and annual air temperature at the Daxigou Meteorological Station for the period 1959–2008 are presented in Fig. 2. Figure 2 shows that both annual precipitation and annual air temperature have obvious upward trends during 1987–2008, which indicates that there are big variations in climate conditions for this period. Therefore, we choose 1987–2008 as study period in order to verify the feasibility and stability of a degree-day model to simulate a long time series of glacier mass balance under these climate conditions.

Data Collection

The meteorological data series come from the Daxigou Meteorological Station, which is located 3 km downstream of Urumqi Glacier No. 1 (Fig. 1). The station has been operated by the Xinjiang Uygur Autonomous Region Meteorological Bureau since

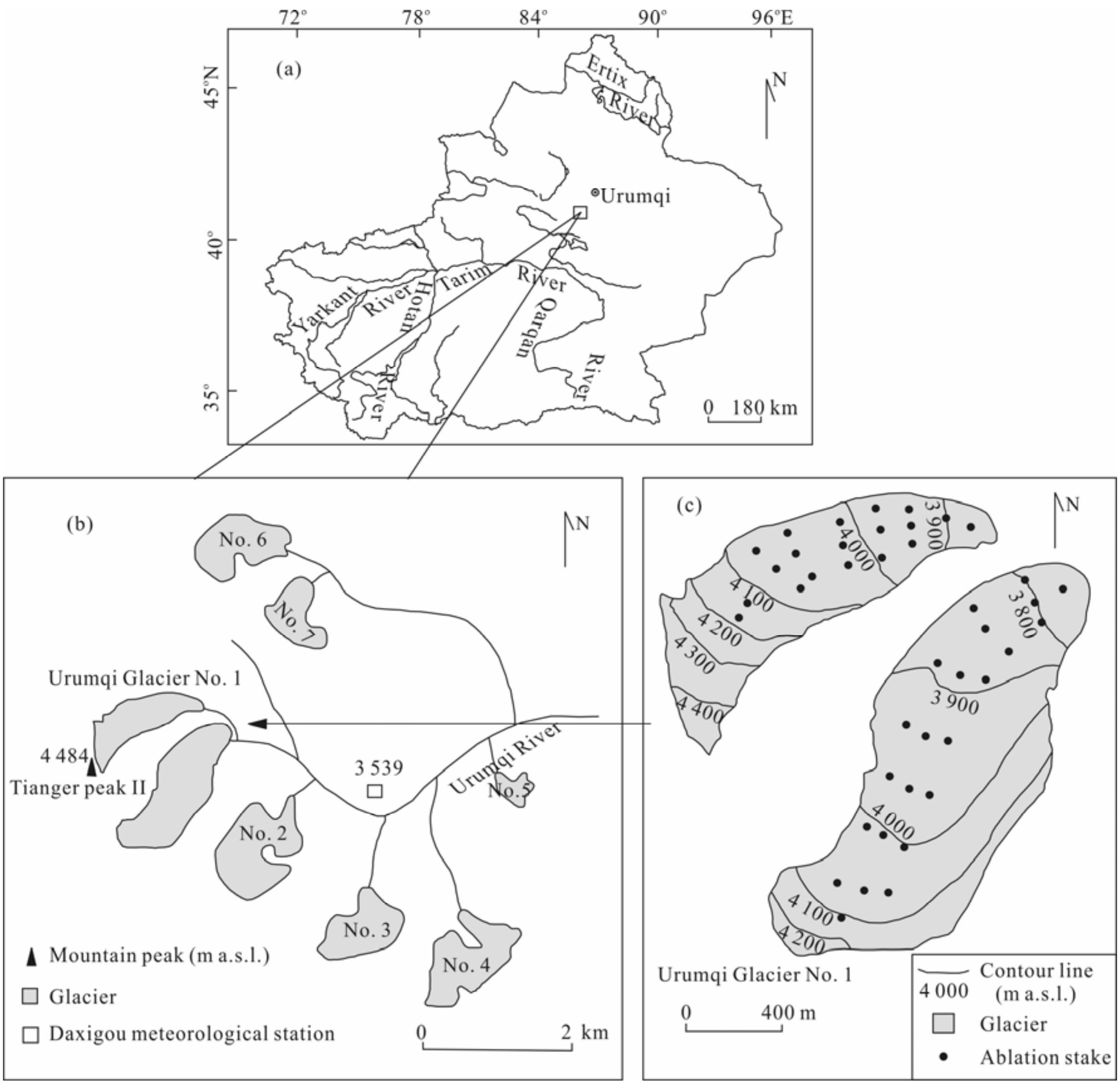

Figure 1. (a) Location maps of Urumqi Glacier No. 1 at the headwaters of the Urumqi River in Xinjiang, (b) glaciers and the location of the Daxigou Meteorological Station, and (c) showing the approximate position of ablation stakes in 2008 (black dots).

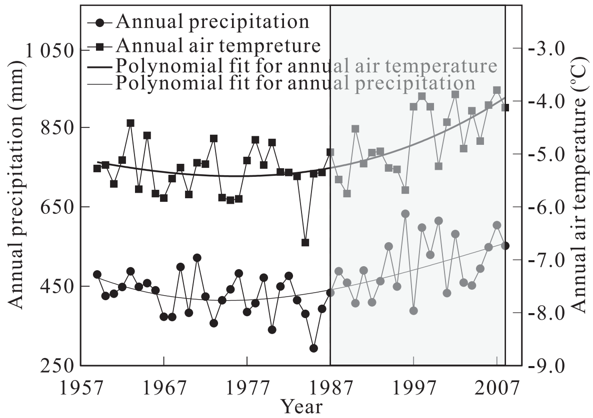

Figure 2. The variations of annual precipitation and annual air temperature at the Daxigou Meteorological Station for the period 1959–2008. The shaded area indicates the study period 1987–2008.

1958, and a continuous time series of air temperature and precipitation data are available for the study period.

The mass balance of Urumqi Glacier No. 1 has been measured by the Tianshan Glaciological Station every year since 1959 using the glaciological method. The observational results of mass balance have been submitted to the WGMS since 1981. The mean specific mass balances have been calculated separately for the east and west branches since 1988 (Huintjes et al., 2010). In the study period from September 1, 1987 to August 31, 2008, ablation stakes were drilled into the glacier at different altitudes to monitor the glacier mass balance. The distribution of ablation stakes on the glacier in 2008 is shown in Fig. 1. The observations of mass balance are conducted from May to September each year at intervals of 30 days. Results are converted to water equivalent by using the measured densities for snow and ice. The specific mass balance is calculated from repeated measurements at ablation stakes at different altitudes. The point mass balance data are then extrapolated to the entire glacier as a linear function of altitude. Data on altitude profiles of mass balance and mean mass balances are available for both the summer or winter and the entire budget year. The mass balance data have been published in the annual reports of the Tianshan Glaciological Station since 1959.

METHODOLOGY

Degree-Day Mass Balance Model

The mass balance of Urumqi Glacier No. 1 is simulated by using a degree-day model. The degree-day modeling approach was first used for an Alpine glacier by Finsterwalder and Schunk (1887), and since then, it has been used all over the world for the estimation of mass balance of glaciers and snow or ice melt (e.g., Möller and Schneider, 2010; Anderson et al., 2006; Zhang et al., 2006; Hock, 2005, 2003, 1999; Schuler et al., 2005; Braithwaite and Zhang, 2000; Liu et al., 1998; Braithwaite, 1995, 1985; Jóhannesson et al., 1995; Collins, 1934). In this study, the model allows the calculation of accumulation, ablation, and mass balance from simple meteorological data recorded by the Daxigou Meteorological Station. Precipitation and temperature are the only meteorological input data required.

In this model, glacier ablation and accumulation are calculated from monthly mean air temperature and monthly precipitation observations. With a vertical lapse rate of 0.006 ℃·m^{-1} (e.g., Zhang et al., 2006), monthly mean air temperatures of the glacier for the ablation and accumulation calculations are estimated at each altitude by extrapolating from the Daxigou Meteorological Station. The simulation of the precipitation distribution for the glacier zone is presented in the following section on Precipitation.

The monthly melt m is calculated as follows (e.g., Braithwaite and Zhang, 2000; Braithwaite and Olesen, 1989)

$$m=\mathrm{DDF}\cdot\mathrm{PDD} \tag{1}$$

where DDF is the degree-day factor, different for snow and ice, and PDD is the sum of positive degree days within the month (i.e., sum of positive air temperatures within the month). PDD is given by e.g., Aðalgeirsdóttir et al. (2006), Jóhannesson et al. (1995), Braithwaite (1985)

$$\mathrm{PDD}=\frac{365/12}{\sigma\sqrt{2\pi}}\int_0^{\infty} T\mathrm{e}^{\frac{-\left(T-T_{\mathrm{m}}\right)^2}{2\sigma^2}}\,\mathrm{d}T \tag{2}$$

where T is temperature, and T_{m} is the monthly mean temperature in which case fluctuations of the daily mean temperatures about the monthly average are assumed to be normally distributed with a standard deviation σ=4.0 ℃, as calculated from the daily mean temperatures of the Daxigou Meteorological Station during 1987–2008.

Urumqi Glacier No. 1 is a cold type glacier, and when the melt is less than a specified threshold proportion of the snow depth, all the meltwater is refrozen or stored in the snow pack and no runoff occurs. In this case, melt can be calculated by using DDF for snow. As melt reaches or exceeds the threshold, all the snow pack turns into ice and the DDF for ice is used. The refrozen or stored meltwater in the snow pack is represented by the parameter *f*. This leads to a delay in the onset of runoff from the annual snow pack with respect to the start of melt on the glacier. Threshold proportion of snow pack used to calculate refrozen meltwater is set to 0.58 (Li, 2010). The ablation *a* is defined as the negative of the melt *m* plus *f*. The densities of glacier ice and snow are set to 870 and 375 kg·m^{-3}, respectively, as calculated from the mean measured densities for ice and snow of Urumqi Glacier No. 1 for the period 1987–2008.

To calculate the monthly accumulation *c*, the precipitation is partitioned into rain and snow according to the probability that air temperatures within the month lie above or below 0 ℃ (Braithwaite and Zhang, 2000). *c* is given in terms of the snow density ρ_{snow}, and the monthly snowfall P_{snow} by

$$c=\rho_{\text{snow}}P_{\text{snow}} \tag{3}$$

The mass balance *b* is given as the sum of the accumulation and the ablation by (e.g., Aðalgeirsdóttir et al., 2006; Jóhannesson et al., 1995)

$$b=c+a=c-m+f \tag{4}$$

The above expressions may be used to calculate the cumulative mass balance over a specified time interval, which is usually whole or part of a mass balance year. In our study, a mass balance year is from September 1 in one calendar year to August 31 in the following year.

For determining the mean specific mass balance of the whole glacier, the glacier can be divided into a set of altitude bands at intervals of 100 m. The model assumes that altitude is the only controlling spatial variable. The mean specific mass balance over the whole glacier for the mass balance year is *B* defined by (e.g., Braithwaite and Zhang, 2000)

$$B=\frac{1}{S_{\text{total}}}\sum_{i=1}^{n} s_i b_i \tag{5}$$

where S_{total} is the total area of the glacier, s_i is the area of the *i*th altitude band, and b_i is the modeled annual mass balance of the *i*th altitude band for the mass balance year. The area of each altitude band is measured from 5 m resolution digital elevation models (DEMs) based on the glacier topographic maps made by the Tianshan Glaciological Station in 1986, 2001, and 2006, respectively, and the degree-day model is run for the entire glacier based on the DEMs.

Precipitation

For the distribution of the precipitation on Urumqi Glacier No. 1, Yang et al. (1992) found that the summer precipitation of the glacier increased with increasing altitude, until the glacier firn basin is at about 4 030 m a.s.l., which is the maximum precipitation zone of the glacier. Moreover, Li et al. (2006) found that the mean annual precipitation of the accumulation zone at 4 130 m a.s.l. for Urumqi Glacier No. 1 is around 700 mm w.e.. Based on these studies (Li et al., 2006; Yang et al., 1992), with a range of degree-day factors as 2.0–6.0 and 3.0–10.0 mm w.e. d^{-1}·℃$^{-1}$ for snow and ice, respectively, the precipitation at each altitude of the glacier is adjusted until an optimal least squares fit is obtained to the measured mass balance (Braithwaite et al., 2002). The monthly precipitation P_{glacier} for specific altitudes on the glacier is described by

$$P_{\text{glacier}}=K\cdot P_{\text{Daxigou}}/100 \tag{6}$$

where P_{Daxigou} is the monthly precipitation at the Daxigou Meteorological Station, and *K* is the precipitation gradient parameter that represents the spatial differences in precipitation relative to altitude change.

Model Parameter Calibration

The mass balance of Urumqi Glacier No. 1 is modeled for the period from September 1, 1987 to August 31, 2008. The model parameters are determined by calibration, whereby values are adjusted such that modeled results are in optimal agreement with observations. The dataset covering the 21 year period 1987/1988–2007/2008 is divided into two parts. The 10 year period 1987/1988–1996/1997 is used to calibrate the model parameters, and the remaining 11 year data series (1997/1998–2007/2008) serve as an independent dataset to validate the performance of the model.

The model is calibrated by simulating the mass balance for the period 1987/1988–1996/1997. In the model calibration, parameters are optimized using a least square method to minimize the differences between modeled and measured mass balance (Braithwaite et al., 2002). The fixed parameters are presented in Table 1 and the adjusted parameters are the degree-day factors and precipitation. The adjusted range of degree-day factors are 2.0–6.0 and 3.0–10.0 mm w.e. d^{-1}·℃$^{-1}$ for snow and ice, respectively. The precipitation at specific altitudes is adjusted to make the model fit the measured mass balance by using the least square method (see also above section on Precipitation). Finally, optimized parameters are obtained (Table 2), and the optimized distribution of the precipitation gradient parameter *K* with altitude is presented in Fig. 3. Based on the parameters in Tables 1 and 2, and Fig. 3, the model outputs and the observations are presented in Figs. 4, 5, and 6. Figure 4 shows the direct comparison of modeled and measured mass balance at the ablation stakes for the calibration period. Figure 5 shows the mass balance profile with altitude (the mass balance year 1993/1994 is in the calibration period). Figure 6 shows the detailed comparison of mean specific mass balance time series (the shaded area in Fig. 6 indicates the calibration period).

Table 1 Fixed parameters for the model

Parameter	Value	Unit
Temperature lapse rate	0.006	℃·m^{-1}
Temperature standard deviation σ within the month	4.0	℃
Snow density in the model	375	kg·m^{-3}
Ice density in the model	870	kg·m^{-3}
Threshold temperature for precipitation as snow or rain	0	℃
Threshold proportion of snow pack used to calculate refrozen meltwater	0.58	–
Altitude of Daxigou Meteorological Station	3 539	m a.s.l.

Table 2 Optimized parameters (degree-day factor for snowmelt (DDF_{snow}) and ice melt (DDF_{ice}) for the model

Parameter	Value	Unit
Degree-day factor for snow	2.7	mm w.e. d^{-1}·℃$^{-1}$
Degree-day factor for ice	8.9	mm w.e. d^{-1}·℃$^{-1}$

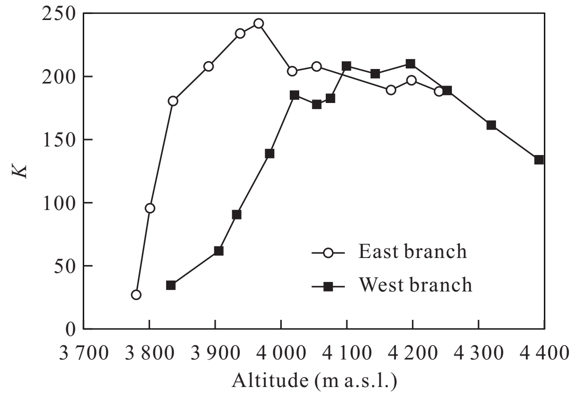

Figure 3. Precipitation gradient parameter *K* versus altitude for Urumqi Glacier No. 1.

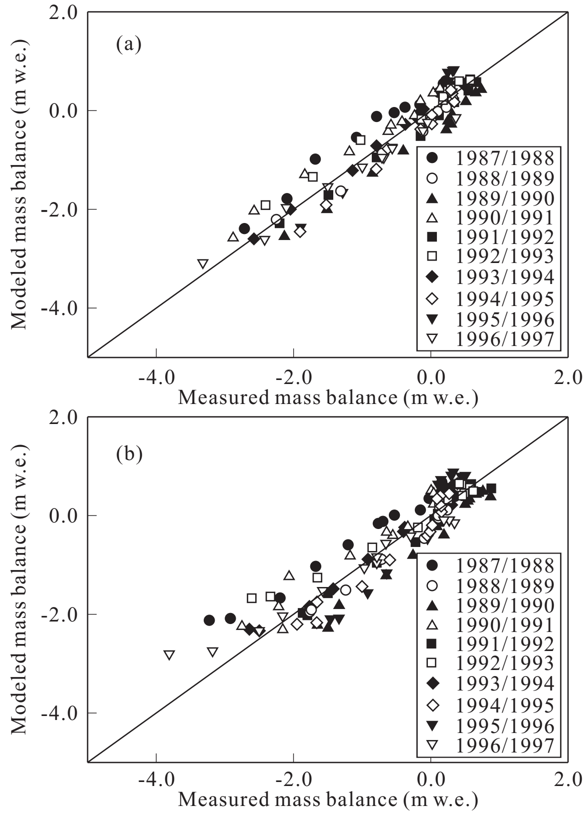

Figure 4. Modeled and measured annual mass balance of Urumqi Glacier No. 1 at the ablation stakes for the calibration period 1987/1988–1996/1997. (a) East branch; (b) west branch.

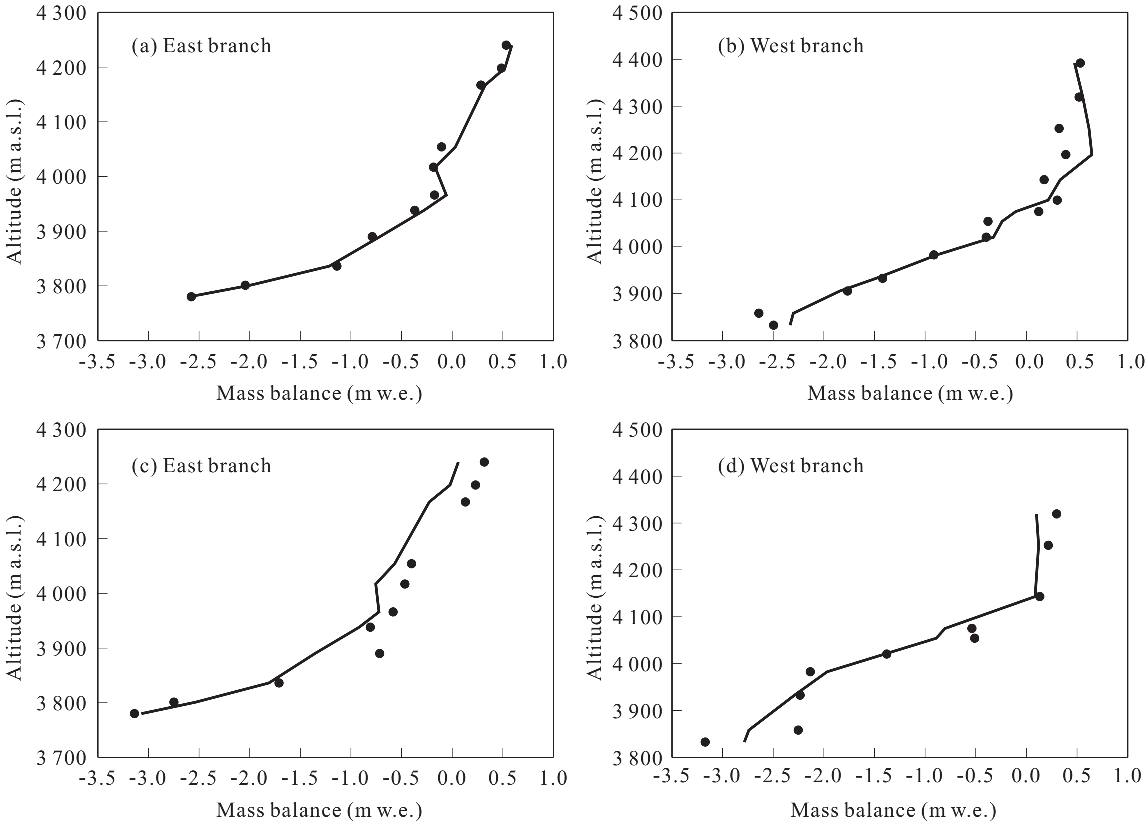

Figure 5. Examples of measured (dots) and modeled (lines) annual mass balance at the ablation stake profiles of Urumqi Glacier No. 1 for the mass balance years 1993/1994 and 2005/2006. (a) and (b) designate a good agreement between measurements and simulations in 1993/1994; (c) and (d) designate a less satisfying agreement between measurements and simulations in 2005/2006. The number of the ablation stake profiles of the west branch for the mass balance years 1993/1994 and 2005/2006 is different due to different distribution of ablation stakes.

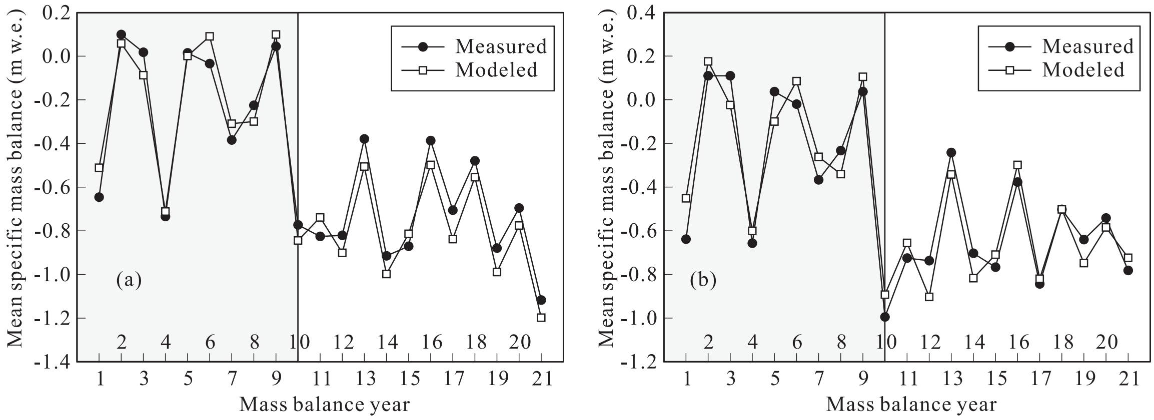

Figure 6. The temporal evolution of mean specific mass balances for Urumqi Glacier No. 1 during the mass balance years 1987/1988 to 2007/2008. The shaded area indicates the calibration period. (a) East branch; (b) west branch; 1. 1987/1988; 2. 1988/1989; 3. 1989/1990; 4. 1990/1991; 5. 1991/1992; 6. 1992/1993; 7. 1993/1994; 8. 1994/1995; 9. 1995/1996; 10. 1996/1997; 11. 1997/1998; 12. 1998/1999; 13. 1999/2000; 14. 2000/2001; 15. 2001/2002; 16. 2002/2003; 17. 2003/2004; 18. 2004/2005; 19. 2005/2006; 20. 2006/2007; 21. 2007/2008.

RESULTS AND DISCUSSION

Model Performance

Figure 4 compares the modeled and measured annual mass balance of Urumqi Glacier No. 1 at the ablation stakes for the calibration period 1987/1988–1996/1997. Figures 4a and 4b show the results of the east and west branches, respectively. Considering the simplicity of the degree-day mass balance model, there is good agreement between modeled and measured mass balance, although not all points are in the line of unity slope (Fig. 4). Figure 4 shows a strong correlation (R^2=0.90 for the east branch and R^2=0.87 for the west branch), which reveals that the modeled results are in good agreement with the observations for the calibration period.

To further understand the spatial variations of modeled and measured mass balance, examples of the mass balance profile with altitude are shown in Fig. 5. Figures 5a and 5b show a good agreement between simulations and measurements in 1993/1994 during the study period. Figures 5c and 5d show a less satisfying agreement between simulations and measurements in 2005/2006 during the study period. Figure 5 shows that the main discrepancies are located at the higher area of the glacier and at the snout. For the higher area of the glacier, the model does not take into account all causes of mass balance variation. For example, redistribution of the original snowfall by wind transport is not considered. At the snout of the glacier, one reason for the discrepancy between simulations and measurements could be different albedo of the glacier surface between the snout and other areas of the glacier, which is partly caused by pollution on the glacier surface by dust blown from lower areas, as well as debris accumulated around the boundary of the glacier. Thus, the degree-day factors in the model cannot give accurate results. Another reason could be the slope and aspect of the snout since this could lead to different absorption of radiation independent on altitude but depending on the inclination and aspect of the lower glacier. For the mismatch between modeled and measured mass balance at the snout in Figs. 4a and 4b, their reasons could also be different albedo, slope, and aspect of the snout of the glacier.

In order to further validate the model performance, the temporal evolution of mean specific mass balance for the whole glacier during the study period is presented in Fig. 6, which is based on Equation (5) and the parameters in Tables 1 and 2 and Fig. 3. In Fig. 6, the shaded area denotes the calibration period, and the remaining area indicates the validation period. Figures 6a and 6b show the results of the east and west branches of Urumqi Glacier No. 1, respectively. In Fig. 6, the overall behavior and the temporal evolution of mean specific mass balance of the glacier are reproduced correctly, although there are some differences between measurements and simulations that can be partially explained by the factors discussed in the previous paragraph. Moreover, the detailed comparison of modeled and measured results in Fig. 6 shows a strong correlation (R^2=0.95 for the east branch and R^2=0.91 for the west branch). If the calibration period 1987/1988–1996/1997 and the validation period 1997/1998–2007/2008 are examined, respectively, we find not only that the model explains the mean specific mass balance very well (R^2=0.94 for the east branch and R^2=0.92 for the west branch) in the calibration period but also that the modeled results and the observations are in good agreement (R^2=0.91 for the east branch and R^2=0.80 for the west branch) in the validation period. In Fig.6, for the period from 1987/1988 to 1995/1996, mean specific mass balances varied between positive and negative values. Since the mass balance year 1996/1997, the east and west branches of the glacier have experienced negative mean specific mass balances. Specially, in Fig. 6, a severe jump to negative mass balance values is apparent between the mass balance year 1995/1996 and the mass balance year 1996/1997, which can be explained according to Fig. 2. In Fig. 2, annual air temperature increased suddenly and annual precipitation decreased suddenly between 1996 and 1997. Thus, the severe jump to negative mass balance values in Fig. 6 could come from sudden changes in annual air temperature and annual precipitation between 1996 and 1997.

Mass Balance Sensitivity

The mass balance sensitivity of glaciers is of interest as a general measure of the hydrological effect of changes in the mass balance of glacier areas due to climate changes (Aðalgeirsdóttir et al., 2006). In our study, as in others (e.g., Aðalgeirsdóttir et al., 2006; Oerlemans et al., 1998; Jóhannesson, 1997), we define the static sensitivity S of glacier mass balance as the ratio of the change in the specific mass balance of the glacier to the change of temperature

$$S = \frac{\Delta B}{\Delta T} \quad (7)$$

where ΔB is the change in mean specific mass balance resulting from a change in temperature ΔT. Although S is defined with respect to a small uniform change in temperature, it is useful to compute the change in specific mass balance as a consequence of a finite temperature change, which may vary through the year with and without a precipitation increase. The static mass balance sensitivity S is calculated for a warming of ΔT=1 ℃ with and without a 5% precipitation increase. The warming is assumed with no seasonal difference. The static mass balance sensitivity S of the east branch of Urumqi Glacier No. 1 for a warming of ΔT=1 ℃ with and without a 5% precipitation increase, is -0.80 and -0.87 m w.e. $a^{-1}\cdot℃^{-1}$, respectively (Table 3). For the west branch, the values are -0.68 and -0.74 m w.e. $a^{-1}\cdot℃^{-1}$, respectively (Table 3). The static sensitivity S of the mass balance to a 1 ℃ temperature increase for Urumqi Glacier No. 1 is comparable to the results found for other glacier areas around the world. The results for these other ice caps or glaciers are in the range of -0.10–(-2.01) m w.e. $a^{-1}\cdot℃^{-1}$ (Aðalgeirsdóttir et al., 2006; De Woul and Hock, 2005; Braithwaite et al., 2002; Braithwaite and Zhang, 1999; Oerlemans et al., 1998; Jóhannesson, 1997). According to their results, continental ice caps and glaciers have relatively lower sensitivities than marine ice caps and glaciers. For example, the value of S for the Devon Ice Cap in Canada is about -0.10 m w.e. $a^{-1}\cdot℃^{-1}$ (De Woul and Hock, 2005), and the value of Hofsjökull in Iceland is -0.58 m w.e. $a^{-1}\cdot℃^{-1}$ (Aðalgeirsdóttir et al., 2006). By contrast, marine ice caps and glaciers are more sensitive to climate change. For example, the values of S for Dyngjujökull and southern Vatinajökull in Iceland are about -2.01 m w.e. $a^{-1}\cdot℃^{-1}$ (De Woul and Hock, 2005) and -1.13 m w.e. $a^{-1}\cdot℃^{-1}$ (Aðalgeirsdóttir et al., 2006), respectively. Thus, compared with the static sensitivity values for other ice caps or glaciers around the world, the values for Urumqi Glacier No. 1 lie between the values for continental ice caps or glaciers and those for marine ice caps or glaciers.

Table 3 Static sensitivity of the mass balance to a 1 ℃ temperature increase with and without a 5% precipitation increase for Urumqi Glacier No. 1

Urumqi Glacier No. 1	$S_{\triangle P=0}$	Unit	$S_{\triangle P=5\%}$	Unit
East branch	-0.87	m w.e. $a^{-1}\cdot℃^{-1}$	-0.80	m w.e. $a^{-1}\cdot℃^{-1}$
West branch	-0.74	m w.e. $a^{-1}\cdot℃^{-1}$	-0.68	m w.e. $a^{-1}\cdot℃^{-1}$

Parameters Stability

The degree-day mass balance model used here reproduces the variations in mass balance with altitude and time, using the same parameter set. An important question is whether model parameters, especially the degree-day factors determined from the current climate, can be used to predict future mass balance changes associated with a different climate. Thus, for the current climate, the stability of theses parameters, especially the degree-day factors in the degree-day mass balance model, needs to be investigated.

Braithwaite (1995) studied the variation of degree-day factors for ablation on the Greenland ice sheet using energy balance modeling and found that the spatial and temporal changes of the degree-day factors are mainly caused by glacier surface albedo and summer mean air temperature, respectively. For Urumqi Glacier No. 1, there is little debris on the glacier surface except at the snout, so the effect of albedo on the degree-day factors mainly arises from the different albedos for snow and ice on the glacier surface. In our model, the effect of the albedos of snow and ice on the degree-day factors has been taken into account by using different degree-day factors. With respect to the effect of summer mean air temperature on the degree-day factors, according to the observed temperature data from the Daxigou Meteorological Station during the study period, the maximum summer mean air temperature was 4.5 ℃ (in the mass balance year 2007/2008), and the minimum summer mean air temperature was 2.0 ℃ (in the mass balance year 1992/1993), so the maximum change in the summer mean air temperature was 2.5 ℃. However, given a temperature vertical lapse rate of 0.006 $℃\cdot m^{-1}$ and an elevation change of over 500 m for the glacier, air temperature variation over the altitude range of the glacier, of 3.0 ℃, is greater than the maximum summer mean air temperature change. In other words, the variation in the summer mean air temperature is within the range of variation of air temperatures of the glacier in the model. Moreover, the satisfactory simulation results of mass balance for Urumqi Glacier No. 1 using degree-day models with optimal degree-day factors for snow and ice indicate that the degree-day factors used in the model are applicable and stable.

As mentioned in the Introduction, one of the goals of this study is to provide a reference for predicting the future glacier mass balance changes and permit extension of the simulation method to other glacier areas in western China. It is recognized that glaciers of different geometry, located in different climate regimes, will respond in different ways to a climatic signal (Kuhn et al., 1985) and that the model and parameters used in Urumqi Glacier No. 1 are too limited to generalize reliably. However, it is still possible to provide a reference for applying the model and parameters to a particular glacier category, one in which the climate and geometry of the glaciers are similar to Urumqi Glacier No. 1. This is of interest and importance because the sustention of small glaciers has drawn wide attention in western China as well as around the world (e.g., Yao et al., 2004). In our study, air temperature change over the altitude range of Urumqi Glacier No. 1 is much greater than the expected CO_2-induced temperature change during this century, and year-to-year variations in regional temperatures of the glacier are in the same order of magnitude as the expected climatic warming during the next 50–100 years (e.g., Liu et al.,1998; Jóhannesson et al., 1995). Thus, climate conditions in the near future are likely to remain within the already observed range on the glaciers, unless the climate changes are so large or rapid that the climate of the region changes in a fundamental way. In other words, parameter values, determined from mass balance observations for the current climate, may be expected to be meaningful for studies of future glacier mass balance. Accordingly, small glaciers (with areas less than Urumqi Glacier No. 1's) in western China have climatic backgrounds similar to Urumqi Glacier No. 1's, so the successful application of the degree-day mass balance model to Urumqi Glacier No. 1 can provide a reference for extending the model to these other glaciers.

CONCLUSIONS

In this study, a degree-day model is applied to simulate the mass balance for Urumqi Glacier No. 1 during the mass balance years 1987/1988 to 2007/2008 based on temperature and precipitation data from the Daxigou Meteorological Station. The model is calibrated by simulating point measurements of mass balance, mass balance profiles, and mean specific mass balance during 1987/1988–1996/1997. The optimized parameters are obtained by using a least square method to make the model fit the measured mass balance through the model calibration. Specially, the optimal values in the degree-day factors for snow and ice are 2.7 and 8.9 mm w.e. $d^{-1}\cdot ℃^{-1}$, respectively, and the optimized distribution of the precipitation gradient parameter K with altitude is presented in Fig. 3. Based on these optimized parameters, the model is validated for the period 1997/1998–2007/2008, and the model outputs indicate that the modeled results are in good agreement with the observations, which reveals that it is feasible and satisfactory to apply a degree-day model to simulate a long time series of glacier mass balance in western China. In addition, the static mass balance sensitivity of Urumqi Glacier No. 1 is analyzed by computing the mass balance of the glacier for a temperature increase of 1 ℃, with and without a 5% precipitation increase. The static mass balance sensitivity of the east branch for a warming of 1 ℃, with and without a 5% precipitation increase, is -0.80 and -0.87 m w.e. $a^{-1}\cdot ℃^{-1}$, respectively. For the west branch, the values are -0.68 and -0.74 m w.e. $a^{-1}\cdot ℃^{-1}$, respectively. In comparison with the static sensitivity values of other ice caps or glaciers around the world, the values for Urumqi Glacier No. 1 lie between values for continental ice caps or glaciers and those for marine ice caps or glaciers. Furthermore, analysis of parameter stability indicates that the parameters in the model, especially the degree-day factors, determined from the current climate conditions can be applied in the prediction of future mass balance changes for Urumqi Glacier No. 1. Also, the application of the degree-day mass balance model to Urumqi Glacier No. 1 provides a reference for extending the model to other small glaciers in western China.

ACKNOWLEDGMENTS

We thank Mrs. Jeanne Briggs and Prof. Ronald Briggs for helpful comments, suggestions and language editing that greatly improved the manuscript. This study was jointly supported by the Knowledge Innovation Project of the Chinese Academy of Sciences (No. KZCX2-EW-311), the National Basic Research Program of China (No. 2007CB411501), the National Natural Science Foundation of China (Nos. 1141001040, J0930003/J0109).

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