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Response of glacier mass balance to climate change in the Tianshan Mountains during the second half of the twentieth century

Qiao Liu[1] · **Shiyin Liu**[2]

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Abstract Systematic differences in glacier mass balance response to climate warming are apparent in the Tianshan Mountains, which are primarily caused by different climatic regimes and glacier hypsography. Combined mass balance data of nine monitored glaciers in the Tianshan Mountains shows that most glaciers accelerated their mass losing rate since 1970s (averaged from −24.6 mm w.e. a^{-1} in 1957–1970 to −444.6 mm w.e. a^{-1} in 1971–2009), but also exhibiting discrepancy and consistency during the second half of the twentieth century. To see their climatic–mass balance relationships, we employ a simple temperature index mass balance model on five well monitored glaciers in Tianshan. The model is calibrated by the observed annual, summer and winter mass balance data over the period of 1957–1980 and validated over 1981–2002. A comparison of modeled and measured annual mass balance yields an overall standard deviation of 0.465 m w.e. during the period of model runs. The calibrated mass balance model is also used to perform sensitivity experiments, which indicates the significant differences of individual glaciers in response to climate changes. This study, for the first time, tests a temperature index mass balance model on the selected observed glaciers in the Tianshan Mountains. Although there exists considerable uncertainties, we propose its potential possibility of improvement and applicability for regional glacier mass balance reconstructions and future predictions.

Keywords Glacier mass balance · Climate change · Tianshan Mountains · Central Asia

✉ Qiao Liu
liuqiao@imde.ac.cn

✉ Shiyin Liu

1 Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu, China

2 State Key Laboratory of Cryospheric Sciences, Cold and Arid Region Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China

1 Introduction

There are 15,953 glaciers with a total area of 15,416 km^2 and a total volume of 1048 km^3 in the Tianshan Mountains, central Asia (Aizen et al. 2007a). As the most important fresh water supply (Unger-Shayesteh et al. 2013), total contribution of glacier melt water to the river runoff was estimated to be about 10 % at the outlets of Tianshan Mountain valleys (Aizen et al. 1997), and in the Tarim basin this values reaches 50 % (Yang 1991). During the second half of the twentieth century, the average rise in air temperature in Tianshan region ranges from 0.01 (Aizen et al. 1997) to 0.02 K a^{-1} (Bolch 2007), which has led to a general negative glacier mass balance and total ice volume decrease. Glacier recession in Tianshan has been indicated by remote sensing observations of regional glacial covered area (Aizen et al. 2007b; Bolch 2007; Narama et al. 2010) and by direct mass balance records of several typical glaciers (Sorg et al. 2012). Glaciers shrinkage has caused remarkable runoff changes in the region's glacier melt water fed rivers (Gao et al. 2010; Sorg et al. 2012; Zhang et al. 2012). These hydrological changes have driven recent concerns about the glacier changes and water availability in the central Asia (Immerzeel et al. 2010; Sorg et al. 2012).

Building the relationship between glacier mass balance and climatic signals is one of the key missions on understanding past, current and projected future behaviors of glaciers for glaciology (Oerlemans et al. 1998). Response

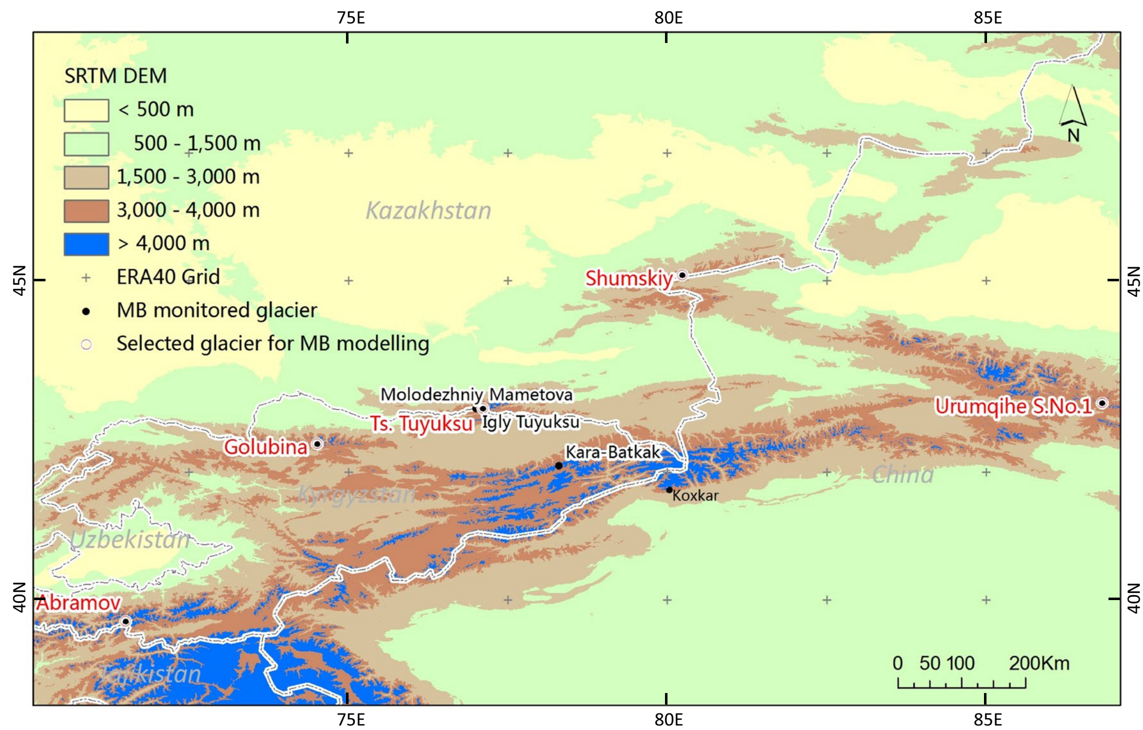

Fig. 1 Distribution of monitored glaciers in the Tianshan Mountains

processes of individual glacier mass balance to climate warming, however, were not consistent in different parts of the Tianshan Mountains. It was generally accepted that glacier shrinkage is less remarkable in the continental inner ranges than in the more humid outer ranges of Tianshan Mountains (Sorg et al. 2012). Those differences of glacier responses are primarily due to the different local climatic regimes and the discrepancy in glacier scale, response times, and spatial distribution.

In this paper, we combine directly-measured mass balance data (1957–2009) of nine glaciers in the Tianshan Mountains from the annual reports of the World Glacier Monitoring Service (WGMS). Based on these measured mass balance data, we analyze the temporal variations and differences of glacier mass balances during the period of 1957–2009. To derive a better understanding of their mass balance changes, a temperature index mass balance model, forced by the regional reanalysis climate data (ERA-40), is applied to five of these glaciers, which have more comprehensive observations. Their annual mass balance and mass balance profiles are modeled, and compared to the observations. Moreover, based on the model, their sensitivities to temperature and precipitation changes are calculated. We further discuss the model result and the potential applicability of the modeling approaches for regional reconstruction and future prediction of glacier mass balance in the Tianshan Mountains.

2 Glacier mass balance monitoring in the Tianshan Mountains

2.1 Historical and current glaciological observations

Worldwide glacier mass balance monitoring has been coordinated at the international level since the late twentieth century after the International Geophysical Year (IGY 1957–59) (Dyurgerov and Meier 1997; Braithwaite 2002). Today, standardized data on glacier distribution and changes are compiled and disseminated within the Global Terrestrial Network for Glaciers, which is run jointly by the WGMS, the US National Snow and Ice Data Center (NSIDC), and the Global Land Ice Measurements from Space (GLIMS) initiative (Zemp 2012). Since the 1950s, directed measurements of mass balance had been carried out on several glaciers in the Tianshan Mountains to understand their processes and the relationship with climatic conditions. In Central Asia, in situ glacier monitoring has a long tradition (Kotlyakov 1980). Most glaciers in the Tianshan Mountains are monitored by the former Union of Soviet Socialist Republics (USSR), as an ongoing work that was started during the IGY (Fig. 1). Extensive mass balance measurements have been made over several decades since 1950s using glaciological method on these reference glaciers. However, most of the glaciological monitoring works were interrupted after the collapse of the USSR in the early 1990s. In

Table 1 List of monitored glaciers in Tianshan concerned in this study

Glacier name	Location		Altitude extent (Min–Max, m asl)	Area (km^2)	Mean aspect (accumulation area/ablation area)	Monitoring period
Abramov[a]	N39.62	E71.56	3620–4960	22.50	SE/E	1968–1998
Shumskiy[a]	N45.08	E80.28	3126–4464	2.81	NE/N	1967–1991
Ts. Tuyuksu[a]	N43.06	E77.09	3414–4219	2.66	NW/N	1957–2009
Igly Tuyuksu	N43.00	E77.10	3450–4220	1.72	NW/NW	1976–1990
Molodezhniy	N43.00	E77.10	3450–4150	1.43	NE/NE	1976–1990
Mametova	N43.00	E77.10	3610–4190	0.35	W/W	1976–1990
Kara-Batkak	N42.10	E78.30	3293–4829	4.19	N/N	1957–1998
Golubina[a]	N42.45	E74.50	3250–4437	6.21	N/NW	1969–1994
Glacier No 1[a]	N43.12	E86.81	3736–4486	1.84	NE/NE	1959–2009

[a] Selected glaciers for mass balance modeling

the Tianshan region, only two glaciers have the continued in situ mass balance measurement records: the central Tuyuksu Glacier (Ts. Tuyuksu, in Kyrgyzstan) and the Urumqihe No.1 Glacier (in China), which are currently annually reported to the WGMS (2011). Mass balance data of three small glaciers observed in the Tuyuksu catchment (Molodezhniy, Mametova and Igly Tuyuksu) only span from 1976 to 1990. Recently re-established and newly established glaciological monitoring is being carried out on several glaciers in the Tianshan region. A scientific group from Germany, Kyrgyzstan, Uzbekistan, Switzerland, Czech, US and China has recently re-initiated monitoring observations of three glaciers in Kyrgyzstan, including Abramov, Golubina, and Kara-Batkak Glaciers, which were previously monitored by the USSR and Russia until 1998 (Unger-Shayesteh 2011). A program of long-term field observations was started in 2003 at the Koxkar Glacier, a typical debris-covered glacier in China (Han et al. 2005; Zhang et al. 2006, 2007; Han et al. 2010; Xin et al. 2011).

Based on the biennial Glacier Mass Balance Bulletin (GMBB) and the five-yearly Fluctuations of Glaciers (FoG) by the WGMS, directly-measured mass balance data between 1957 and 2009 of nine glaciers in Tianshan are combined in this study to analyze their mass balance variations and test a mass balance model on five of the selected glaciers that with more comprehensive mass balance data (Table 1). The 9 monitored glaciers are spatially distributed in different region with an extant of 15.3° in longitude from west to east and 5.4° in latitude from south to north. Six of these glaciers have a small area (<3 km^2) and only Abramov Glacier has an area larger than 20 km^2. Altitudes of these glaciers range from 3126 to 4960 m asl, and most of them are primary north facing. Note that the Abramov glacier actually belongs to Pamir Mountains. Since it is a large glacier and has one of the longest monitoring records in central Asia, the Abramov glacier has been included in many glaciological studies for Pamir-Tianshan, specifically as one of the reference glaciers in central Asia (Sorg et al. 2012).

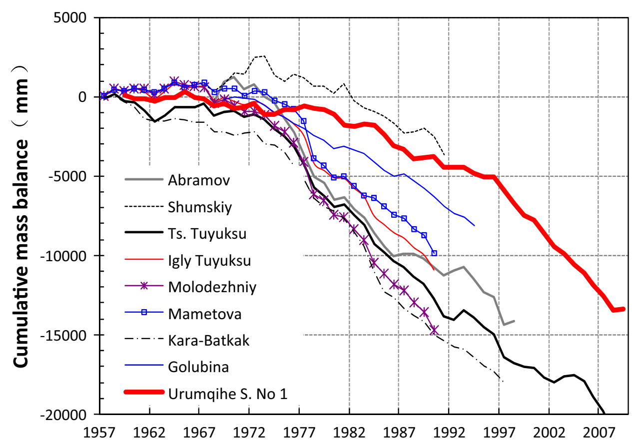

Fig. 2 Cumulative annual net mass balances for nine monitored glaciers in the Tianshan Mountains

2.2 Observed mass balance changes in the Tianshan Mountains between 1957 and 2009

Mass balance variations of Tianshan glaciers have been highlighted in many scientific papers (Dyurgerov et al. 1992, 1994; Cao 1998; Aizen et al. 2006; Sorg et al. 2012). Figure 2 shows the cumulative mass balance of the nine glaciers from 1957 to 2009, displaying a general negative mass-balance trend during the whole recorded period. From 1950s to the early 1970s, most observed glaciers show quasi-stable mass balance changes with some periods indicating slight mass gain. Starting with variously low positive or low magnitude negative mass balances in the 1950s and 1960s, the mass loss rates for eight of the nine glaciers (Urumqihe No. 1 being the exception) accelerated abruptly in the 1970s. Some glaciers, including Urumqihe

Table 2 Correlation coefficients (R) of annual balances during the concurrent period of observations (1969–1990)

	Abramov	Shumskiy	Ts. Tuyuksu	Igly Tuyuksu	Molodezhniy	Mametova	Kara-Batkak	Golubina
Abramov	1							
Shumskiy	0.47	1						
Ts. Tuyuksu	0.78	0.59	1					
Igly Tuyuksu	0.64	0.52	0.94	1				
Molodezhniy	0.71	0.50	0.95	0.98	1			
Mametova	0.58	0.55	0.78	0.85	0.84	1		
Kara-Batkak	0.57	0.32	0.70	0.72	0.68	0.41	1	
Golubina	0.56	0.41	0.69	0.59	0.58	0.49	0.46	1
Urumqihe No.1	−0.01	−0.02	−0.12	0.01	−0.02	−0.01	0.16	0.06

Negative values indicate inverse correlation

No. 1, continued to become more negative through the 1990s, such that all nine glaciers have exhibited sharp negative trends since the 1980s (with a few exceptional years of positive or near-zero balances).

Although the plots of cumulative mass balance show some discrepancies between individual glaciers, the overall consistency of their variation is indicated during several remarkable periods. In Fig. 2, at least five sequences of years are detected that shows a common positive mass balance: 1963–1964, 1969, 1972, 1979–1981 and 1992–1993. On the other hand, consistent negative mass balance periods are also obvious: 1968, 1971, 1975–1978 and 1983–1984. Glaciers located in the inner part and north slope of central Tianshan, such as the Kara-Batkak glacier and the Ts. Tuyuksu glacier, experienced the most negative mass balance, whereas glaciers in far north or east part of Tianshan, such as the Shumskiy glacier and the Urumqihe No.1 glacier, were comparatively gentle in their mass lose rates. Correlative analysis of their annual mass balance variation for the concurrent period of observation (1969–1990) show that mass balance series has more similar variation pattern if they are closer to each other, such as mass balance of glaciers in the Tuyuksu catchment show nearly the same variation trend (Table 2). The Ts. Tuyuksu glacier shows the highest correlation with others with a mean $R^2 = 0.72$, whereas the Urumqihe No.1 glacier showing the lowest correlation between the others with a mean $R^2 = 0.16$.

3 Mass balance modeling

3.1 The temperature-index mass balance model

There are many methods to calculate a glacier mass balance (e.g. Braithwaite and Zhang 1999; Oerlemans and Reichert 2000; Hock 2005; Machguth et al. 2009). For simple and acceptable solutions, a classical temperature index method (degree day model) (Braithwaite and Zhang 2000; Hock 2003; Rasmussen et al. 2011) and an extended model including information on the global radiation (Hock 1999) have been widely used in glacier mass balance modeling studies. In this study, we calculated annual mass balance of five selected glaciers (Table 1; Fig. 1) in the Tianshan Mountains based on a degree day model developed by Braithwaite and Zhang (2000), in which annual balance (B_a) for the whole glacier was estimated as a sum of specific mass balance of each elevation band:

$$B_a = \frac{1}{S}\sum_{1}^{n} S_i b_i \tag{1}$$

where n is the number of elevation bands, b_i is the specific annual balance and S_i is the area of altitude band i, and S is total glacier area, which are from the glacial hypsometry data (glacial area-altitude distribution) in the FoG report of 'Fluctuations of Glaciers 1985–1990' (WGMS 1993). For specific mass balance of each elevation band, the b_i is defined as:

$$b_i = c_i + a_i \tag{2}$$

where c_i and a_i is the accumulation (positive) and ablation (negative), respectively, for the specific elevation band.

Ablation of snow and ice is calculated based on assumption that melt is linearly correlated to the air temperature, which is usually expressed as positive degree day sums (PDD, °C) multiplied by a degree day factor (DDF, mm °C^{-1} day^{-1}):

$$a_i = DDF \cdot PDD_i \quad (when\ T_i > T_0) \tag{3}$$

where T_i is air temperature at the specific elevation band and T_0 is a threshold temperature for melt. To simplify the model, we assume that ablation occurs when the air temperature is above zero ($T_0 = 0$ °C) (e.g., Huss et al. 2008; Machguth et al. 2009; Rasmussen and Wenger 2009; Rasmussen et al. 2011). Previous studies have suggested that the degree day factors for snow are generally lower than ice

Table 3 Calibrated parameters of mass balance model for the five selected glaciers

Glacier	DDF (snow) (mm °C^{-1} day^{-1})	DDF (ice) (mm °C^{-1} day^{-1})	−dT/dz (°C 100 m^{-1})	DP/dz (altitude ranges) (mm month^{-1}, 100 m^{-1})	$T_{threshold}$ (°C)
Abramov	5.8	6.9	0.58	+30 (<4350 m); +23.3 (>4350 m)	2.5
Shumskiy	2.5	4.1	0.61	+3.3 (<3860 m); −10 (>3860 m)	2.0
Ts. Tuyuksu	4.1	5.7	0.39	+6.7 (<3850 m); −25 (>3850 m)	1.8
Golubina	4.6	6.5	0.47	+18.3(<4025 m); −43 (>4025 m)	2.1
Urumqihe No.1	5.0	6.7	0.41	+18 (<4225 m); −5 (>4225 m)	2.0

(Braithwaite and Zhang 1999, 2000; Hock 2003), the DDFs in the model are separately determined for snow and ice.

Accumulation at the specific elevation band is estimated by assuming that precipitation at this altitude (P_i, extrapolated from the nearby ERA-40 grid data) is split between rain and snow when the air temperature is above or below a threshold temperature ($T_{threshold}$):

$$C_i = \begin{cases} P_i, & T_i < T_{threshold}; \\ 0, & T_i \geq T_{threshold} \end{cases} \tag{4}$$

where T_i is air temperature at the specific elevation band and $T_{threshold}$ the snow/rain threshold temperature determined by model calibration (see Table 3 in Sect. 3.3).

Although evaporation and sublimation may contribute significantly to the energy balance (Wagnon et al. 1999), they are usually neglected in the ablation calculation in most degree day models for their small contribution to the total balance of glaciers (Hock 2003; Radić and Hock 2006). Few studies have quantified the contribution of evaporation and sublimation to the total balance of glaciers in the Tianshan due to the lack of observational data. According to Aizen et al. (1996), Cicenko suggested in 1966 that evaporation could be balanced by condensation on glaciers in the Central Tianshan. Refreezing is not taken into account and we assumed that any melt water and rainfall is immediately removed away from the glacier. The preceding two simplifications (neglecting evaporation and sublimation, and refreezing) each have opposite signs in terms of their effect on calculated versus actual mass balances. If they each have small magnitudes, the net error due to these simplifications is expected to be small.

3.2 ERA-40 climate data for model forcing

For the required model inputs of temperature and precipitation, the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data is used. The ERA-40 data is a global reanalysis for the period mid-1957 to mid-2002, with a temporal resolution of 6 h and spectral resolution T_L159 (~125 km), corresponding to a grid spacing close to 125 km (1.125°) (Simmons et al. 2004). The ERA-40 data set is integrated forward and combined with observational data for the simulation period, such that its temperature and precipitation series correlate well with observations and capture their interannual variability (Radić and Hock 2006). Due to the limited climatic observations in the Tianshan region, especially for the higher locations close to the glaciers, it is impracticable to validate the ERA-40 data sets. Radic and Hock (2006) suggested that the ERA-40 data can be used for mass balance modeling independent of meteorological observations, which is also confirmed by Rye et al. (2010).

In this study, we use monthly ERA-40 data of 2 m air temperature and total precipitation from five grid points nearest to the studied glaciers (Fig. 3a). Based on the elevation differences between ERA-40 grid points and glacier locations, the air temperature and precipitation are linearly interpolated by the calibrated lapse rates *dT/dz* and *dP/dz*, which are the calibrated parameters for the model running (see the next section). As an example of the interpolated result, Fig. 3b shows the comparison of winter (DJF), summer (JJA) and annual mean air temperature and total precipitation averaged over 1957–2002 between the five studied glaciers that from western to eastern Tianshan Mountains. Seasonal cycles for temperature and precipitation at each glaciers are shown in Fig. 3c. Climatology of the five glaciers resulting from the ERA-40 data is well consistent with the generally acknowledged understanding of the spatial patterns of climatic conditions of the Tianshan Mountains: (1) the outer ranges in western (Abramov Glacier) and northern (Shumskiy Glacier) Tianshan with a relatively moist climate, (2) the inner ranges in central Tianshan (Ts. Tuyuksu Glacier) and eastern Tianshan (Urumqihe No. 1 Glacier) with a pronounced continental climate, and (3) relatively more precipitation occurs during cold seasons in the western (Abramov Glacier) than the eastern (Urumqihe No.1 Glacier) Tianshan (Sorg et al. 2012).

3.3 Model operation and calibration

The model runs for a 45-year period (1957–2002), using monthly time step. Model inputs include monthly PDD of air temperature (T), monthly total precipitation (P), mean

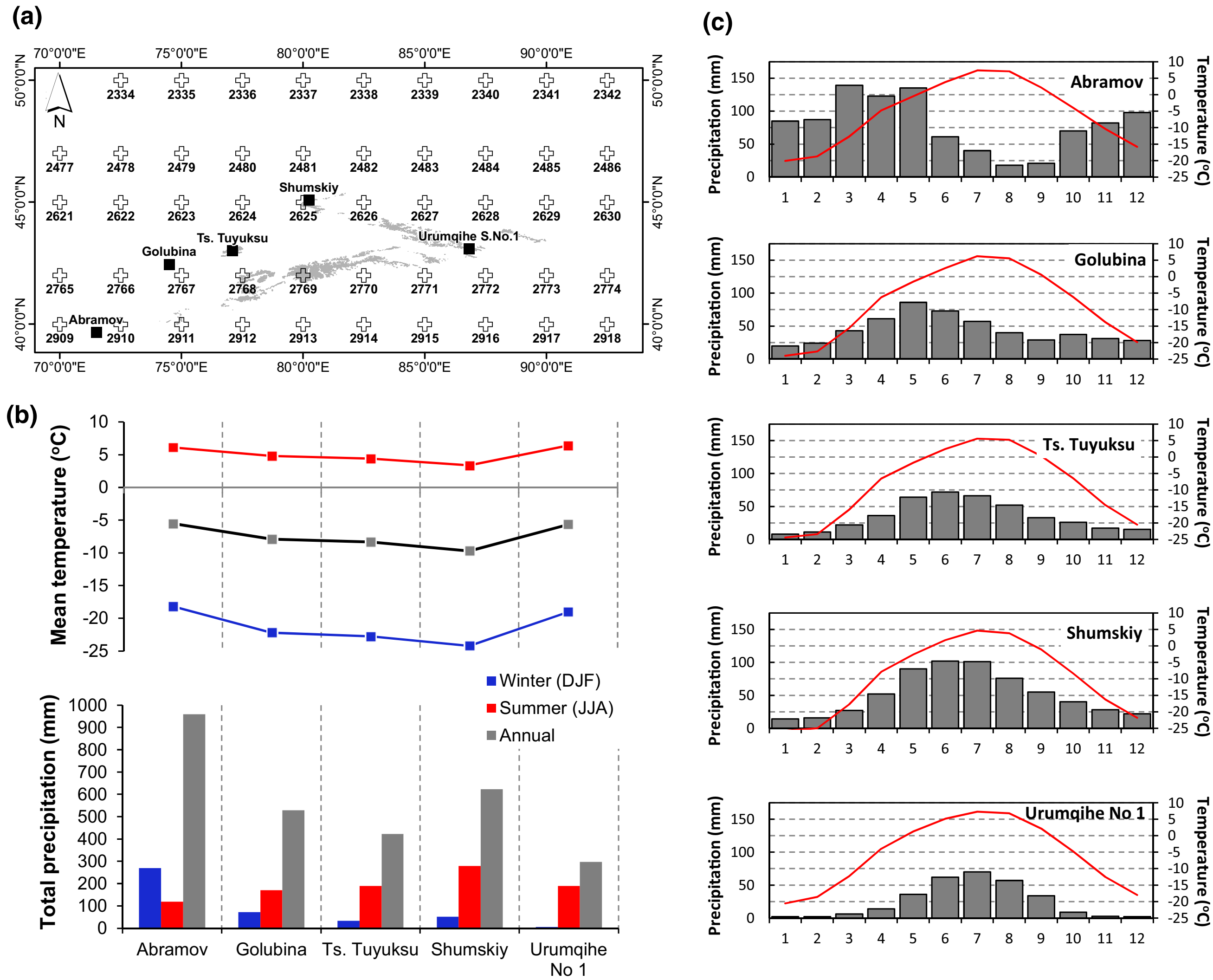

Fig. 3 **a** Locations for ERA-40 grid (*white cross*) and the five glaciers (*black square*); **b** comparison of winter (DJF), summer (JJA) and annual mean air temperature and total precipitation between five studied glaciers over the period 1957–2002; **c** monthly distribution of temperature (*red line*) and precipitation (*grey bar*) at the mean elevation of each glaciers

altitude (m asl) and glacier area (s_{band}) of each specific elevation band (Fig. 4). Monthly PDD of temperature and sum of precipitation are calculated based on the nearest ERA-40 daily gridded data described above. They are linearly interpolated to the each altitude of specific band based on the calibrated temperature and precipitation lapse rates (*dT/dz* and *dP/dZ*) for individual glaciers.

The model outputs include annual mass balance (B_a), balance for each elevation band (b_i) and the equilibrium-line altitude (ELA, where $b = 0$ and is calculated by fixing the elevation of the zero balance point on the balance gradient db/dz). For each glacier, we calibrate the model over the periods before 1980 based on available observed mass balance data, and then validated the model with the measurements obtained after 1980. Available data of mass balance gradients of the five selected glaciers covers only a limited period (Table 1). For each elevation band, mean annual (October–September), summer (April–September) and winter (October–March) balance for the period 1957–1980 are calculated. These mass balance profiles are used to calibrate the mass balance model (Fig. 4).

We calibrate the model based on (1) observed annual mass balances of five glaciers between 1957 and 1980; (2) observed multi-year mean mass balance profiles and ELA of five glaciers. To best match these two criteria, we adjust values for the following model parameters: degree-day factors (DDFs) for snow and ice, temperature laps rate (*dT/dz*), monthly precipitation lapse rate (*dP/dz*) and temperature thresholds ($T_{threshold}$) for snow-rain separations. Since no direct observations support the dT/dz and dP/dz, they are deduced from the fit of model results to measured balances. For dT/dz, the value variation ranges are constrained

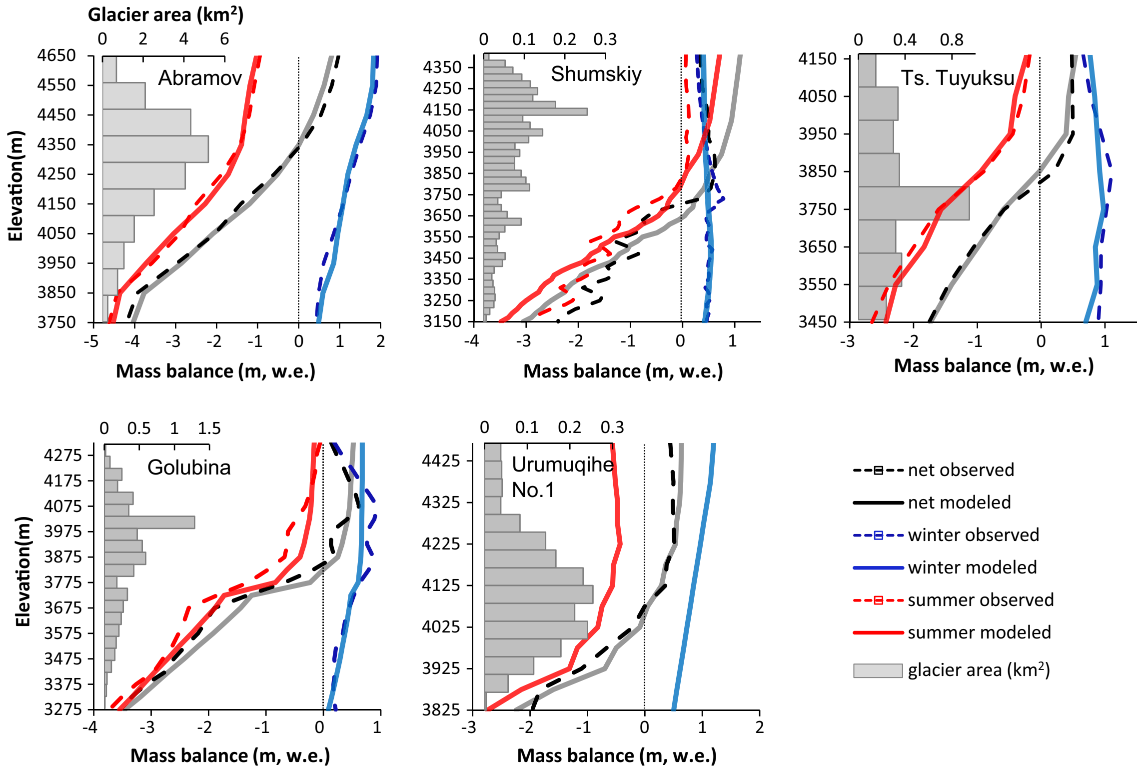

Fig. 4 Observed and model calibrated mean annual, winter and summer mass balance profiles, and glacier area distribution with specific elevation bands of the five selected glaciers. Note that the altitude intervals are different for each glaciers, depending on the original dataset released by the WGMS

between 0.4 and 0.7; for dP/dz, we use observed winter profiles (db/dz in winter) to derive its initial values. Observed winter profiles (Fig. 4) show that linear precipitation gradients do not always work well on some glaciers, e.g., the Shumskiy, Golubina and Ts. Tuyuksu Glacier. Therefore, *dP/dz* is calibrated for different altitude ranges for these glaciers. For the Urumqihe No. 1 glacier, summer and winter MB data was not available in the WGMS database. Its winter balance is calibrated based on annual report of WGMS (WGMS 2011), that the amount of precipitation on the glacier is estimated as 600–700 mm at about 4100 m a.s.l. Table 3 lists the calibrated parameters for each glacier.

4 Model results

4.1 Modeled annual mass balance between 1957 and 2002

Comparisons of observed and modeled annual, winter and summer balance for the five glaciers are shown in the Fig. 5. For most cases, remarkable positive or negative mass balance years are well reproduced by the model. Take the Ts. Tuyuksu Glacier as an example, the model well reproduced the mass balance changes between 1970s and earlier 1980s. Both the sharp decline in the annual mass balance between 1972 and 1978 and the following increase in mass until 1981 are presented in the model results. Compared with the winter balance, the modeled annual and summer balances show more similar temporal variation trends (Fig. 5) with the observations. For the errors between observed and modeled values during the period of model running, the results yield an overall standard deviation of 0.318 m for the annual mass balances, 0.223 m for summer and 0.305 m for winter (Fig. 6).

The model performs generally well in reproducing the mass balances changes of the five glaciers during the period of 1957–2002. However, there exists some larger deviations in the model results compared with the respective measurements, i.e., several significant over or underestimations are found in the results. The reported extreme positive mass balance (1.35 m w.e.) of the Abramov Glacier in 1969 is not reproduced by the model output (0.18 m w.e.). For the extreme negative mass balance years, such as in 1984 and 1997, the model output obviously overestimates and

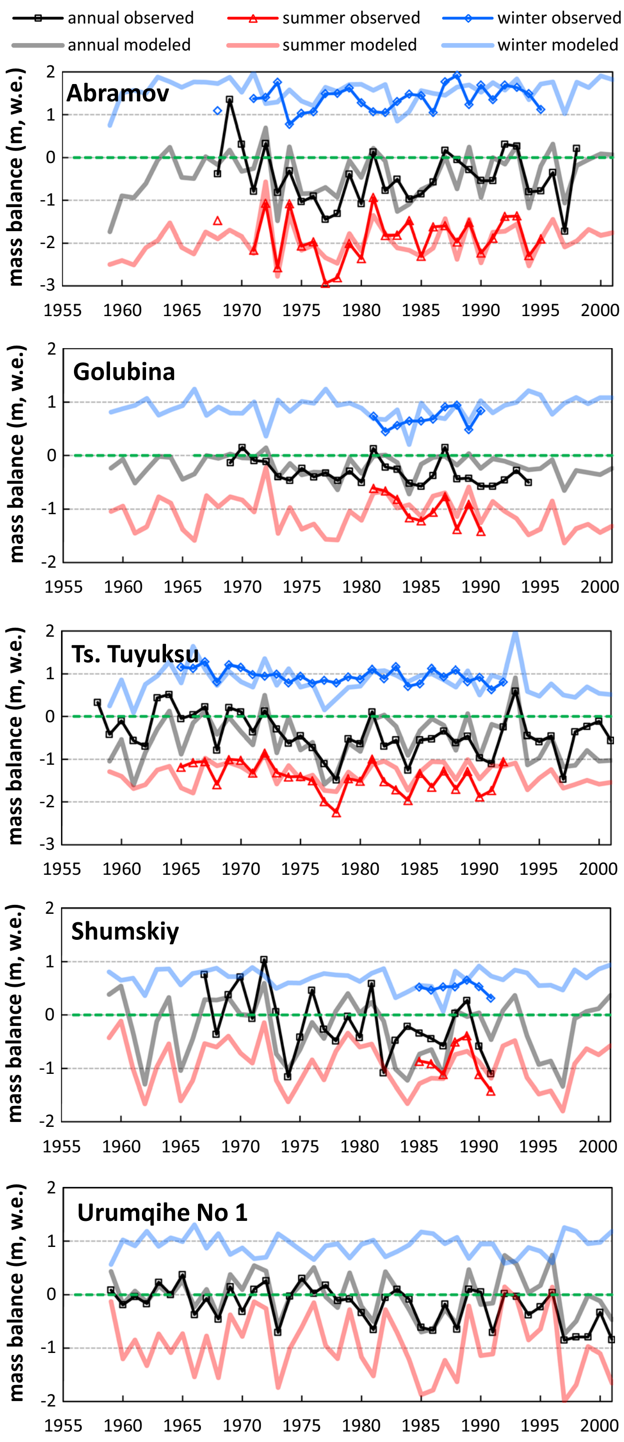

Fig. 5 Observed and model annual, summer and winter balance of five selected glaciers (1957–2002)

underestimates the mass balance levels, respectively. In other cases of some specific periods, the modeled mass balances are overall overestimated (e.g. results of the Golubina Glacier between 1989 and 1994) or underestimated (e.g. results of the Ts. Tuyuksu Glacier between 1958 and 1966).

4.2 Mass balance sensitivity to air temperature and precipitation increases

After the model parameters are calibrated, sensitivity experiments are carried out to explore the differences in the response to climate change for the five glaciers. The sensitivity analysis is done by performing model runs with perturbed conditions for each step-wise of +1 and −1 K changes in temperature and +10 and −10 % in precipitation from the mean values over the period 1957–2002. Table 4 shows the calculated static sensitivities of the mass balances and ELAs for the five selected glaciers, relative to their mean values for the reference period 1957–2002. These results yield a mean temperature sensitivity of −0.89 m w.e. a^{-1} K^{-1} and precipitation sensitivity of +0.46 m w.e. a^{-1} (10 %)$^{-1}$. For the temperature sensitivity, comparing with previous sensitivity experimental studies, our results are slightly higher, e.g., than other studies of glaciers in high Asia (−0.5 to −0.2 m w.e. a^{-1} K^{-1}) (Liu et al. 1998; Rasmussen 2013) and glaciers in French Alps (−0.25 to −1.55 m w.e. a^{-1} K^{-1}) (Six and Vincent 2014), Sweden (−0.41 to −0.61 m w.e. a^{-1} K^{-1}) (Hock et al. 2007), and global mean (−0.35 to −0.41 m w.e. a^{-1} K^{-1}) (Oerlemans and Fortuin 1992; Braithwaite and Raper 2002; Raper and Braithwaite 2006), but much lower than the New Zealand Southern Alps (−1.1 to −4.0 m w.e. a^{-1} K^{-1}) (Anderson and Mackintosh 2012).

It is obvious that the mass balances of these glaciers are far more sensitive to a 1 K temperature change than to a 10 % precipitation change. Approximately, to maintain the mass balance, a 1 K temperature change would have to be accompanied by about 23 % precipitation increase or decrease. Mass balance changes under colder (−1 K temperature) and drier (−10 % precipitation) climates show less sensitivities than that of warmer and wetter conditions. As the air temperature increases or precipitation decreases, specific mass balance in all elevation bands of these five glaciers experienced a remarkable negative trend, due to which the ELAs accordingly rise significantly. For the ELAs, the results yield a mean sensitivity of +159 m K^{-1} and −87 m (10 %)$^{-1}$ for temperature and precipitation increasing, respectively.

Among the five modeled glaciers, the Abramov Glacier and Ts. Tuyuksu Glacier show the highest sensitivity to climatic conditions and the Shumskiy Glacier is least sensitive. An extreme case occurred on the Ts. Tuyuksu glacier: after a 1 K warming, its new ELA (4337 m) has exceeded its uppermost elevation (4219 m), indicating that the entire glacier area will be exposed to dominant ablation and with very limited accumulation. For the Shumskiy Glacier, the conditions of ELA exceeding the highest points on the glaciers would need an additional 677 m rise of ELA and the Urumqihe No.1 Glacier about 312 m. The Shumskiy

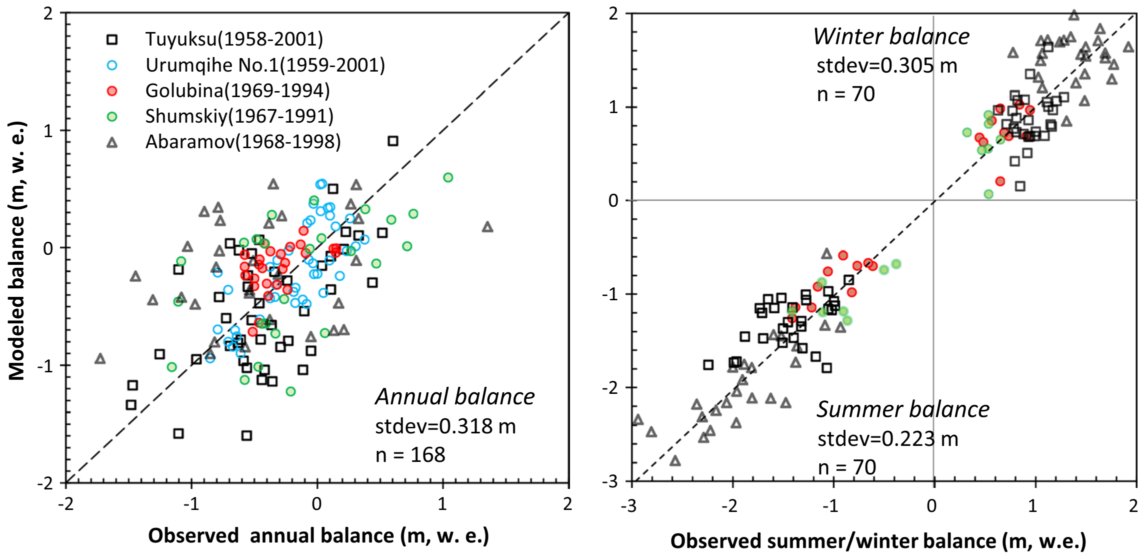

Fig. 6 Comparison of observed and modeled annual, summer and winter balance for the five glaciers

Table 4 Static sensitivities of mass balance and ELA to temperature and precipitation changes (results are relative to the reference period 1957–2002 value)

Glacier	Changes of mass balance (m, w.e.)				Mean ELA	Changes of ELA (m)			
	T + 1 K	T − 1 K	P + 10 %	P − 10 %	(1957–2002)	T + 1 K	T − 1 K	P + 10 %	P − 10 %
Abramov	−1.26	1.04	0.70	−0.34	4392	+189	−157	−106	+50
Golubina	−0.88	0.62	0.50	−0.26	3968	+201	−144	−116	+60
Ts. Tuyuksu	−1.00	0.78	0.56	−0.28	3917	+229	−179	−128	+65
Shumskiy	−0.55	0.53	0.38	−0.20	3736	+61	−58	−42	+22
Urumqihe No.1	−0.77	0.62	0.28	−0.22	4078	+115	−94	−43	+33

Glacier seems more healthy, as it will still hold a significant part of their area within the accumulation zone after a +1 K warming.

5 Discussions

5.1 Uncertainties in the mass balance calculation and the regional mean estimations

Other than modeling approaches, there are three methods for determining the glacier mass balance: glaciological, geodetic and hydrological (Paterson 1994). The geodetic method is the most trusted result to reflect long-term mass balance changes and usually used to calibrate the other methods. However, available geodetic measurements data are very limited and can not offer information about annual, seasonal and spatial patterns of mass balance. For the glaciological method, according to Cogley (2005), uncertainty of directly obtained annual surface mass balance of a single glacier is typically 200 kg m^{-2} a^{-1} (or 222 mm a^{-1} w.e.) due to measurement and analysis errors. The hydrological method calculates the mass balance from the difference between precipitation and discharge by neglecting the sublimation, evaporation and groundwater variations (Sicart et al. 2007; Liu et al. 2010). Hagg et al. (2004) compared the results from three mass balance determination methods applied on the Tuyuksu glacier region and suggested a mean difference of about 100 mm w.e. a^{-1} between geodetic method and glaciological method over the period of 1958–1998.

In this study, observed mean mass balance profiles for the five glaciers between 1957 and 1980 are used to calibrate the model so as to improve the reliability of the modeled winter and summer mass balances (Fig. 4), by which we assume that the amplitude of modeled annual balance is guaranteed. In Fig. 7, we compare the modeled averaged annual balances for five selected glaciers with that of the observed and find that they agree well with each other. This indicates that the simplifications of the model are acceptable here. It shows obviously negative correlation with the mean summer (April–September) temperature

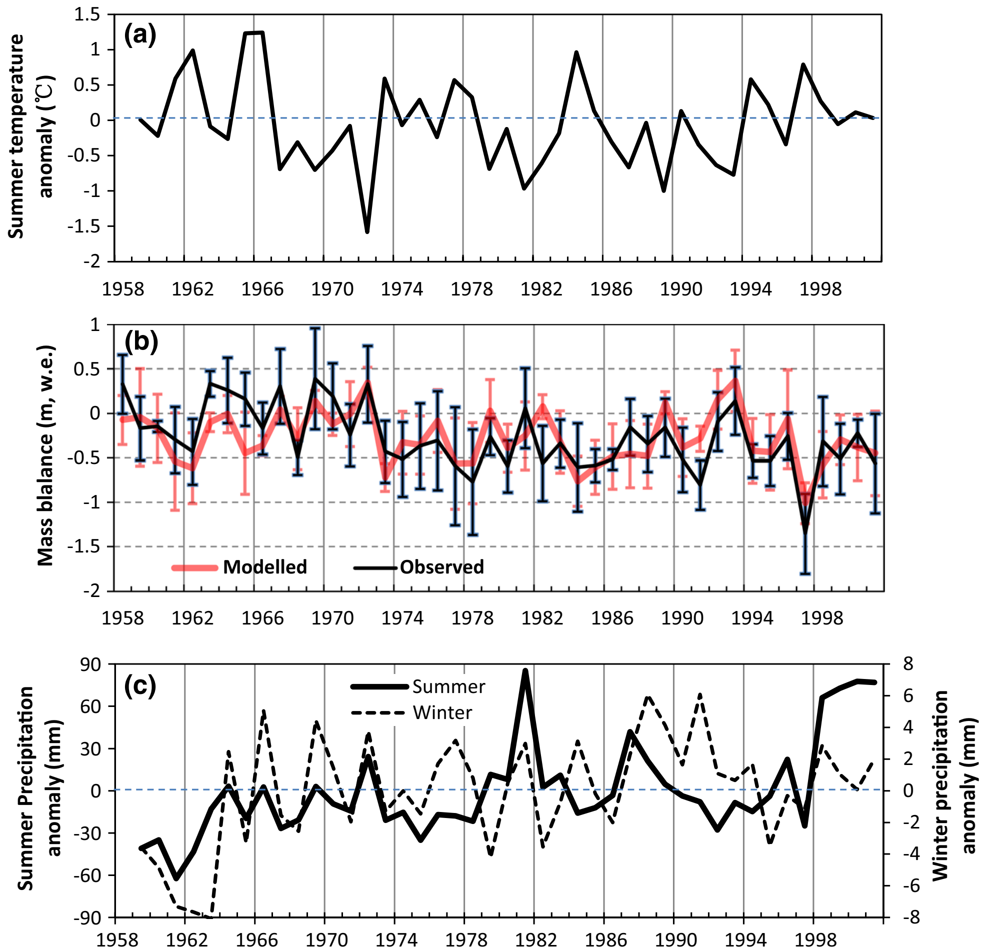

Fig. 7 **a** Mean summer temperature anomaly of ERA-40 gridded data; **b** observed and modeled mean MB of the five glaciers and **c** mean summer and winter precipitation anomaly of ERA-40 gridded data

($R^2 = 0.689$) and slightly positive correlation with precipitation. These glaciers, except for the Abramov Glacier, are classified as summer accumulation type since precipitation between April and September occupies 66–79 % of the annual total. Temperature changes during April and September then play more important role in the MB distribution by altering the percentage between solid and liquid rainfall. Therefore, the mass balance variations in the Tianshan Mountains are mainly caused by air temperature changes; that they are inversely correlated with each other over the entire model run period. Mass balances in some years with extreme high or low precipitation, however, are more or less accumulation dominated.

Although the model itself is simple, only monthly air temperature and precipitation are used as the input, the good correlations of modeled and observed annual mass balance variation displayed in Figs. 5 and 7 confirm that the ERA-40 data is practicable in the mass balance modeling study of mountain glaciers (Radić and Hock 2006; Rye et al. 2010). The model applied here neglects glacier area variations over the past 50 years, i.e., calculated mass balance summed across the glacier will be more negative than actual total glacier mass balance due to neglecting the mass loss of some fraction in the lower ablation altitudes, where ablation rates are high. Observed rates of regional glacier area changes in the Tianshan Mountains ranges from -0.23 % a^{-1} for entire Tianshan (1943–2000; Aizen et al. 2007b) to -0.73 % a^{-1} for northern Tianshan (1955–1999; Bolch 2007). Glacier area-altitude distribution used in our model is not changed (using the values of 1985–1990) during the whole model run period, and that will lead to a growing overestimate of mass loss for the period 1990–2002 compared to the WGMS-reported data (Elsberg et al. 2001; Kaser et al. 2006; Huss et al. 2012).

Additionally, the area of glaciers with mass balance observation occupy only a very small portion [<0.3 % of the total glacierized surface in the Tianshan Mountains, according to data reported by Dyurgerov et al. (1992)], and for most sites in short time scale (<15 years). Most glaciers in Tianshan are "clean" (debris free) but some of them covered by debris, such as several dendritic type glaciers developed around the Tomur Peak in the inner Tianshan, which are mantled by an extensive layer of thick debris. Ice melt rates under those debris differ from the clean ice but at present this is difficult to be determined due to the lack of comprehensive field observations and limited model development (Hagg et al. 2008). Recently, some efforts have given to a big debris covered glacier located at the southern Tomur, the Koxar Glacier, including energy balance and melt processes of ice under the debris with varying thickness (Han et al. 2005), ice cliffs (Han et al. 2010) and also ice contacted with supraglacial lakes or ponds (Xin et al. 2011; Liu et al. 2015). In order to reconstruct and predict mass balance changes of Tianshan glaciers, future model building should be enhanced by more reliable meteorological input, with more persuasive physical expression and calibrated by substantive in situ related observations.

5.2 The discrepancy of mass balance responses

The discrepancy of mass balance responses of the five glaciers is mainly due to their different location and hypsography. Even if under the concurrent background of regional climatic conditions changes, glaciers will respond individually due to their different aspects, sizes, shapes and altitudinal ranges, etc. (Oerlemans et al. 1998). Glaciers respond to a climate change by adjusting its mass balance distribution, e.g., increasing the accumulation area ratio (AAR), until its net mass balance approaches zero and glacier reaches a new equilibrium status (Johannesson et al. 1989; Raper and Braithwaite 2009; Kargel et al. 2013). Lower balance gradients are found on glaciers in the drier polar and sub-polar regions (Oerlemans and Fortuin 1992) and tremendous mass turn over on glaciers in maritime climate regions, e.g. New Zealand (Anderson and Mackintosh 2012), Norway (Rasmussen 2004; Rasmussen et al. 2007) and southeastern Tibet (Aizen and Loktionova 1994; Xie et al. 1999), etc. For the five selected glaciers in this study, their observed mass balance profiles for the period 1957–1980 show large difference in both altitudinal ranges and the db/dz slopes (Fig. 4). These differences are mainly due to their individual hypsography (area distribution with elevation). Glaciers with more area extending to lower elevations, such as the Abramov Glacier, Ts. Tuyuksu Glacier and Golubina Glacier, are more sensitivity to air temperature increase. On the other hand, glaciers with most area distributed in higher elevation, such as the Shumskiy glacier, are insensitivity to the increase of air temperature (Table 4).

The sensitivity of glacier mass balance response to climatic changes is also influenced by monthly distribution of precipitation. Accumulation of glaciers in the Tianshan Mountains is dominated by summer precipitation. Based on the ERA-40 data at five points used for the model input, the precipitation amount between April and September occupy 66–79 % of the annual totals (Fig. 3). Temperature changes during April and September then play a more important role in the mass balance distribution by altering the percentage between solid and liquid precipitation. The Abramov Glacier receives remarkable more precipitation between March and May, in which seasons the percentage between solid and liquid precipitation is highly sensitive to temperature changes. As a consequence, the Abramov Glacier display the highest sensitivity to climatic changes. For the Golubina Glacier and Ts. Tuyuksu Glacier, they receive the maximum precipitation in May and June, earlier than that of the other two glaciers (in July for the Shumskiy and Urumqihe No. 1 Glacier), they therefore show higher sensitivities than the latter (Table 4).

The stability of these glaciers, however, depends on how sensitivity of their ELA fluctuations with respect to the mass balance changes. By plotting the annual ELA against the B_a, the steady state ELA can be indicated by the intersection of the best fit lines and the vertical lines of zero net annual balance ($B_a = 0$) (Benn and Lehmkuhl 2000). Based on the observed ELA of the five selected glaciers, their variations rhythms are nearly synchronized whereas the amplitude and the varying rates are different (Fig. 8). Therefore, over the studied period (1957–2002), only the Shumskiy Glacier was close to the balance budget, with a mean ELA (3666 m asl) about 7 m higher than the balance budget ELA (3659.5 m asl); whereas for the other four glaciers, the mean ELAs were much higher than the steady state ELAs (65, 90, 79 and 23 m for Abramov, Ts. Tuyuksu, Golubina and Urumqihe No.1 Glacier, respectively). It is interesting to note that glaciers with lower regression line slope of ELA against B_a are inclined to be in the steady state, such as the Shumskiy Glacier. Dyurgerov et al. (1992, 1994) have suggested that the relationship between long-term records of ELA and B_a may be approximated by glacier cumulative hypsographical curves. Therefore, in other words, the state of a glacier and how it will respond to the climate variations could be, to some extent, indicated from its hypsography.

6 Conclusions

We have combined mass balance data of nine monitored reference glaciers in the Tianshan Mountains to display their discrepancy and consistency during the second half of the twentieth century. A temperature index mass balance model, forced by the ERA-40 reanalysis climatic data, was

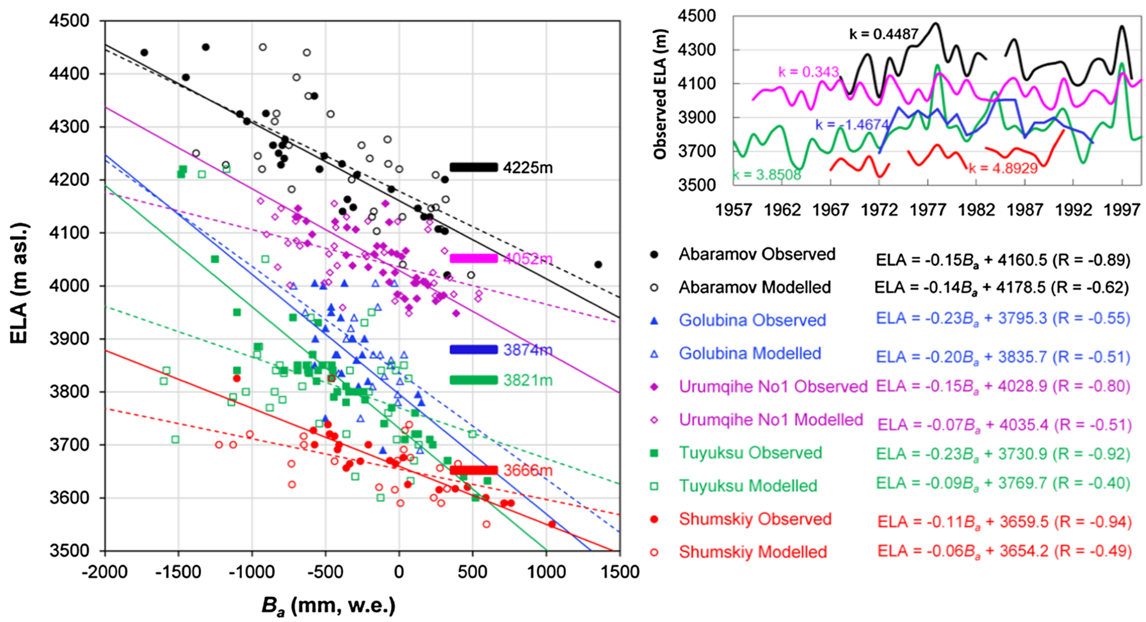

Fig. 8 Correlations between ELA and B_a for the five studied glaciers plotted with *colored regression lines*, note that it is marked with the mean ELAs over the observation periods for each glacier, their linear-fit equations and R values are listed in the right; *Right above* observed ELA variations and trends (marked by k values, k = dELA/dt) of the five glaciers between 1957 and 2000

applied on five well monitored glaciers to discuss its applicability and see how climatic condition changes impact on different glaciers. Our main conclusions are as follows: (1) Mass balances of Tianshan glaciers show generally negative trends during the past half century. However, their mass balance variations show remarkable heterogeneous due to the different location and glacier hypsometry. (2) Mass balance modeling experiments show different glaciers have different responses to climate dynamics, indicated by their discrepancies in mass balance sensitivity to temperature or precipitation changes. It is also suggested that mass balances of Tianshan glaciers are more sensitive to temperature changes than precipitation changes as in other areas. (3) The simple temperature index model we used can well produce the mass balance fluctuations and the events in several typical years with extreme positive or negative values. The model applied here is simple, but there exists much space for the model improvement. The modeling approaches will be potentially applicable for long time periods reconstruction and prediction of glacier mass balance variations in the Tianshan Mountains.

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