Spatial Heterogeneity in Glacier Mass-Balance Sensitivity across High Mountain Asia

Table S1. Detailed information of monitored glaciers used to model mass balance in HMA.

Glaciers	Orientation	Lat N	Lon E	Area km²	Low-high elevation m a.s.l.	Monitoring period
Muztag Ata	W	38.23	75.05	1.087	5233–5927	2005–2010
Siachen	NW/SE	35.47	77.04	1078.26	3620–5753	1999–2007
AX010	E/SE	27.70	86.57	0.57	4952–5360	1996–1999
Yala	E/SE	28.25	85.62	1.61	5168–5661	1996–1999
Pokalde	NW	27.90	86.80	0.08	5430–5660	2010–2014
Changmekhangpu	S	27.95	88.68	4.43	4840–5520	1980–1986
Parlung No.12	NE	29.30	96.90	0.23	5139–5375	2005–2010
Parlung No.10	NE	29.28	96.90	4.433	4907–5636	2005–2009
Parlung No.94	NW	29.38	96.97	2.792	5037–5635	2005–2009
Parlung No.390	SE	29.35	97.02	0.372	5195–5469	2006–2009
Baishui Glacier No.1	E	27.10	100.19	1.281	4390–5096	2009–2013
Leviy Aktru	E	50.08	87.72	5.95	2559–4043	1977–2010
Maliy aktru	NE	50.04	87.74	3.8	2220–3710	1962–2010
Praviy	NE	50.08	87.73	4.8	2480–3750	1980–1990
Shumskiy	N	45.08	80.23	2.81	3126–4464	1968–1991
Muravlev	N	45.10	80.23	0.92	3378–4040	1979–1991
Urumqi No.1	N	43.11	86.81	1.58	3773–4443	1959–2014
Golubina	NW	42.46	74.49	6.21	3250–4437	1969–1994
Ts.Tuyuksu	N	43.05	77.08	2.66	3414–4219	1957–2010
Igly Tuyuksu	N	43.05	77.09	1.72	3450–4220	1957–1964
Molodezhniy	E	43.05	77.06	1.43	3450–4150	1957–1964
Mametova	NW	43.07	77.10	0.35	3610–4190	1957–1964
Kara-Batkak	NW	42.14	78.27	4.19	3293–4829	1957–1998
Sary	NW	41.83	78.17	2.64	3950–4800	1985–1990
Mayakovskiy	NW	43.02	77.11	0.18	3570–4000	1976–1990
Ordzhonikidze	NW	43.06	77.10	0.31	3480–4120	1976–1990
Zoya	NE	43.05	77.07	0.36	3570–4070	1976–1990
Visyachiy	N	43.04	77.08	0.6	3480–3850	1976–1990
Akshiyrak	NW	41.79	78.15	6.47	3746–4679	2011–2014
Abramov	N	39.62	71.56	22.5	3620–4960	1968–1996
Chorabari	N	30.76	79.05	6.72	6400–6895	2004–2010
Shaune	N	31.28	78.33	4.97	4400–5360	1982–1991
Tipra	N	30.73	79.68	7	3720–5730	1982–1988
Gara	NE	31.40	78.50	5.2	4710–5600	1975–1983
Gor Garang	SW	31.37	78.49	2	4760–5400	1977–1985
Neh Nar	NW	34.16	75.52	1.7	3920–4925	1976–1984
Kangwure	NE	28.45	85.75	1.327	5710–5994	1992–2010
Naimona'nyi	N	30.45	81.33	7.348	5539–7263	2005–2009
Dunagiri	N	30.55	79.90	2.56	4240–5150	1985–1990
Gurenhekou	SE	30.18	90.46	1.333	5585–6036	2005–2010
Zhadang	NW	30.47	90.63	1.506	5529–5958	2006–2008
Qiyi	N	39.24	97.75	2.531	4317–5113	1975–2010

Yanglonghe No.5	NE	39.23	98.57	1.243	4460–5228	1977–1979
Xiaodongkemadi	S/SW	33.17	92.13	1.8	5211–6095	1989–2010
Meikuang	N	35.75	94.30	1.053	4836–5504	1989–2000

Note: The continental glaciers are labeled in black letters, maritime glaciers with red letters, and subcontinental glaciers with blue letters. Muztag Ata of mass balance is adapted from the World Glacier Monitoring Service (WGMS) [1] and Zhu et al., 2018 [2], and Baishui Glacier No. 1 is adapted from Du et al., 2015 [3]. The long time series of mass balance for Urumqi No.1, Kangwure, and Qiyi have been reconstructed using the relationship between the monitoring mass balance and meteorological data [4].

Long time series of annual mass balance and mass balance gradient are an effective means of calibrating model parameters [5,6], and are used to constrain the simulation results according to the minimum root mean square error (RMSE) between modeled and observed mass balance series (or mass balance gradient series) at different time scales, such as annual, summer, and winter series during the period of observation. The parameters obtained by this method are regarded as the best optimization parameters. To achieve a minimum RMSE, we set the parameter step to iteratively obtain seven optimization parameters—Tlap, Glap, fsnow, fice, kp, dpre, and Tsnow (the ranges are shown in Table 1)—until the modeled mass balance agreed with the observed mass balance series. The optimization parameter is shown in Table S2.

For those annual glacier mass balance monitoring periods less than five years, even those without summer and winter annual or gradient mass balance data, the parameters obtained by minimum RMSE are still considered to be the best parameters. Figure 1 shows the mass balance gradient between the modeled and observed values during the monitoring period.

Table S2. The optimization parameters for 45 monitored glaciers in HMA. *Tlap* (°C(100 m)$^{-1}$), *kp*, *dpre* ((100 m)$^{-1}$), *Glap* (°C(100 m)$^{-1}$), *Tsnow* (°C), *fsnow* (mm w.e.d^{-1}°C^{-1}), *fice* (mm w.e.d^{-1}°C^{-1}).

Glaciers	*Tlap*	*kp*	*dpre*	*Glap*	*Tsnow*	f_{snow}	f_{ice}	RMSE
Muztag Ata	−0.53	5.00	0.14	−0.49	1.60	4.00	4.00	0.27
Siachen	−0.60	3.50	0.03	−0.42	1.80	4.20	5.90	0.32
AX010	−0.83	1.40	0.01	−0.56	2.00	4.00	8.40	0.21
Yala	−0.61	1.60	0.08	−0.64	0.80	4.00	4.20	0.47
Pokalde	−0.65	1.50	0.05	−0.50	0.60	3.00	7.00	0.31
Changmekhangpu	−0.60	1.70	0.07	−0.50	0.50	3.50	4.70	0.16
Parlung No.12	−0.61	2.80	0.06	−0.57	1.00	6.20	7.60	0.26
Parlung No.10	−0.61	2.80	0.05	−0.50	0.80	4.90	7.80	0.18
Parlung No.94	−0.54	2.80	0.01	−0.51	1.00	3.90	8.40	0.33
Parlung No.390	−0.61	2.80	0.07	−0.37	1.00	2.60	7.80	0.60
Baishui Glacier No.1	−0.60	3.70	0.01	−0.48	1.60	4.20	8.40	0.33
Leviy Aktru	−0.47	4.30	0.01	−0.34	0.80	3.40	4.00	0.28
Maliy aktru	−0.55	4.30	0.08	−0.40	0.80	2.80	4.00	0.32
Praviy	−0.55	5.70	0.00	−0.60	0.80	2.80	4.10	0.31
Shumskiy	−0.51	2.40	0.00	−0.40	2.00	2.00	4.00	0.53
Muravlev	−0.58	1.20	0.06	−0.37	0.80	3.20	4.20	0.37
Urumqi No.1	−0.65	1.70	0.01	−0.80	2.00	5.60	5.60	0.25
Golubina	−0.78	3.00	0.09	−0.46	0.80	2.00	4.00	0.30
Ts.Tuyuksu	−0.68	3.30	0.03	−0.36	1.80	2.50	4.00	0.41
Igly Tuyuksu	−0.65	3.30	0.10	−0.20	2.00	2.20	4.30	0.36
Molodezhniy	−0.68	3.30	0.11	−0.36	2.00	2.40	4.30	0.35

Mametova	−0.67	3.30	0.17	−0.25	1.60	2.30	4.00	0.55
Kara-Batkak	−0.69	4.00	0.08	−0.27	1.60	3.50	4.40	0.31
Sary	−0.69	4.41	0.01	−0.63	0.80	4.00	4.50	0.25
Mayakovskiy	−0.69	3.30	0.06	−0.46	0.80	2.50	4.20	0.33
Ordzhonikidze	−0.68	3.30	0.08	−0.26	2.00	2.40	4.30	0.34
Zoya	−0.75	3.30	0.08	−0.10	1.60	2.60	4.20	0.33
Visyachiy	−0.73	3.30	0.08	−0.10	1.40	2.60	4.20	0.36
Akshiyrak	−0.65	2.90	0.08	−0.50	1.60	2.10	4.10	0.28
Abramov	−0.82	2.30	0.00	−0.81	1.00	4.50	4.80	0.27
Chorabari	−0.70	2.00	0.03	−0.32	2.00	2.00	4.00	0.11
Shaune	−0.70	2.00	0.07	−0.16	1.40	3.10	5.40	0.22
Tipra	−0.65	2.10	0.02	−0.20	0.80	2.60	4.30	0.23
Gara	−0.67	1.50	0.05	−0.30	1.00	3.80	4.20	0.45
Gor Garang	−0.71	1.40	0.01	−0.28	1.60	2.80	4.40	0.34
Neh Nar	−0.85	3.60	0.01	−0.20	0.80	2.00	4.00	0.45
Kangwure	−0.40	1.10	0.07	−0.80	0.80	4.40	4.60	0.30
Naimona'nyi	−0.65	1.50	0.04	−0.64	0.80	3.90	4.20	0.14
Dunagiri	−0.67	2.10	0.04	−0.30	1.00	2.40	4.20	0.27
Gurenhekou	−0.79	1.40	0.01	−0.46	2.00	2.20	4.00	0.11
Zhadang	−0.74	1.40	0.01	−0.37	1.40	2.00	7.00	0.02
Qiyi	−0.57	4.60	0.10	−0.47	0.80	5.20	5.80	0.22
Yanglonghe No.5	−0.53	3.80	0.01	−0.60	0.80	2.20	4.00	0.28
Xiaodongkemadi	−0.62	3.00	0.07	−0.53	1.60	2.00	6.20	0.29
Meikuang	−0.65	3.90	0.04	−0.26	0.50	2.00	4.00	0.24

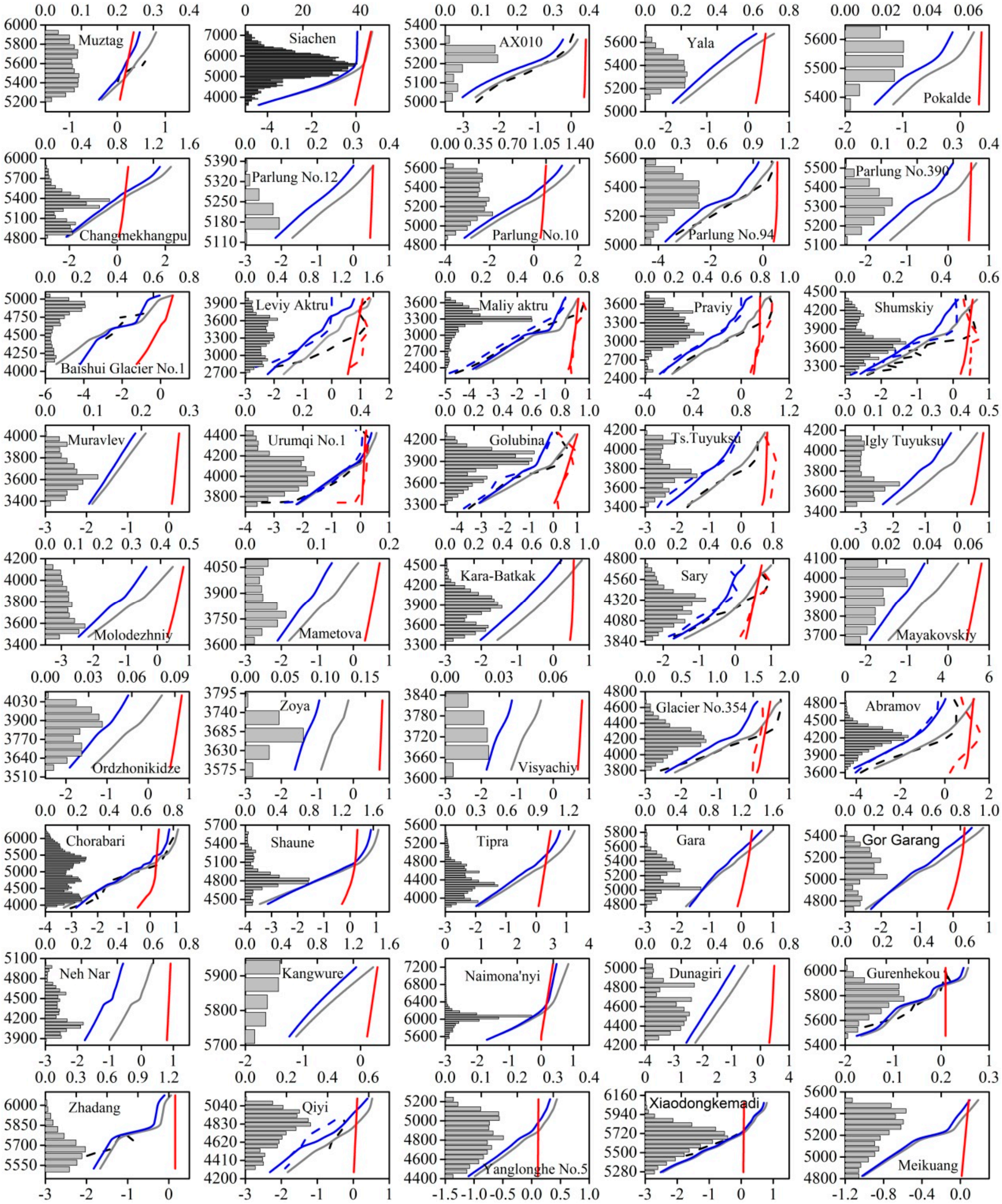

Figure S1. The comparison of the annual, summer winter and mass balance profiles for the observed and model calibrated. Note the upper axis is the glacier area, the y axis is the elevation (m a.s.l.), and the x axis is the mass balance (m w.e.). Siachen does not have observed data, while some observed results are from references, such as Muztag data from [7], Gurenhekou data from [8], Zhangdang data from [9], Xiongdongkemdi data from [10], Qiyi data from [11], Baishui glacier No. 1 data from [3]. Leviy Aktru, Maliy aktru, Praviy, Shumskiy, Muravlev, Urumqi No. 1, Golubina, Ts.Tuyuksu, Sary, Akshiyrak, Abramov, Chorabari, AX010, and Parlung No. 94 mass balance gradient data is from the WGMS.

Figure 2 shows the evolution of the long-term sequences of the modelled mass balance during the period of 1952–2014 in HMA. Although the mass balance values vary among the glaciers, the mass balance trends in same regions are similar. For the Altai, mass balance trends exhibit a good agreement because the glaciers are distributed in neighboring areas. In the Tianshan Mountains, the mass balance trend exhibit a clear acceleration starting in 1970, which is consistent with the cumulative observed annual mass balance results [5]. A negative–positive–negative change trend is observed in the mass balance time series in the Central Himalayas, such as Shaune, Tipra, Gara, Chorabari, and significant acceleration has occurred since approximately 1980. The similarities of time series changes in glaciers in the same region indicate that the climate component directly controls the mass balance [12,13], while mass glacier deviations are the result of the sensitivity responses of individual glaciers [14]. The mass balance of glaciers in the Indian monsoon region, e.g., Parlung No. 12, Parlung No. 10, Parlung No. 94, Parlung No. 390, and Baishui Glacier No. 1, have been negative for the last 10 years. On the contrary, the mass balance of Muztag Ata has been persistently positive and exhibits an increasing trend. All the results suggest that the spatial heterogeneity in mass balance is significant under the complex climate background in HMA, but that consistency exists within a given region. The reason for differences could be explained by the sensitivity of mass balance.

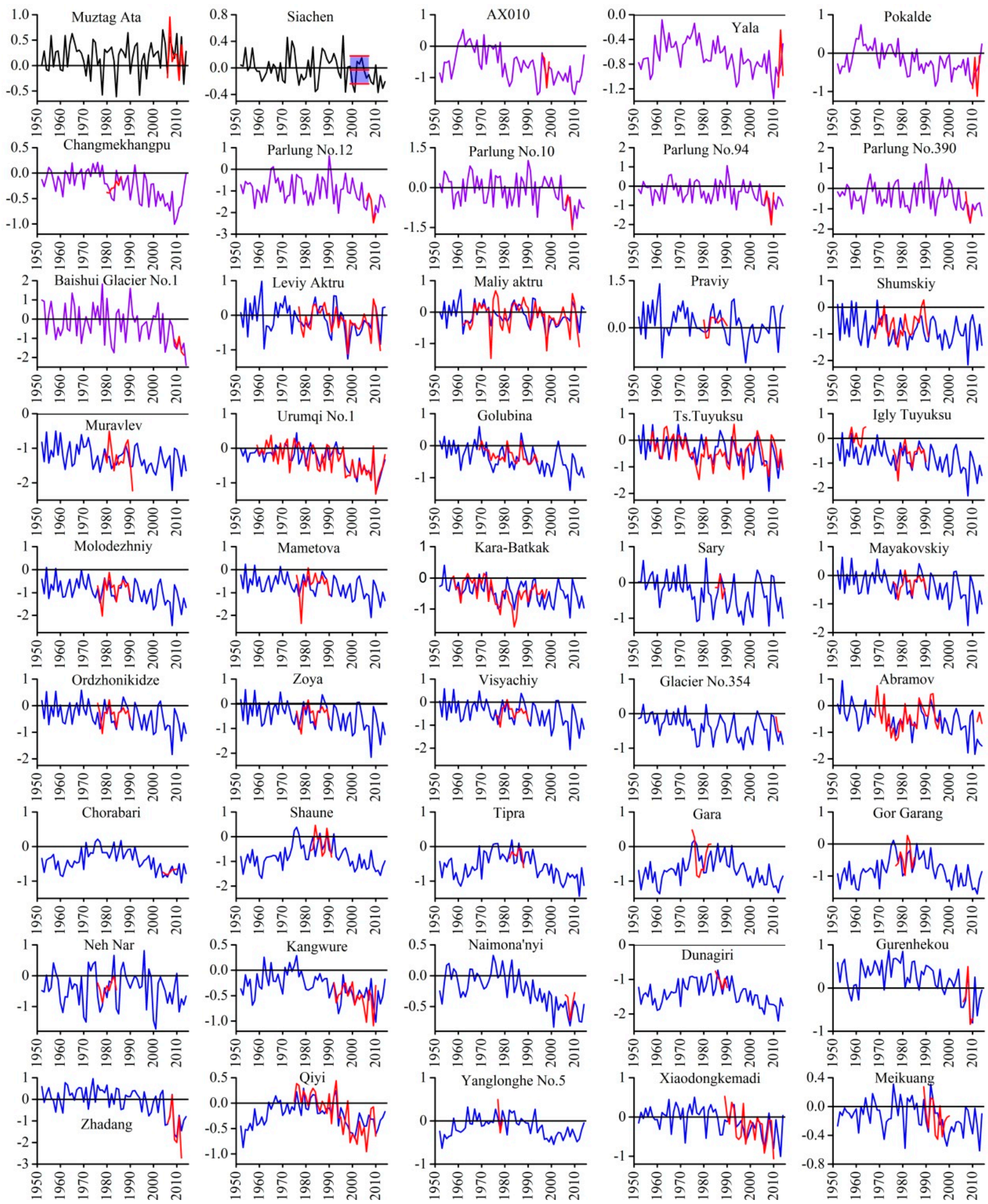

Figure S2. The modeled and observed annual mass balance of each glacier in HMA for 1952–2014.

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