Quaternary International 454 (2017) 68–84

Contents lists available at ScienceDirect

Quaternary International

journal homepage: www.elsevier.com/locate/quaint

Glacier mass-balance and length variation observed in China during the periods 1959–2015 and 1930–2014

Yanjun Che [a], Mingjun Zhang [a,*], Zhongqin Li [a,b], Huilin Li [b], Shengjie Wang [a,b], Meiping Sun [a], Shuping Zha [c,d]

[a] College of Geography and Environmental Science, Northwest Normal University, Lanzhou, 730070, Gansu, China
[b] State Key Laboratory of Cryospheric Sciences, Northwest Institute of Eco-Environment and Resources/Tianshan Glaciological Station, Chinese Academy of Sciences, Lanzhou, 730000, Gansu, China
[c] Opening Foundation of Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology, Nanjing, 210000, China
[d] School of Geographic Science, Nantong University, Nantong, 226007, China

ARTICLE INFO

Article history:
Received 8 January 2017
Received in revised form
17 May 2017
Accepted 9 July 2017
Available online 21 July 2017

Keywords:
Glacier mass balance
Glacier fluctuations
Glacier monitoring
China

ABSTRACT

The importance of glaciers for providing runoff is reflected in the extensive glacier measurement record for China. In this paper, we summarized the mass-balance and front-variation data of glaciers in China that have long-term records. Mass balance has been measured for 22 glaciers; length (or front-position) records exist for 96 glaciers. We found that the mean rate of glacial mass balance decreased by −0.015 m w.e. (water equivalent) per year during the period 1959–2015, which was lower than that for glaciers globally (−0.013 m w.e. per year). It was indicated that the rate of glacial melting (mass loss) increased in China, which was higher than that in glaciers worldwide. However, glacial frontal positions varied among mountains in time and space. Glaciers in the Karakoram Mountains mean advanced 379 m during the 1968–2000 period, while glaciers in the Pamir Mountains remained relatively stable from the 1960s through the 2000s, i.e., retreated 28 m. Glaciers in Hengduan Mountains retreated farthest (1250 m maximum) from 1930 to 2005.

1. Introduction

The importance of glacier in affecting regional hydrological cycles and tracking climate change is reflected in the extensive glacier measurement record. Changes of glaciers, including changes in area, volume, length and mass, provide important data that are widely used to the assessment of climate change, manage regional water resources, and predict sea level rise (Andreassen et al., 2005; Zemp et al., 2013). In China, glaciers cover approximately 0.54% of land area, are mainly distributed in the western mountains, with a volume of 4.3–4.7 × 10^3 km^3 (Liu et al., 2015). The modern glaciological studies in China started from some typical glaciers in the mid-20th century, such as the Urumqi Glacier No.1, located at the headwaters of Urumqi River in northwestern China's Xinjiang. In 1958/59, the Tianshan Glaciological Station of the Chinese Academy of Sciences was built to observe changes in Urumqi Glacier No.1. Since then, this glacier was considered as a reference glacier for the Tianshan Mountains in China (Li et al., 2011). Besides Urumqi Glacier No.1, more in-situ measurements have been operated at many other glaciers in China. As for the total amount of China's glacier, the systemic knowledge may be derived from the Chinese Glacier Inventory. The first Chinese Glacier Inventory (CGI) was compiled during 1978–2002, in order to investigate the distribution of glaciers in China and contribute data to the International Commission on Snow and Ice as part of the world glacier inventory. Detailed results of the first CGI were published in 2005 (Shi et al., 2009). Because of the rapid cryospheric shrinkage in many countries including China, an updated inventory has been considered after the release of the first CGI. The second CGI greatly rely on remote sensing technique, which was initiated in 2007 and finished in 2014 (Guo et al., 2014). These studies of both in-situ measurement and remote sensing-based inventory are helpful for quantifying changes the changes in glaciers and their responses to climate change in China.

The first mass-balance measurement in China was carried out at Urumqi Glacier No.1 in 1958/59 (denoted by 1959) in order to

* Corresponding author.
E-mail address: mjzhang2004@163.com (M. Zhang).

http://dx.doi.org/10.1016/j.quaint.2017.07.003

understand climate fluctuations and the contribution of melting glaciers to runoff (Li et al., 2011). Results of these measurements have been published periodically every several years (e.g., Dong et al., 2013; Han et al., 2005; Jiao et al., 2000; Li et al., 2011; Liu et al., 1997; Zhang, 1981), and are available at the network of WGMS (World Glacier Monitoring Service).

Glacier snout fluctuation (also termed length change or front-position change) mainly results from change in mass balance. Generally, there is a time lag from change in mass-balance to a change in snout position, which mainly depends on the meteorological forcing and morphological characteristic of the glacier (Zecchetto et al., 2016). Measurements of glacier length-change is an important part of glacier monitoring strategies worldwide (Hoelzle et al., 2003). Accordingly, it is widely considered to be a proxy for climate change on a decadal-to-century timescale (Oerlemans, 2000).

In order to understand the variation in mass balance and front position for Chinese glaciers, some works are conducted in this paper. It is important to understand the regional climatic fluctuation in western China. Therefore, two main problems are focused in this work: summarize the records of mass-balance and front-variation and quantitatively assess the glacier changes in time and space. To this end, we compiled datasets in terms of mass balance and front variation. Here, the glacier needs to satisfy one of the two conditions: (1) the glacier data from the *in-situ*, (2) based on ground investigation and the large-scale topographic map or remotely sensed monitor for one glacier. The dataset of glacier change derived from published journals (mainly published in Chinese), books (also mainly published in Chinese), and the World Glacier Monitoring Service (WGMS, 2016). However, the results obtained using different methods, especially data calculating change in length for glaciers, are not merged in this paper (Gardner et al., 2013; Zemp et al., 2015).

2. Datasets and methods

2.1. Glaciological mass-balance data

The stratigraphic method is widely used to calculate the glacier mass balance (Østrem and Brugman, 1991) based on the two successive "summer surface" (surface minima) measurements. The method requires intensive fieldwork and the reference information on the last seasonal and annual components of surface balance. The records of stakes and snow pits on glacier are necessary to calculate annual mass-balance of the *in-situ*, meanwhile, the point results are projected on the large-scale topographical map in order to calculate specific mass balance of the glacier. Generally, this glaciological method of mass balance called the contour line method (Andreassen et al., 2016). In this paper, the related terminologies and formulation of glacier mass balance and front variation follow those of Cogley et al. (2011) and Zemp et al. (2013).

The point mass balance calculated over one hydrological year b_a, which is expressed by

$$b_a = b_w + b_s \tag{1}$$

where b_w indicates the accumulation in winter seasons, b_s indicates the ablation in summer seasons. The point mass balances are calculated to glacier-wide mass balance (B_a) using the glacier mean area S over the same/recent time-span:

$$B_a = \frac{\sum_{i=1}^{n} b_i s_i}{S} \tag{2}$$

where n is the number of interval isolines of mass balance, b_i and s_i are the mean mass balance and area between adjacent isolines, respectively.

It is well known that mass balance is an important indicator in

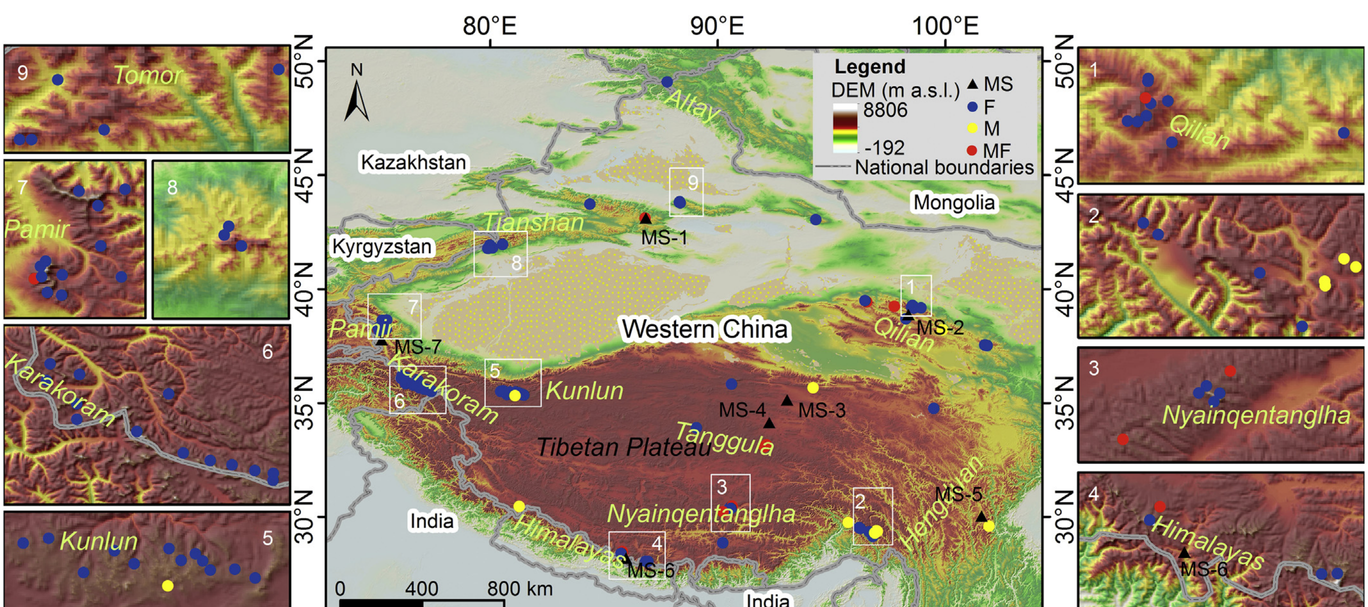

Fig. 1. Spatial distribution of observed glaciers in China. "MS" (black triangle) represents national meteorological stations closest to the indicated glacier: MS-1, Daxigou; MS-2, Tuole; MS-3, Wudaoliang; MS-4, Tuotuohe; MS-5, Kangding; MS-6, Nyalam; and MS-7, Taxkorgan. "M" (yellow circle) represents glaciers with mass balance data from the past several decades, "F" (blue circle) represents glaciers with front position data from the last eight decades, and "MF" (red circle) represents glaciers with both mass balance and front position data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

assessing climate change. Field work required for monitoring glaciers, however, it is very difficult due to the remoteness of most glaciers and their harsh environment. Accordingly, only a limited number of glaciers have been monitored and studied. Based on WGMS datasets and publications, we collected 22 glaciers with more than one hydrological year from the *in-situ* as shown in Fig. 1 and Table 1 (LIGCCAS, 1980; Pu et al., 1995; WGMS, 2016; Xie et al., 2001; Yao et al., 2012). For the assessment of global climate change, 37 glaciers with mass-balance records covering more than 30 years have been identified as "reference" glaciers for glaciers worldwide (Zemp et al., 2009). Urumqi Glacier No.1 is the only reference glacier in China. In this paper, we compiled global mass-balance data from reference glaciers to compare data collected from within China and worldwide.

2.2. Front variation data (length changes or front position)

Data on the retreat or advance of glacier is one important part of information to understand regional climate changes in high-altitudes (Oerlemans, 2005). Measurements of glacial frontal boundaries are considerably easier to obtain from ground measurement or remotely sensed data (e.g., Cook et al., 2005; Schmidt and Nüsser, 2009) than the more field-intensive measurements required for obtaining glacial mass-balance data. Thus, the number of glaciers with long-term records of length change is more than those glaciers with the records of mass balance. In this paper, we only consider the length change (advance/retreat) of one glacier (i.e. the glacier was as a single glacier to be analysed), based on ground investigation and/or sometimes combining the remote sensing or topographic map. As shown in Fig. 1 and Table 1, we collected 96 glaciers in China which satisfy the studied conditions and their dataset derived from WGMS and published over the past eight decades (Du et al., 2008; He and Zhang, 2004; He et al., 2003; Jing et al., 2002; Kang et al., 2007; Li and Su, 1996; Li et al., 2007, 2010; LIGCCAS, 1980; Liu et al., 1999, 2002, 2006; Pu et al., 2004; Pu et al., 2006; Ren et al., 2006; Shangguan et al., 2004a, 2004b; Su and Orlov, 1992; Su and Pu, 1998; Sun and Xie, 1981; Su et al., 1999; TGS, 2016; Wang et al., 2012, 2014; Xie et al., 2006; Yao et al., 2004, 2012; Zhang et al., 2013; Zheng et al., 1999).

2.3. Spatial and temporal regionalization

As shown in Fig. 1, study glaciers are distributed throughout mountain ranges of western China. In this paper, the glaciers are divided into ten groups according to their location, including Altay Mountains (ALM), Eastern Tianshan Mountains (or Chinese Tianshan Mountains) (TSM), Qilian Mountains (QIM), Pamir Mountains (PAM), Karakoram Mountains (KAM), Kunlun Mountains (KUM), Tanggula Mountains (TAM), Nyainqentanglha Mountains (NYM), Hengduan Mountains (HEM), and Himalayas Mountains (HIM). These mountain ranges are widely used to study glacier changes in China (e.g., Liu et al., 2015; Shi and Liu, 2000; Yao et al., 2012), especially in Chinese glacier inventories. All data records of each glacier are integrated into annual time resolution (i.e., the rate of glacier front change in per year, calculating by retreat/advanced distance over time span) in order to take into account inherent regional observational peculiarities, whereas the annual arithmetic mean of mass balance for glaciers in one region is identified as the mean value of mass balance of glaciers for this region in order to reduce the influence of meteorological extremes (Zemp et al., 2013, 2015). To understand the temporal variation of mass balance for glaciers in China, here, we set 10 years to a threshold as the shortest observation and thus choose six glaciers with observation more than 10 years, i.e., Urumqi Glacier No.1, Qiyi, Meikuang, Xiao Dongkemadi, Hailuogou, and Kangwure glaciers. Glaciers in different river basins or mountain ranges generally show different patterns of retreat or advance even in the same period. To quantitatively assess the rate of advance or retreat of glaciers in a given mountain range, therefore, the mean annual change in length for all glaciers in the region is calculated to determine annual change by range, i.e., the annual mean change in length of glaciers in one mountain range is assumed to be the mean value of change for all glaciers in the range.

2.4. Meteorological dataset

The number of meteorological stations are generally scarce in mountain region, especially in those glacierized regions (Immerzeel et al., 2014). Seven meteorological stations, closest to glaciers, are herein chosen to interpret long-term changes of glacier mass balance in mountain region (Fig. 1). The six meteorological stations, including Daxigou, Tuole, Wudaoliang, Tuotuohe, Kangding, Nyalam and Taxkorgan, near to glaciers with long-term mass balance. In addition, the dataset of other meteorological station, Taxkorgan, is used to understand the glacier expansion in Karakoram Mountains. Their datasets of meteorological stations are derived from the China Meteorological Data Service Center (http://data.cma.cn/). The detailed information are listed as following Table 2. Besides, the products of daily air temperature and precipitation (i.e., SURF_CLI_CHN_PRE_DAY_GRID_0.5 and SURF_CLI_CHN_TEM_DAY_GRID_0.5) at spatial resolutions of $0.5° \times 0.5°$ were used to understand the climate change in western China, derived from the China Meteorological Data Service Center (http://data.cma.cn/). These products were widely applied to the study of climate change in China (e.g., Dong et al., 2014; Lin et al., 2015; Shen et al., 2015; Wang et al., 2016).

2.5. Uncertainty assessment

The assessment of uncertainties with respect to the study in glacier mass balance and front position is generally required. Systematic and random errors are important parts in assessing the change of glaciological balance. In the paper, the uncertainty estimation follow the assessments described by Zemp et al. (2013, 2015) and Andreassen et al. (2016). In fact, quantitatively assessed the uncertainties is greatly challenged using the limit sample of observed glaciers (Zemp et al., 2015).

2.5.1. Glaciological mass balance

The systematic works and detailed records during the process of monitoring are key to analyse the accuracy of glacier mass balance. However, the error analysis is very challenged because it contains various sources of uncertainty (Zemp et al., 2013). For the glaciological method of mass balance in terms of the systematic and random errors, generally, there are three main error sources (Zemp et al., 2015), i.e. point measurement (field measurement), spatial extrapolation, and glacier reference area.

2.5.1.1. Point measurement. The uncertainty of point measurement mainly derived from probing to the summer surface, stakes and towers, density measurements of snow, and estimated density of firn (Andreassen et al., 2016). Sometimes, recording and reading may be inaccuracy because probe may penetrate the summer surface layer or stop at layers above the summer surface. It is unavoidable that mass-balance stakes may lean, fall down, and melt out which would generate the incorrect or discontinuous records. The towers may be anchored to firn/ice masses at lower depths and thus be vertically displaced. For measuring density of snow, some errors are unavoidable due to man-made operation or different instruments. Besides, the density of firn is normally not measured

Table 1
Information from glaciers with a record of mass balance and/or length change in China. The second column of "Label": "M" denotes mass balance for the glacier, "F" denotes front variation for the glacier, "MF" denotes variation for mass-balance and front variation. "Lon" and "Lat" denote longitude and latitude, respectively. "Max-Elev", "Min-Elev" and "MA-Elev" denote Maximum, Minimum, and Median elevations of glaciers, respectively. These information, which include the "Location", "Lon", "Lat", "Area (km^2)", "Max-Elev (m)", "Min-Elev (m)" and "MA-Elev (m)" of glacier, are derived from the second Chinese Glacier Inventory, downloaded from http://westdc.westgis.ac.cn/.

Mountains	Code	Glacier name/no. in Chinese inventory	Label	Time span	Lon	Lat	Area (km^2)	Max-Elev (m)	Min-Elev (m)	MA-Elev (m)
Altay	1	Kanas glacier	F	1959–2009	87.78	49.10	26.75	4308.70	2471.80	3273.93
Hengduan	2	Parlung No.4	M	2005–2007	96.98	29.39	2.79	5586.00	5047.50	5357.50
			F	1980–2005						
	3	Hailuogou	M	1988–1998	101.92	29.58	24.53	7142.80	2979.40	5387.40
			F	1930–1998						
	4	Baishui No.1	F	1957–2002	100.19	27.10	1.28	5047.10	4395.80	4833.8
	5	Mingyong	F	1932–2002	98.70	28.43	12.38	6400.50	3028.50	5238.50
	6	Demula	M	2006–2010	97.02	29.36	0.37	5443.20	5177.70	5312.70
	7	Parlung No.94	M	2005–2014	96.98	29.39	2.79	5586.00	5047.50	5357.50
Himalayas	8	MiddleRongbu	F	1966–2004	86.83	28.05	77.09	7980.10	5162.90	5950.83
	9	East Rongbu	F	1966–2004	86.93	28.05	41.73	7551.20	5607.00	6429.21
	10	Kangwure	M	1991–2010	85.82	28.47	1.87	6101.00	5716.60	5901.32
			F	1976–2001						
	11	Dasuopu	F	1968–2007	85.75	28.39	25.04	7416.40	5586.40	6490.97
	12	Naimona'nyi	M	2005–2010	81.28	30.45	4.92	7556.80	5664.20	6702.20
Karakoram	13	5Y654D42	F	1976–2000	76.28	35.95	5.68	6448.10	4970.40	5651.40
	14	5Y654D48	F	1976–2000	76.28	35.86	182.54	7239.50	4094.40	5413.40
	15	5Y654D53	F	1968–2000	76.10	36.08	365.20	6981.50	3973.10	5379.10
	16	5Y654D77	F	1968–2000	76.30	36.12	11.92	6243.30	4665.30	5465.30
	17	5Y654D78	F	1968–2000	76.30	36.12	–	–	–	–
	18	5Y654D97	F	1976–2000	76.12	36.18	19.69	6441.10	4677.20	5695.20
	19	5Y654C81	F	1976–2000	77.42	35.54	31.07	6244.80	5323.30	5741.61
	20	5Y654C92	F	1976–2000	77.31	35.56	39.55	6585.20	5021.30	5691.30
	21	5Y654C116	F	1976–2000	77.18	35.59	94.70	7185.70	4759.20	5591.83
	22	5Y654C128	F	1976–2000	77.05	35.62	110.77	7392.60	4528.50	5542.28
	23	5Y654C145	F	1976–2000	76.90	35.66	82.90	7193.00	4407.80	5521.80
	24	5Y654C163	F	1976–2000	76.63	35.79	108.53	7962.20	4231.50	5715.06
	25	5Y653K72	F	1976–2000	77.42	35.50	71.67	6564.90	5231.30	5761.03
	26	5Y653Q185	F	1976–2000	76.81	36.01	3.20	6326.70	5093.20	5813.20
Kunlun	27	Halong	F	1966–1981	99.49	34.76	20.61	6220.10	4566.60	5216.60
	28	Malan	F	1970–2000	90.61	35.83	47.46	5789.10	5004.50	5545.38
	29	Maztag Ata	M	2005–2010	75.06	38.24	1.09	5935.00	5237.10	5584.10
			F	2002–2010						
	30	5Y641F49	F	1970–2001	81.39	35.39	41.89	6341.60	5457.10	5979.10
	31	5Y641F70	F	1970–2001	81.25	35.43	38.53	6605.30	5257.50	6176.50
	32	5Y641F73	F	1970–2001	81.22	35.46	26.20	6597.00	4721.10	6109.77
	33	5Y641H67	F	1970–2001	80.57	35.53	44.20	6453.10	5289.10	6048.10
	34	5Y641F46	F	1970–2001	81.48	35.35	84.97	6739.70	5366.80	5962.80
	35	5Y641H74	F	1970–2001	80.46	35.51	128.39	6441.80	5254.60	5993.91
	36	5Y641G38	F	1970–2001	80.86	35.47	91.07	6653.50	5154.70	6193.18
	37	5Y641F98	F	1970–2001	81.10	35.48	61.91	6673.40	4920.50	6146.50
	38	5Y641G55	F	1970–2001	80.73	35.38	201.79	6714.00	4896.40	6090.34
	39	5Y641F85	F	1970–2001	81.16	35.43	82.31	6829.60	5032.40	6187.36
	40	5Y641F63	F	1970–2001	81.29	35.39	136.98	6731.40	5132.60	6137.37
	41	5Y641G23	F	1970–2001	80.95	35.41	238.96	6857.00	4730.40	6159.39
	42	MeiKuang	M	1988–1995	94.18	35.67	1.05	5504.70	4839.60	5275.60
				1996–2001						
	43	Chongce Ice Cap	M	1997–1998	81.10	35.32	166.08	6836.30	5305.30	6151.30
Nyainqentanglha	44	Yanong	F	1980–2001	96.66	29.33	179.59	6341.90	3969.10	5186.10
	45	Azha	F	1980–2001	96.82	29.13	13.51	5482.80	2459.20	3524.40
	46	5O282B123	F	1980–2001	96.27	29.48	21.27	5454.50	4009.60	4729.60
	47	5O282B136	F	1980–2001	96.22	29.52	12.05	5260.00	3946.20	4696.20
	48	Lanong	F	1970–2007	90.55	30.42	7.52	6371.00	5410.60	5871.60
	49	Panu	F	1970–2007	90.52	30.39	13.46	6371.30	5386.50	5885.32
	50	Xibu	F	1970–1999	90.60	30.39	29.13	7087.60	5228.40	5846.81
	51	Zhadang	M	2005–2008	90.64	30.47	1.54	6061.40	5540.10	5686.07
			F	1970–2007						
	52	5O270C49	F	1970–2007	90.58	30.36	0.43	6680.00	5742.40	6004.40
	53	Gurenhekou	M	2005–2010	90.24	30.21	5.17	6219.30	5482.80	5881.14
			F	1974–2006						
	54	Qiangyong	F	1975–2001	90.22	28.86	6.25	6607.50	5098.20	6007.20
	55	24K	M	2007–2008	95.73	29.76	6.08	5621.30	3899.20	4685.20
	56	Parlung No.10	M	2005–2009	96.90	29.29	4.43	5641.70	4913.10	5288.10
	57	Parlung No.12	M	2005–2010	96.90	29.30	0.23	5376.60	5144.00	5219.00
	58	Zhongxi	M	2007–2010	91.45	30.87	1.60	–	–	–
Pamir	59	5Y663E14	F	1963–2001	75.09	38.25	19.92	7243.00	4423.50	5806.50
	60	5Y663E1	F	1963–2001	75.11	38.32	9.16	7143.60	4506.00	5439.00
	61	5Y663E8	F	1963–2001	75.09	38.29	9.25	7448.00	4263.40	6059.40
	62	5Y663D87	F	1963–2001	75.18	38.26	80.87	7519.70	3913.50	4918.54
	63	5Y663B7	F	1963–2001	75.46	38.63	13.90	5810.70	3670.20	4749.20

(continued on next page)

Table 1 (*continued*)

Mountains	Code	Glacier name/no. in Chinese inventory	Label	Time span	Lon	Lat	Area (km^2)	Max-Elev (m)	Min-Elev (m)	MA-Elev (m)
	64	5Y662D35	F	1964–2001	75.34	38.56	93.43	7561.40	3077.90	4654.46
	65	5Y656I27	F	1976–2001	75.18	38.17	7.95	6291.40	4603.90	5363.90
	66	5Y656I22	F	1976–2001	75.12	38.18	1.70	6096.60	5264.60	5618.60
	67	5Y663D24	F	1963–2001	75.35	38.38	3.96	5776.30	4784.10	5101.10
	68	5Y663D36	F	1963–2001	75.44	38.25	9.96	5491.40	4706.50	5011.83
	69	5Y663B25	F	1963–2001	75.25	38.62	115.38	7575.20	2817.60	4559.57
Qilian	70	Laohugou No.12	M	1975–1976	96.54	39.44	20.42	5445.90	4299.60	4971.60
			F	1957–2005						
	71	Qiyi	M	1974–2010	97.76	39.24	2.53	5114.70	4323.70	4809.70
			F	1956–2008						
	72	Ningchan River No.3	F	1956–1976	101.82	37.51	1.22	4753.40	4165.50	4517.50
	73	Ningchan River No.4	F	1956–1976	101.81	37.52	1.20	4821.80	4237.40	4541.40
	74	Ningchan River No.7	F	1956–1976	101.80	37.53	0.62	4773.80	4311.90	4562.90
	75	Shuiguan River No.1	F	1956–1976	101.79	37.53	0.36	4681.50	4217.40	4472.40
	76	Shuiguan River No.2	F	1956–1976	101.77	37.53	2.79	4900.90	4124.10	4460.10
	77	Shuiguan River No.3	F	1956–1976	101.76	37.53	1.34	4895.60	4202.80	4440.80
	78	Shuiguan River No.4	M	1962–1963	101.75	37.54	1.44	4918.40	4262.10	4578.10
			M	1975–1977						
			F	1956–1976						
	79	Laohugoudaban	F	1956–1976	101.74	37.55	1.38	4839.90	4286.70	4540.70
	80	Shifang River No.2	F	1956–1977	98.61	39.15	2.40	5232.80	4154.40	4875.35
	81	Dahaizi River No.4	F	1956–1977	98.60	39.23	0.95	4919.10	4283.80	4603.18
	82	Yanglong River No.1	F	1956–1976	98.57	39.23	4.08	5406.70	4291.10	4817.10
	83	Yanglong River No.5	M	1976–1979	98.56	39.24	1.24	5229.80	4453.20	4839.20
			F	1956–1976						
	84	Yanglong River No.9	F	1956–1977	98.57	39.27	0.04	4665.70	4457.50	4584.50
	85	Yanglong River No.11	F	1956–1977	98.57	39.27	0.03	4805.70	4587.40	4736.40
	86	Sanchakou	F	1956–1977	98.53	39.19	0.10	5178.90	4836.90	5058.90
	87	West Suzhulian	F	1956–1977	98.55	39.19	1.87	5514.50	4443.80	5079.80
	88	East Suzhulian	F	1956–1977	98.56	39.20	4.44	5485.50	4350.80	5026.80
	89	Wawusi No.11	F	1956–1975	98.27	38.69	0.38	5086.00	4525.10	4810.10
	90	Heidabangou No.1	F	1956–1977	98.93	39.17	0.02	4557.10	4441.40	4515.40
	91	Laohugou No.20	F	1962–1976	96.47	39.49	1.08	5105.50	4651.70	4931.70
Tanggula	92	Xiao Dongkemadi	M	1988–2010	92.06	33.08	15.97	6074.80	5280.90	5666.90
			F	1991–2012						
	93	Da Dongkemadi	M	1992–1993	92.13	33.17	–	–	–	–
			F	1991–2001						
	94	Purogangri	F	1974–2000	89.07	33.91	0.15	6009.80	5725.30	5895.30
Tianshan	95	Urumqi Glacier No.1	M	1958–2015	86.81	43.11	1.58	4446.70	3766.10	4031.87
			F	1962–2014						
	96	Heigou No.8	F	1962–2009	88.36	43.78	6.08	5208.10	3401.40	4239.40
	97	Sigong No.4	F	1962–2009	88.32	43.83	2.64	4323.30	3657.40	3955.40
	98	Qingbingtan No.72	F	1964–2009	79.89	41.78	6.60	5707.60	3792.20	4593.20
	99	Koxkar	F	1942–2004	80.11	41.80	86.88	5652.70	3000.80	4404.80
	100	Haxilegen No.51	F	1964–2001	84.39	43.73	1.10	3903.40	3494.50	3631.50
	101	Miaoergou	F	1972–2005	94.32	43.05	2.00	4505.90	4144.60	4316.22
	102	Qingbingtan No.74	F	1964–2009	79.93	41.78	9.21	5679.90	3850.00	4353.04
	103	5Y725D5	F	1962–2006	88.31	43.81	7.81	5428.60	3532.60	3937.60
	104	5Y674E15	F	1964–2009	80.55	41.96	32.08	5433.10	3476.70	4405.70
	105	5Y673P37	F	1964–2009	79.99	41.93	363.19	7033.00	2890.00	4480.93

Note that two glaciers, 5Y654D77 and 5Y654D78, in the first Chinese Glacier Inventory were merged into one glacier in the second Chinese Glacier Inventory, due to the expansion of the glacial front. "-" is expressive of no data.

Table 2
Information of the meteorological stations.

	Daxigou	Tuole	Wudaoliang	Tuotuohe	Kangding	Nyalam	Taxkorgan
Longitude(°)	86.50	98.37	93.05	92.26	101.58	85.58	75.23
Latitude (°)	43.06	38.87	35.13	34.13	30.03	28.11	37.77
Elevation (m a.s.l.)	3539.0	3365	4612.2	4533.1	2615.7	3810	3090.1
Time span	1959–2015	1959–2008	1959–2015	1959–2015	1959–2015	1967–2015	1968–2000
Distance from glacier (km)	3	67	120	107	59	36	230

but estimated. Zemp et al. (2013) found the error of field measurements at point locations was ±0.14 m w.e. per year, while the error of ±0.25 m w.e. per year was found on Nigardsbreen glacier by Andreassen et al. (2016).

2.5.1.2. Spatial extrapolation. During the process of long-term monitoring, in general, the number and distribution of stakes and snow pits need to readjust following melt situation on glacier surface (Fischer, 2010). For example, ablation of Urumqi Glacier No.1 was measured at 32 stakes in 1958/59 (TGS, 1981). In 1990/91, the maximum number of 81 stakes was measured to understand the spatial pattern of mass balance (TGS, 1991). Recent years, a basic pattern with 40–50 stakes and several snow pits are kept on the Urumqi Glacier No.1 (TGS, 2016). Different errors will occur due to the different extrapolation from point to spatial balances (Zemp et al., 2015). Therefore, properly modify with the field experience is needed to those glacier zone, such as the steepest glaciers, crevasse, and avalanche. Different glaciologist with different levels of glaciological knowledge may contribute to different uncertainties in calculating, and it is greatly difficult to assess. When Hock and Jensen (1999) used Kriging Interpolation to calculate the specific mass balance from point to a glacier, they found that the pattern of stakes and snow pits was sensitive to the extrapolation. The uncertainty from spatial interpolation was ±0.21 m w.e. per year from an assessment of Nigardsbreen glacier conducted by Andreassen et al. (2016). In addition, an estimated uncertainty of ±0.28 m w.e. per year in the spatial integration was contributed to the local representativeness, the interpolation method, and the extrapolation to unmeasured areas (Zemp et al., 2013).

2.5.1.3. Glacier reference area. Large-scale topographical map of glacier is widely used to calculate the mass balance. However, there is a time lag between the date of mass balance measurement and the date of reference area used for calculating mass balance. When a new map or Digital Elevation Models (DEM) has been compiled, it was used for long time from then onwards to next one. Hence, the timeliness of a map is very important to ice divide and glacier area-altitude changes. For example, a total of 8 topographic maps (in 1962, 1973, 1981, 1986, 1994, 2001, 2006, and 2009) were used in calculating mass balance from 1959 to 2015 (Wang et al., 2014). The uncertainty of glacier reference area was ±0.06 m w.e. per year on the Nigardsbreen glacier (Andreassen et al., 2016). Zemp et al. (2013) found that uncertainty of a root mean square by 0.01 m w.e. peryear and a corresponding uncertainty of 0.10 m w.e. per year resulted from reference area.

In addition, the rest of related uncertainties with respect to time systems, internal mass balance and basal balances need to be considered (Zemp et al., 2013). But it is difficult to assess these uncertainties because measurement of mass balance conducted on the glacier surface. Related balance of internal glacier and basal bed are very scarce, generally.

2.5.2. Uncertainties in the front variation

Front variation is probably the most prominent behavior of glacier to climate change, at least in morphology of glacier terminus. The measurement of glacier front position are varied since records began (WGMS, 2016), i.e. direct observation in the 19th century (WGMS, 2008), mainly including reconstructed (e.g., historical literature, geomorphological evidence, and dating of moraines), derived from maps, ground survey (e.g., GPS, tachymetry, and tape), photogrammetry, and explain under C14 remarks. Sometimes, one or more methods/materials were used for one glacier in different periods. For example, six methods were used to assess the front variation for Urumqi Glacier No.1 (Table S2). Topographical Map was used to measure the front position during the period 1962–1973, while Stereophotogrammetric Survey was used during the periods 1973–1981 and 1986–2001, Aerial Photograph during the period 1981–1986, Theodolite during the period 2001–2006, Total Station during the period 2006–2009, and RTK-GPS from 2009 to now. It is acknowledged that different measurement implies different uncertainty. Here, quantitatively assess these uncertainties is greatly difficult because it is difficult to obtain those older material and complex of integrating to these methods.

3. Results

3.1. The character of glacier sample

As shown in Fig. 1 and Table 1, mass balance has been measured for 22 glaciers in China over 1 to 57 glaciological years. The first measurement was carried on Urumqi Glacier No.1 in 1958/59 and measurements continue there. However, monitoring was interrupted during the period 1967–1979. Fortunately, the missing data had been extrapolated using the meteorological data collected from Daxigou meteorological station, located 3 km away from the glacier (Zhang, 1981). In China, more than 10 glaciers were observed during 2005–2010 with a maximum of 14 glaciers observed in 2007/08. It is not known how many glaciers have been observed since 2013 due to the long lag time inherent in calculating and publishing data on mass-balance.

Front variation data have been recorded for 96 glaciers since 1930 (Fig. 1 and Table 1). As shown in Fig. 2a, more than 65 glaciers were observed during the period 1970–2000. However, the number of observations decreased after 2000. The reason for fewer observations is that glacial changes over a larger region are now of more interest and improvements in remote sensing now allow scientists to measure glacial changes over a wider region for less

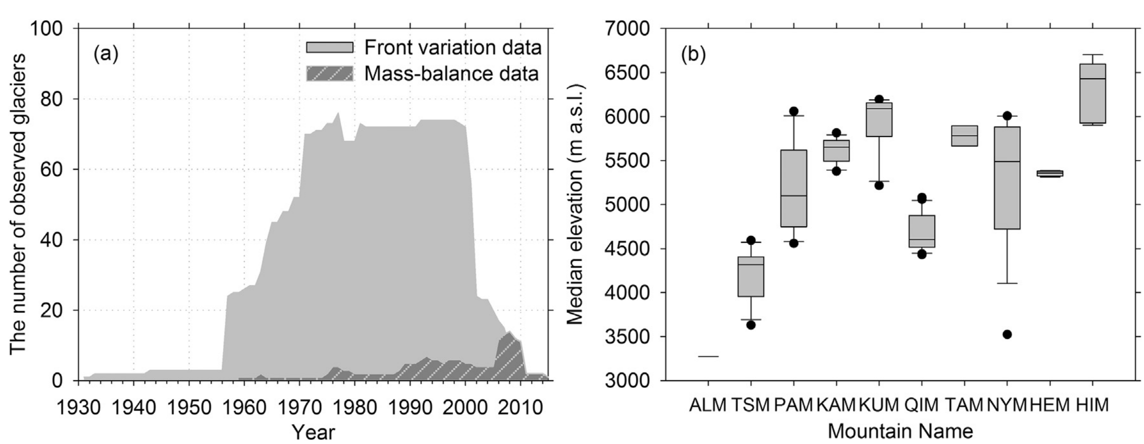

Fig. 2. (a) The number of glaciers with records of front-variation and mass-balance data. (b) The median elevation of all glaciers with fluctuation records, including front variation and mass-balance change for glaciers discussed in this paper. The lower boundary of the box indicates the 25th percentile, while the upper boundary indicates 75th percentile. The line within the box marks the 50th percentile (median), whiskers (error bars) present the 10th and 90th percentiles; Dots below and above whiskers indicate outliers. For mountain names, “ALM” denotes the Altay Mountains, “TSM” denotes Tianshan Mountains, “QIM” denotes Qilian Mountains, “PAM” denotes “Pamir Mountains”, “KAM” denotes Karakoram Mountains, “KUM” denotes Kunlun Mountains, “TAM” denotes Tanggula Mountains, “NYM” denotes Nyainqentanglha Mountains, “HEM” denotes Hengduan Mountains, and “HIM” denotes Himalayas Mountains.

effort (Bishop et al., 2004; Cook et al., 2005; Gardner et al., 2013).

The median elevation of glacier, generally, is as a proxy in the studies of Equilibrium-Line Altitude (ELA) (Ding and Xie, 1991; Sakai et al., 2015). Here, we also adopted the median elevation of glacier to describe the distribution of ELA for those glaciers in western China. As shown in Fig. 2b, the glaciers in Himalayas Mountains have the highest ELA in China, while the glaciers in Altay mountains have the lowest ELA, albeit only one glacier (i.e. Kanas) was observed in this region. Generally, the ELA is defined as a function of climate change and the temperature and precipitation are primary controlling parameters (Porter, 1975; Meierding, 1982; Sagredo et al., 2016). Thus, the spatial distribution and vertical change with respect to ELA was generated by climate change. As shown in Fig. 1 and 2b, here, two spatial patterns can be found in terms of distributed ELA in China: (1) the mean ELA of glaciers in the mountain ranges decreases from south to north, a response to the decrease in temperature with increasing latitude (Mukhopadhyay and Khan, 2017; Sagredo et al., 2016), and (2) the ELA increases from east to the west (i.e., with increasing distance from the coast of Pacific Ocean) due to drier conditions inland (Andreassen et al., 2005; Porter, 1975).

3.2. General change in mass balance of observed glaciers

As shown in Fig. 3a, there are decreases in mass balance from 1959 to 2015, although some sharp fluctuations have occurred.

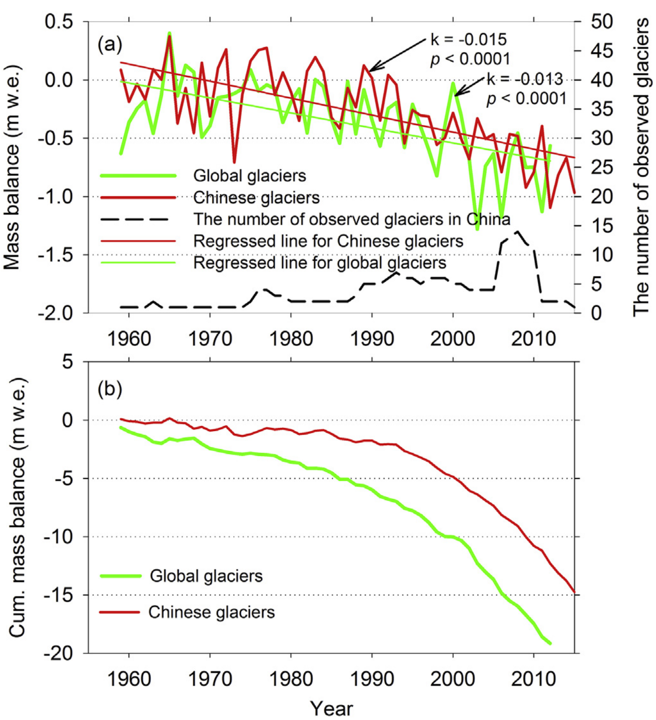

Fig. 3. A comparison of global and Chinese glacial mass balance calculations from 1959 to 2015. (a) Annual mean mass balance calculations are shown from 1959 to 2015. In addition, the "*k*" is expressive of slope of changed trend in w.e. per year and "*p*" is the significance of statistic test. The number of observed glaciers per year are denoted using a dashed black line (corresponding to right y-axis), (b) Cumulative annual mean of mass balance terms relative to 1959. ("Cum." denotes cumulative.) In both plots, the average of 37 reference glaciers (with >30 ongoing observations) were used to determine the average change for glaciers worldwide. The annual mean for mass balance for worldwide (green line) is shown for the1959 to 2012 period in plot (a). The cumulative annual mean of glacial mass balance is shown for the 1959–2012 period for glaciers worldwide (green line) in plot (b). Source: WGMS (2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

However, the annual mass balance for Chinese glaciers shows larger fluctuations during the period 1959–1990. After then, there is a significant decrease and relatively small fluctuation. More glaciers were monitored after 2005 in order to further understand the regime between mass balance and climatic change in mountains (Fig. 3a). To compare these changes of Chinese glaciers with those in glaciers worldwide, the mean annual mass balance of 37 'reference' glaciers (from 1959 to 2012) were used to represent the annual mass balance of glaciers worldwide. Obviously, the change in annual mass balance between glaciers in China and glaciers worldwide follow a similar trend of retreat. The mass-balance of glaciers in China decreased by −0.015 m w.e. per year (water equivalent in per year) (negative denotes glacier mass loss/melting, while positive denotes glacier accumulating) ($p < 0.0001$) during 1959–2015, while it decreased by −0.013 m w.e. per year ($p < 0.0001$) in glaciers worldwide during 1959–2012.

The cumulative net mass-balance varied noticeably, if the year 1959 is referenced as the beginning of the time series, as shown in Fig. 3b. Change in glaciers in the mountains of China is similar to those of glaciers worldwide. During 1959–1980 period, the changes in cumulative mass balance was not significant, however, strongly declined after 1990 in China while after 1980s in worldwide. Chinese glaciers showed a total mass loss of −14.74 m w.e. during the period 1959–2015, compared to −19.14 m w.e. among glaciers worldwide during the period 1959–2012. We can recognize that the water equivalent of annual glacier melting in China was lower than that in worldwide, while the rate of accelerated melting in China (−0.015 m w.e. per year, $p < 0.0001$) was faster than that in worldwide (−0.013 m w.e. per year, $p < 0.0001$), during past five decades. Obviously, the increased melting of glacier mass balance was found in China and worldwide, though their magnitudes differ. We consider it related to the climate change, Shi et al. (2014) showed that the rate of mean surface temperature increased by 0.023 °C per year in China during 1951–2009 while increased by 0.013 °C per year in global during 1956–2005 (IPCC, 2007, 2012). The more detailed analysis in terms of relation between mass balance and climate change in space will be discussed in discussion section.

3.3. Spatial variation of mass balance

There are many discrepancies in annual mass balance among glaciers in the dataset (Table 1). To understand the spatial differences, glaciers are divided into seven groups according to their location (Fig. 4). In each group/region, mass balance was determined for at least one glacier. It is significant that the glacial shrinkage is occurring in all regions, even though there are some gaps in mass-balance data for some regions (e.g., Kunlun and Hengduan mountains). The monitoring period for glaciers in Tianshan and Qilian mountains are relatively long for China, which show that the rate of mass balance has decreased by −0.015 m w.e. per year ($p < 0.0001$) in Tianshan Mountains during 1959–2015, compare to decrease by −0.021 m w.e. per year ($p < 0.0001$) in Qilian Mountains during the periods 1962–1963 and 1975–2010. Change in annual mass balance for glaciers in the Hengduan Mountains shows the largest range in values, relative to other mountains, ranging from −1.80 m w.e. to 0.44 m w.e. In contrast, the fluctuation in Himalayas Mountains is relatively small, ranging from only −0.79 m w.e. to −0.23 m w.e. (Note that the period of data for glaciers in the Kunlun, Nyainqentanglha, and Himalayas Mountains are so short that trends were not significant at the 0.05 level.)

3.4. Changed trends of glacier mass balance in long-term observation

It is challenged to assess the change of mass balance over an

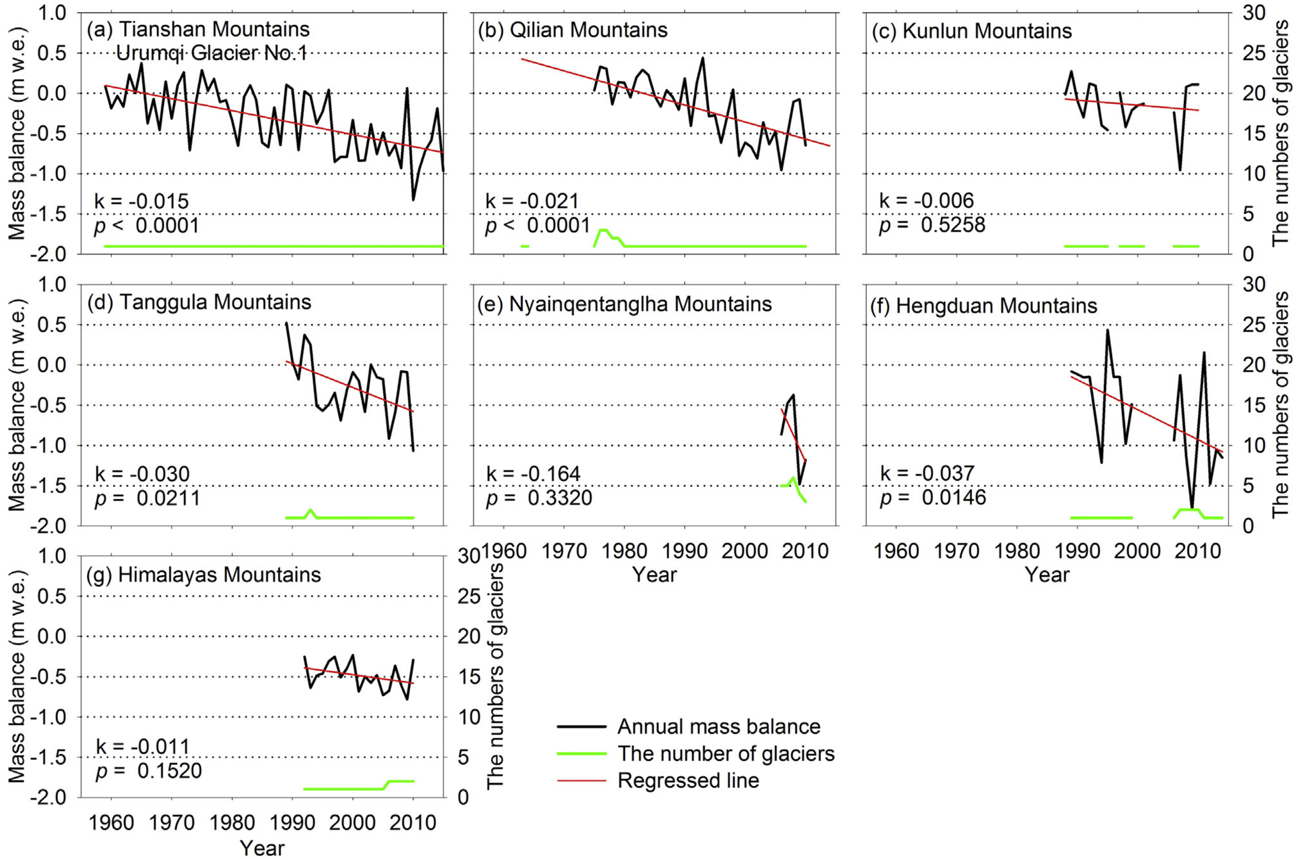

Fig. 4. Mass-balance details for mountain ranges determined from the 1959 to 2015 time span.

extended time period based on the limit sample of glacier in China. Six glaciers with mass-balance data of >10 years, therefore, were chosen to analyse the temporal variation in mass balance over the past several decades. The six glaciers include Urumqi Glacier No.1 during 1959–2015 in the Tianshan Mountains, Qiyi Glacier during 1975–2010 in the Qilian Mountains, Meikuang Glacier during 1989–1995 and 1997–2001 in the Kunlun Mountains, Xiao Dongkemadi Glacier during 1989–2010 in the Tanggula Mountains, Hailuogou Glacier during 1989–1998 in the Hengduan Mountains, and Kangwure Glacier during 1992–2010 in the Himalayas. All of the six glaciers show a net mass loss overall (Fig. 5). Hailuogou Glacier showed the largest fluctuation in mass balance during 1990–2000, although its trend was not significant at the 0.1 level. During the period of monitoring, the decreased trend of Xiao Dongkemadi glacier in mass balance was the strongest by −0.030 m w.e. per year ($p = 0.0216$), while that of Urumqi Glacier No.1 was the weakest overall. Note that the changed trend of Meikuang was not significant at the 0.1 level.

3.5. Changes of glacier length (front variation) in China

As shown in Fig. 6, there are great differences in time and space with respect to front variation of glaciers in the different mountain ranges. Glaciers in Pamir retreated 28 m during 1963–2001, while glaciers in the Karakoram Mountains advanced 379 m during 1968–2000 because some glaciers advanced during that period (Table S2), as reported by other studies (e.g., Gardelle et al., 2012; Quincey et al., 2011). Glaciers in the Tianshan Mountains, advanced 500 m from 1942 to 1962. After that period, glaciers began retreating and are still retreating, i.e., retreated 112 m during 1942–2014. Glaciers in the Kunlun Mountains also advanced prior to 1970, but then began to retreat afterwards. Glaciers in the Hengduan Mountains, showed rapid retreat during 1930–1959 period, i.e., the maximum distance (1438 m) of glacial retreat found in this study period. However, distance of retreat declined to 1032 in 1982 due to the advance of some glaciers after that period. After 1982, all glaciers began to retreat until the decade from 2000 to 2010. It is obvious that glacial retreat did not subside in China after the year 2000, nor did it in other regions of earth (Andreassen et al., 2005; Zemp et al., 2015). Note that glaciers in the Tanggula Mountains were relatively stable during the study period.

4. Discussion

4.1. Mass balance and climatic condition

There is a general trend of glacial retreat and mass deficit worldwide during past several decades, except for individual regions (Andreassen et al., 2005; Pratap et al., 2016; Zemp et al., 2015). The case is similar for China. Based on observed mass-balance data (long- and short-term time series), we found that there is an average mass balance of −0.26 m w.e. per year (1959–2015 in China) and −0.35 m w.e. per year (1959–2012 worldwide). The change in rate of China mass balance to global mass balance differs over time and regions (Figs. 3 and 4). However, the mean annual mass balance in Italian ranged from −1.79 m w.e. to −0.76 m w.e. during 2004–2013 (Carturan et al., 2016). In the Indian Himalaya, the mean cumulative specific mass balance showed −0.31 m w.e. per year during 1975–1980, −0.44 m w.e. per year during 1981–1990, and −0.906 m w.e. per year during

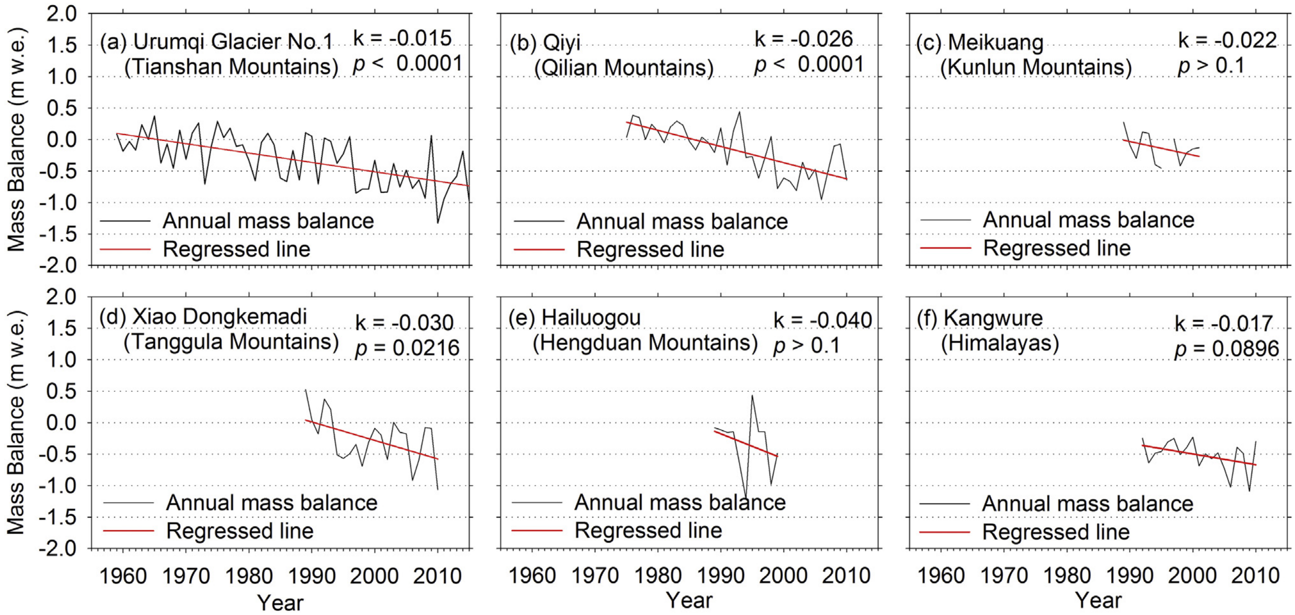

Fig. 5. Mass-balance change of glaciers in different mountains in the study period. In plots, "*k*" denotes the slop of regressed line in m w.e. per year and the "*p*" denotes the significance level.

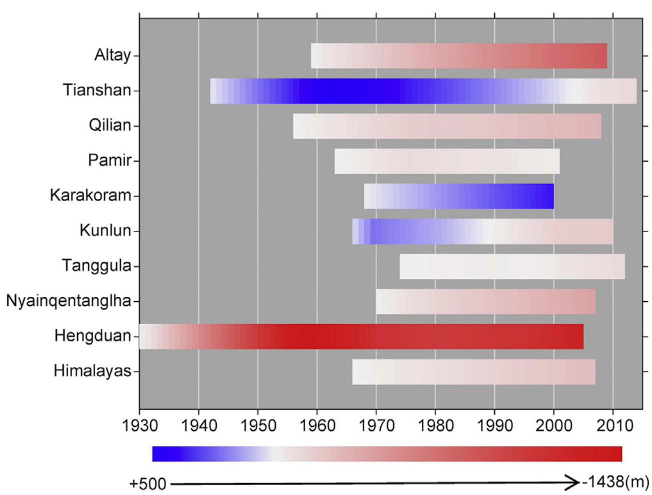

Fig. 6. Front variation observed in China during past eight decades. The figure indicates a qualitative summary of cumulative mean annual front variations for each region, where the mean of cumulative annual front variation of glaciers in one region is defined as the mean value of glacial change for all glaciers in the region. The colour ranges from dark blue for maximum glacial extent (+500 m) to dark red for minimum glacial extent (−1438 m) relative to extent in baseline year of the study period (i.e., 0 m in white). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2001–2010, respectively (Pratap et al., 2016). In addition, revised glaciological mass balance showed a more consistent signal of glacier change since 1960s and six glaciers had a significant mass loss (14–22 m w.e.) while four glaciers were nearly in balance in Norway (Andreassen et al., 2016). In Svalbard, mass balance was estimated at 0.082 m w.e. per year corresponding to a mass input of 175 GT during the period 1957–2014 (Østby et al., 2017). All over the world, the most negative mean annual mass balance of −0.81 m w.e. per year occurred during 2001–2010, while minor mass changed during the 1960s and 1970s (Zemp et al., 2015). Mass balance data from long-term records (>10 years), during 1959–2015, indicates that the mass loss of glaciers in China was accelerating (Fig. 5). To understand the regime of mass balance and climate change, here, we chose six meteorological stations closest to the six glaciers of long-term observation, including Daxigou for Urumqi Glacier No.1, Tuole for Qiyi Glacier, Wudaoliang for Meikuang Glacier, Tuotuohe for Xiao Dongkemadi Glacier, Kangding for Hailuogou Glacier, and Nyalam for Kangwure (Fig. 1 and Table 2).

Changes of mass balance are highly correlated with summer temperatures and/or winter precipitation, generally, which are widely used to interpret the change of mass balance with climate change in glacial regions (Immerzeel et al., 2014). It is acknowledged that the glacial changes mainly result from regional climate change. Thus, the correlation coefficient between mass balance of glaciers and temperature and precipitation of adjacent meteorological stations were calculated, respectively (Table 3). The temperature indicator includes Summer Mean air Temperature ($r_{T\text{-sum}}$, SMT) (i.e., May to August), Annual Mean air Temperature ($r_{T\text{-ann}}$, AnnMT), and annual Positive Degree Days ($r_{T\text{-PDD}}$, PDD). The precipitation indicator includes winter ($r_{P\text{-win}}$) (i.e., September to April) and annual precipitations ($r_{P\text{-ann}}$). The results indicated significantly negative correlation at the significance level of $p < 0.05$ or $p < 0.01$ between annual net mass balance and AnnMT. There were significantly negative correlation ($p < 0.01$) between mass balance and PDD, excepting the correlation coefficient between mass balance between mass balance of Kangwure Glacier and PDD of Nyalam, with $r_{T\text{-PDD}} = -0.33$. For between mass balance and SMT, there were also significantly negative correlation excepted for the correlation coefficient between mass balance of Kangwure Glacier and SMT of Nyalam. There was no significant correlation between mass balance of Kangwure Glacier and SMT possibly related to local topography and atmospheric circulation. However, the correlation coefficients were no perfect between mass balance and precipitation, including the winter and annual precipitations. The reason possibly resulted from the different contributions of winter and annual precipitations depending on the source and at different elevations and sites (Hewitt, 2013). Moreover, the precipitation records of those permanent weather stations in the lower elevation hardly reflect what is happening in glacier source areas (Winiger et al., 2005).

Table 3
Correlation coefficient between mass balance of long-term glacier and temperature and precipitation of adjacent meteorological stations.

Glacier Name Meteorological station	Years	r_T			r_P	
		MB vs. T_{sum}	MB vs. T_{ann}	MB vs. T_{PDD}	MB vs. P_{win}	MB vs. P_{ann}
Urumqi Glacier No. 1 Daxigou	57	−0.67***	−0.57***	−0.74***	−0.01	−0.10
Qiyi Glacier Tuole	34	−0.82***	−0.68***	−0.80***	0.30*	0.37**
Meikuang Glacier Wudaoliang	12	−0.79***	−0.56**	−0.74***	−0.07	0.27
Xiao Dongkemadi Glacier Tuotuohe	22	−0.81***	−0.53***	−0.73***	−0.21	0.00
Hailuogou Glacier Kangding	11	−0.54*	−0.74***	−0.74***	0.16	0.35
Kangwure Glacier Nyalam	19	−0.31	−0.49**	−0.33	−0.19	−0.16

Note: *** is the statistically significant at the 0.01 level, ** is the statistically significant at the 0.05 level, and * is the statistically significant at the 0.10 level. r_T is expressive of the correlation coefficient between Mass Balance (MB) and Temperature (T_{sum}: summer mean air temperature, T_{ann}: annual mean air temperature, and T_{PDD}: annual Positive Degree Days). r_P is expressive of the correlation coefficient between MB and Precipitation (P_{win}: winter precipitation, P_{ann}: annual precipitation). Besides, Years indicates the number of glacier mass balance observed and corresponding meteorological record.

We also estimated the changed rates of SMT, AnnT, and PDD during 1959–2015. The results indicated that temperatures in the six meteorological stations were significantly increased (Fig. 7). There were heterogeneity in the six meteorological stations with respect to changed trends of SMT, AnnMT, and PDD. Greatly increased rates in terms of the air temperatures of Tuole contributed to higher mass loss of Qiyi Glacier with the increase of $k = -0.026$ m w.e. per year ($p < 0.0001$) (Fig. 5).

The contribution of winter and annual precipitations is very important and no ignored to glacier mass balance, though the correlation between the precipitations and mass balance showed no prefect as in Table 3. Here, we also estimated the change in annual precipitations of the six meteorological stations (Fig. 8). Changes in annual precipitation had a distant difference among the six meteorological stations. Significant increase exited in annual precipitation of Daxigou, Wudaoliang, Tuotuohe, and Kangding and they ranged from 1.60 mm per year to 2.36 mm per year. The annual precipitation in Tuole showed the strongest decreased by −5.56 mm per year. However, there was no significant trend in Nyalam.

4.2. Different variation in glacier front position

Variations among glacial fronts is driven by changes in glacial mass balance and/or climate change and it is subjected to a time lag (Zecchetto et al., 2016). Glacial retreat since the Little Ice Age, i.e. during the period 15th-19th centuries in China (Su and Shi, 2002; Wang, 1991; Wang et al., 1998; Zhu, 1973), can be recognized

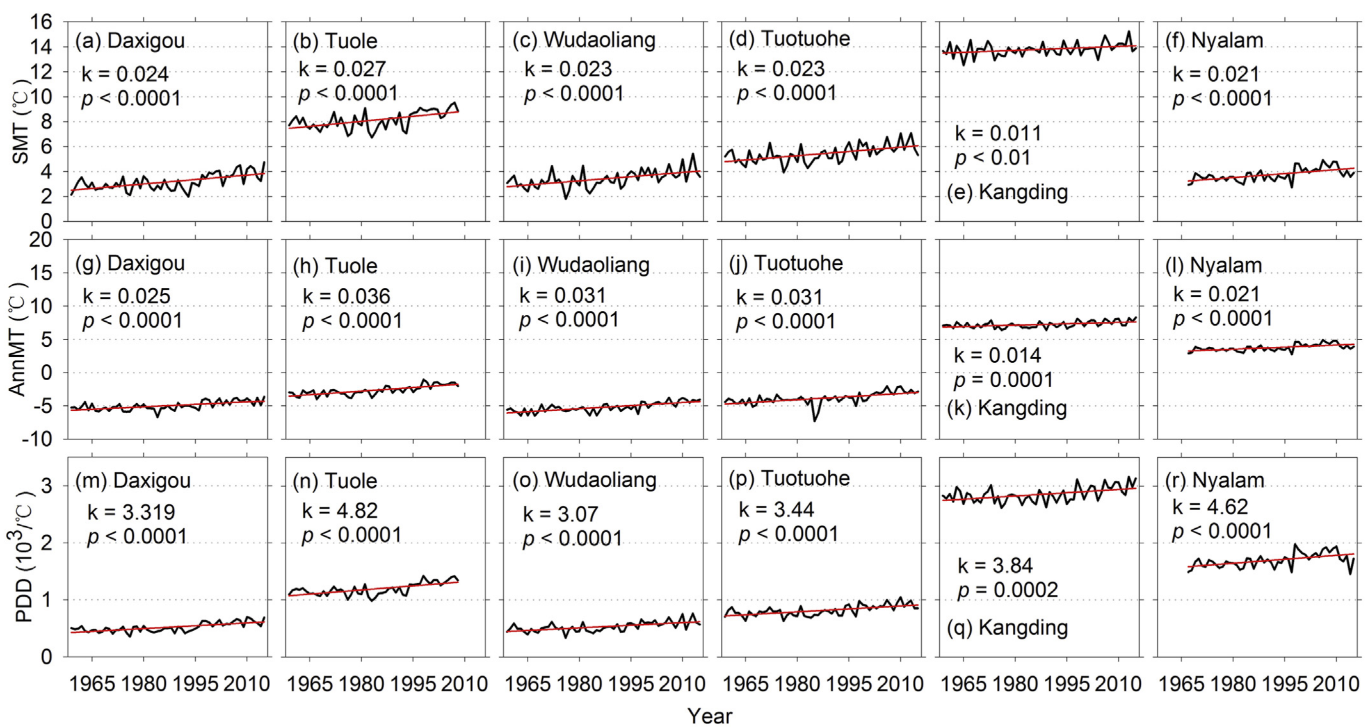

Fig. 7. Changes in temperatures of the meteorological stations, including Summer Mean air Temperature (SMT), Annual Mean air Temperature (AnnMT), and annual Positive Degree Days (PDD). In plots, black line expressive of temperatures and red line expressive of regressed line, while "k" is the slope of the regressed line in °C per year and "p" is the significance level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

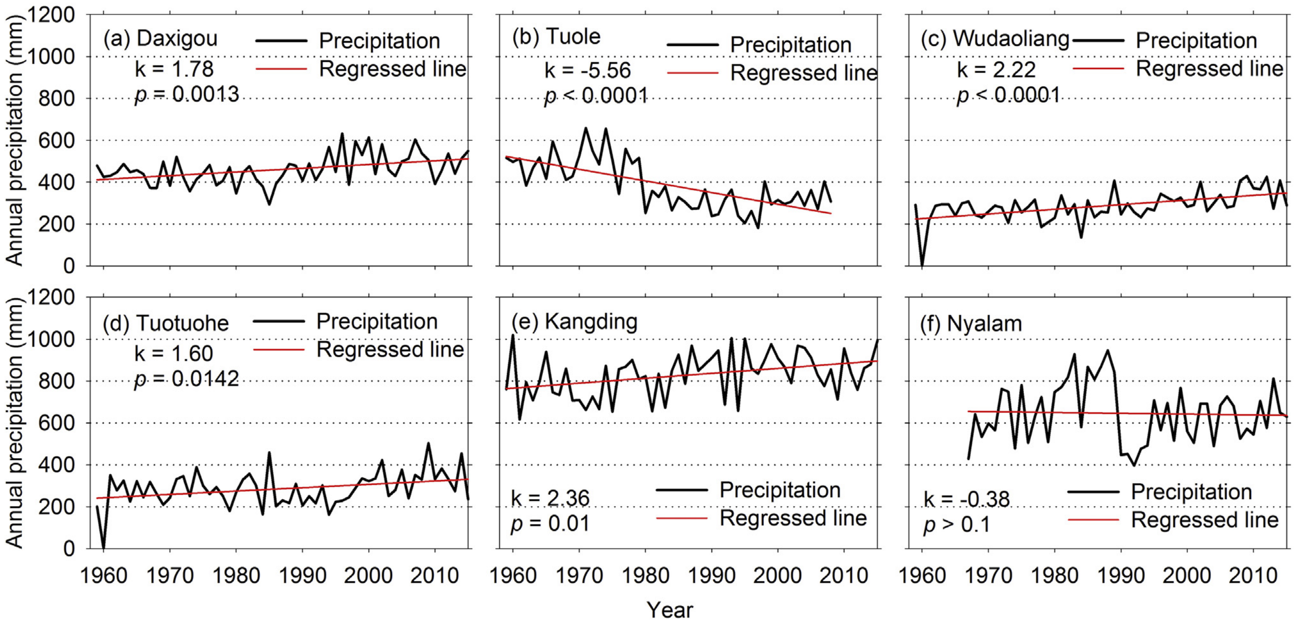

Fig. 8. Changes in annual precipitation of the meteorological stations. In plots, "k" is the slope of regressed line in mm per year and "*p*" is the significance level.

from field data, satellite images, and aerial photos for tens of thousands of glaciers around the world (e.g., Andreassen et al., 2005, 2016; Davies and Glasser, 2012; Oerlemans, 2000; Zemp et al., 2015). In China, the earliest recorded front position was recorded at the Hailuogou glacier in Hengduan Mountains, first recorded with aerial photos in 1930 (Li and Su, 1996). When we set 1930 as the reference (benchmark) year for frontal position, we found that Hailuogou's front had retreated 1296 m by 2014. Further, we determined that the glacial retreat in Hengduan Mountains was the most rapid over the past around 80 years (Fig. 6), and provided retreat data for two glaciers in these mountains that had retreated furthest, the Hailuogou (1150 m, 1930–1966) and Mingyong (2000 m, 1932–1959) (Table S2). Overall, glaciers in Hengduan Mountains retreated the maximum 1438 m by 1957. However, this period of retreat reversed, so that from 1957 to 1982, mean glacial position advanced. For example, Baishui No.1 glacier advanced 800 m during the 1957–1982 period, while Mingyong glacier advanced approximately 1230 m.

Variations in glacial length exist among mountain ranges. For example, glaciers were observed to advance in the Tianshan Mountains from 1943 to 1962, with a cumulative advance of 500 m. Glaciers in Pamir during the period 1963–2001 were relatively stable (advanced 28 m), while those glaciers in Karakoram advanced 379 m during the 1968–2000 period. The anomaly in Karakoram was also found by earlier studies, e.g., Gardelle et al. (2012), Hewitt (2005, 2011, 2013), and Quincey et al. (2011). Glaciers in Nanga Parbat massif retreat of ~200 m during the period 1934–2007 (Schmidt and Nüsser, 2009). In addition, retreating, stable, and advancing glacier fronts were observed in Himalayan Mountains from 2000 to 2008 (Scherler et al., 2011). There were at least 58 glaciers advanced during the period 1983–2008 in New Zealand (Mackintosh et al., 2017). Besides, the advancing and surge glaciers found in Svalbard Island (Jiskoot et al., 2000). Globally, relatively largest retreat of >1000 m was found in Alaska, Southern Andes, and New Zealand since 1950 (Zemp et al., 2015).

4.3. *Spatial heterogeneity in climatic change of western China*

The spatial heterogeneity in mass balance and front variation are likely resulted from spatial variation in climate change and variability. To understand the heterogeneity in space, the change trend in Annual Mean air Temperature (AnnMT), annual Positive Degree Days (PDD), annual precipitation, and Snowfall To Precipitation (STP) were analysed using Mann-Kendall and Sen's slop (Mann, 1945; Kendall, 1948; Sen, 1968) in western China during the period 1961–2015 (Fig. 9). Significantly warming trend nearly covered the entire western China. The warming rate of AnnMT mainly concentrated in 0.01–0.04 °C per year (Fig. 9a). The largest warming rate mainly distributed to the central and northern regions of Tibetan Plateau and eastern region of Altay Mountains, with more than the increased rate of 0.04 °C per year. Meanwhile, there were higher warming trend with respect to PDD in those places corresponding to increased AnnMT (Fig. 9b). However, great discrepancies existed in precipitation variation in space (Fig. 9c). There were significantly increasing in Altay, Tianshan, Pamir, Karakoram, and Qilian mountains and central region of Tibetan Plateau. In addition, the maximal increasing and decreasing rates of precipitation occurred in southeast Tibetan Plateau, with the rates of >5 mm per year and < −3 mm per year, respectively. Besides, the changes of STP assessed in western China using a conveniently temperature threshold by 2 °C to split into solid and liquid precipitations (Ding et al., 2014; Guo and Li, 2015). We could found that there were significantly decreased trend in STP, mainly locating in western Qilian Mountains and northwest and southeast regions of Tibetan Plateau (Fig. 9d). Meanwhile, a few of slightly increased in STP occurred in southwest Altay, northeast Tianshan, and northwest Qilian mountains.

4.4. *Karakoram anomaly in terms of glacier front variation*

Most mountain glaciers in the world have undergone terminal recession in recent decades (Oerlemans, 2001), while some short-term advances and surges were observed in many Karakoram glaciers in the late 1970 (Hewitt, 2013). There was a phenomenon that many central Karakoram glaciers began expanding in the late 1990s and first described to "Karakoram Anomaly" by Hewitt (2005). In this paper, we collected 14 glaciers in China at the north slope of Karakoram Mountains to assess the glacier front variation from

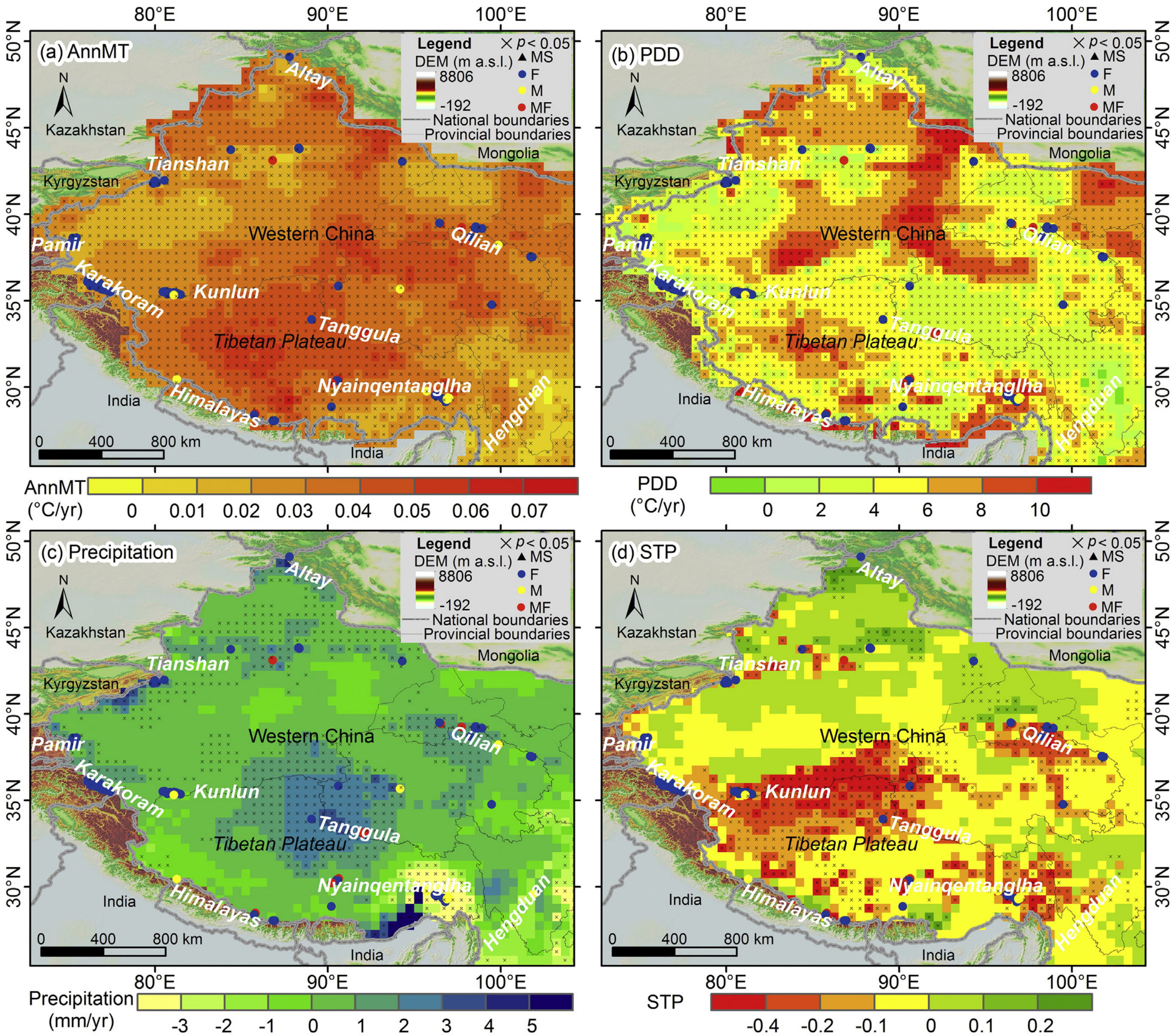

Fig. 9. Changed trends and rates in Annual Mean air Temperature (AnnMT), annual Positive Degree Days (PDD), annual Precipitation, and Snowfall To Precipitation (STP) in western China. "*p*" is the significance level.

1960s to 2000 (Table S2). Two glaciers coded as 5Y654D42 and 5Y653Q185 retreated 478 m and 278 m during the period 1976–2000, respectively. Four glaciers advanced, i.e., 5Y654D48 advanced 2050 m during 1976–2000, 5Y654D77 advanced 910 m during 1968–2000, 5Y654D78 advanced 140 m during 1968–2000, and 5Y654D97 advanced 1998 m during 1976–2000. However, the rest of 8 glaciers kept the relatively stable state in terms of the glacier front. It can be acknowledged that the retreat glaciers have relatively smaller area and higher elevation, while those stable and advanced glaciers have relatively larger area and widely-span elevation in Karakoram Mountains (Table 1 and Table S2). Besides, Bolch et al. (2012) found that some large glaciers have advanced or been stable in the Karakoram. They suggested that 25% the glaciers in western Karakoram were stable or advancing during the period 1976–2007.

Why did the many Karakoram glaciers show the stable and expand? In this paper, we recognized this phenomenon following the glacial feature, regional climate, accumulation and ablation, elevation effect, and glacier surge:

4.4.1. Glacier feature

The Karakoram glacier is commonly described as a winter accumulation regime or "Mid-latitude" type (i.e., winter accumulation and summer ablation) along with the Hindu Kush and Pamir (Ageta and Fujita, 1996; Hewitt, 2014). On the other hand, most Karakoram glacier are covered by heavy supraglacial debris. However, debris thicker than 4–5 cm reduces ablation and it becomes negligible beneath 1–2 m (Hewitt, 2005). Dusty, dirty ice, and debris thinner than 4 cm can accelerate glacier melting, which are more sensitive to climate change. The glacier cover increases in proportion to the height and extent of high elevations up to the highest, the K2 Massif. The glacier elevation ranges from the top of K2 (8610 m a.s.l.) to the lowest glacier terminus which can reach down to below 3000 m a.s.l. Besides, they have mean glaciered basin area of 370.0 km^2 and mean glacier length of 31.2 km (Hewitt, 2013).

4.4.2. Regional climate

The glacier in Karakoram is influenced by three distinct weather systems at different times of year (Hewitt, 2005). A westerly circulation and cyclonic storms dominate in winter. The other two systems, including storm paths and incidence of clear weather, affected by continental anticyclones. For the high-altitude snow accumulation, two-thirds occurs in winter while the other one-third comes from summer snowfall because the monsoon may advance over the region in most years (Hewitt, 2005; Mayewski and Jeschke, 1979; Wake, 1989). In addition, the clear-versus-cloudy weather is also an important factor in summer though 80–85% of glacier ablation is interpreted by direct solar radiation. It is acknowledged that sometimes cloudy weather from increased precipitation in summer can decline glacier melting (Hewitt, 2013). Taxkorgan is the closest meteorological station to Karakoram glaciers in all mountain meteorological stations of China Meteorological Administration. Based on the meteorological records from 1961 to 2010, we found increases in SMT and AnnMT (Fig. 10a). There are significantly increased trends in summer and annual precipitations, while no significantly trend in winter precipitation (Fig. 10b).

In addition, based on the records at valley meteorological stations, Archer and Fowler (2004) found that an increase in winter precipitation and declining summer mean and minimum temperature since the early 1960s. However, a study of climate change during the period 1980–2009 in the region conducted by Bocchiola and Diolaiuti (2013), which indicated no significantly changed trend in annual precipitation excepted for few stations with increasing in northwest Karakoram. In addition, maximum and minimum temperatures were increased almost over the region while some decreases of minimum temperature in few stations. Qureshi et al. (2017) indicated the summer mean air temperature and annual precipitation significantly increased by 0.02 °C per year and 0.2 mm per year, respectively. Similarly, as shown in Fig. 9, the increased rates of SMT and PDD were ~0.02 °C per year and 0.8–5.0 °C per year, respectively. The annual precipitation showed significantly increased by 1.6 mm per year in northwest Karakoram, while no significant trend in STP. However, a possible increase in snowfall over the Karakoram was revealed in the 21st century by regional climate modelling (Wiltshire, 2014). As a consequence, there are significant trends in SMT (increased and decreased), PDD (increased), and precipitation (varied) over the Karakoram. Meanwhile, spatial discrepancies of climate variation are very significant in the region because some decreases of SMT also found in some place.

4.4.3. Accumulation and ablation

Following the regime of glacier nourishment, the glaciers in Karakoram Mountains are identified four types, i.e., Turkestan-type, Mustagh type, Alpine type, and Wind-fed type (Hewitt, 2013). The number of Alpine type glacier is relatively few, while most glaciers belong to Mustagh types. Most glaciers have wide accumulation zone and rock walls, and the rock walls make up more than 60% of whole basin areas. The glacier accumulation or input derived from snow avalanches, wind-redistributed snow, direct snowfall, and ice avalanches (Hewitt, 2014). Snow avalanches and wind-redistributed snow are mainly inputs for the glaciers and their contribution reach to two-third of total inputs. Ice avalanches is from disconnected, steep tributaries high up and on steep. Accordingly, many glaciers in Karakoram have a year-round accumulation regime due to higher elevation-span. In addition, the lower elevation of glacier tongue can reach to below 3000 m a.s.l. so that it has more ablation months, sometimes reaches to a year for some glaciers. Hence, on the surface of glacier, the time-span of ablation season ranges from several months or a year in terminus to dozens or several days with increasing elevations, especially no ablation in higher accumulation zone.

It is difficult to directly measure the mass balance of Karakoram glaciers due to the wide and heavy debris-mantle ice in ablation zone. Based several observed glaciers, e.g., Biafo Glacier, Hewitt (2014) described that the ablation of most glaciers were not like the conventionally typical Alpine-type declining with increasing elevation, but presented a distinctly S-shaped profile applies. The annual net-balance of glacier terminus was close to zero due to heavy debris, while the largest ablation occurred in the mid-ablation zone (located in 3500–4500 m a.s.l.). Annual ablation declined again sharply and accumulation increased in the upper ablation zone. In other words, the mass balance often assessed by indirect approaches, deduce from records of meteorological station and river discharge, and sometimes remote sensing (e.g., Bolch et al., 2012; Ferguson et al., 1984; Gardelle et al., 2012). For example, Gardelle et al. (2012) found that slightly increased by 0.11 ± 0.22 m w.e. per year in Karakoram by comparing the images of SRTM in 2000 and SPOT5 in 2008. However, Kääb et al. (2012) showed that the glaciers in the northern and eastern parts of Karakoram have thickened by 0.14 ± 0.06 m per year based on the images of SRTM, ICESat, and LandSat TM and ETM during the period

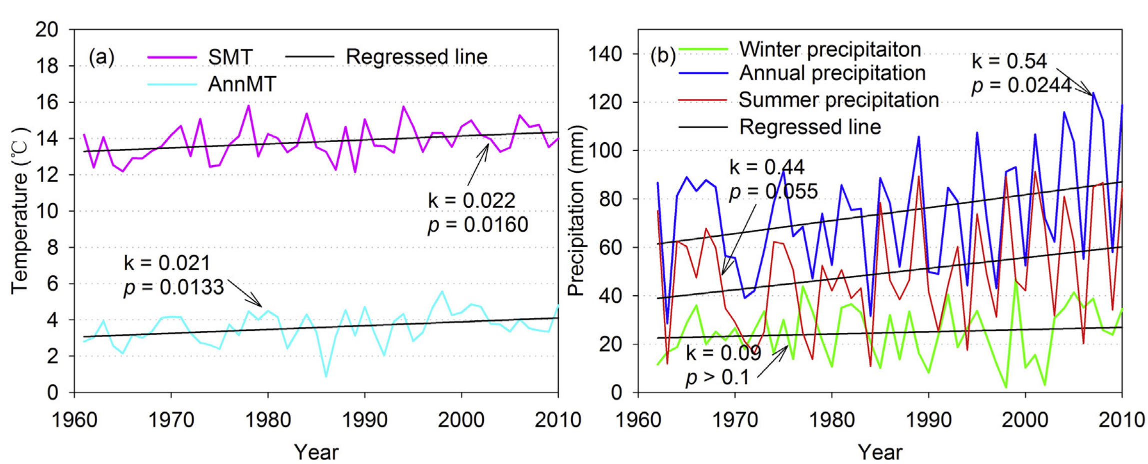

Fig. 10. Climatic change of Taxkorgan near to the Karakoram glacier during the period 1961–2010.

2003–2009.

4.4.4. Elevation effect and glacier surge

In Karakoram, the elevation of most glaciers span more than 3000 m vertically, and several larger glaciers span more than 5000 m (Hewitt, 2005). Large elevation-span generates a distinct discrepancy in vertical precipitation and generates heavy winter and summer snowfall. Annual precipitation of exceed 1000 mm was found in all snow pits, and some over 2000 mm. The maximum precipitation occurs between 5000 and 6000 m a.s.l. (Hewitt, 2011). In addition, the mean slope is excess of 32° and increases with elevation, where above 6000 m a.s.l. is exceed 45°. The heavy snowfall, high elevation, and steepness provide the possible to avalanche and the kinetic energy of ice stream.

One-third of Karakoram glaciers belongs to surge type, possibly (Hewitt, 2013). The glacier of surge type is often in the relatively quiet stage lasting decades to centuries other than the fast flow in short time (Jiskoot, 2011). Before 1980s, event of glacier surge is rarely reported because of limited understanding of glacier surge and constraint of observed technology. More and more surge phenomena, however, have been reported after 1980s. It became a focus of investigations and theory in glacier dynamics, especially in Karakoram called "Karakoram crest" of glacier surge (Clarke et al., 1986; Fowler et al., 2001; Hewitt, 2013; Kamb, 1987; Murray et al., 2003). Accordingly, many studies found the glacier anomaly in Karakoram Mountains, such as glacier surge and advance (Bhambri et al., 2013; Bolch et al., 2012; Cogley, 2011; Copland et al., 2011; Gardelle et al., 2012; Hewitt, 2005, 2011; Quincey et al., 2011; Qureshi et al., 2017; Scherler and Strecker, 2012; Yao et al., 2012). In addition, those studies showed that the event of glacier surge reported mean one in every 2.7 years during the period 1860–2010 (Hewitt, 2013). More and more studies presented that surges and surge cycles are independent and accidental with respect to global climate-related fluctuations and the rhythms in surrounding glaciers, but they need a trigger by weather condition (Eisen et al., 2005; Hewitt, 2013). Evidence showed that the recent Karakoram surges have been controlled by thermal, coinciding with high-altitude warming from long-term precipitation and accumulation patterns (Quincey et al., 2011).

But above all, those records of meteorological stations in valley are not to completely interpret the climate change of high elevation. However, it is undoubted that the climatic anomaly is obvious in climate variation in Karakoram Mountains (Bhutiyani et al., 2010; Fowler and Archer, 2006; Wiltshire, 2014). In this paper, the retreat glaciers of 5Y654D42 and 5Y653Q185 have relatively small area by 5.68 km^2 and 3.20 km^2 (Table 1), respectively. The rest of 12 glaciers showed stable and advanced, with relatively larger area ranging from 11.92 km^2 to 365.20 km^2. For the advanced glaciers, here, we can deduce that they surged during the period 1960s-2000 following their advanced distance (Table S2), such as 5Y654D48 advanced 2050 m from 1976 to 2000. The more detailed information of the glacier surge and advance (e.g. the time of advance and glacier front position in every year) need to more works in the field in future.

5. Conclusions and outlook

It is clear that the glaciers in China have been retreated over the past eight decades with several exception in certain regions, such as glaciers in Karakoram Mountains. The mean mass balance of glaciers in this study decreased by −0.015 m w.e. per year ($p < 0.0001$), which is a larger mean mass loss than for glaciers worldwide (−0.013 m w.e. per year, $P < 0.0001$). A total of cumulative mass balance in China was −14.74 m w.e. during 1959–2015, which is lesser than that worldwide (−19.14 m w.e., 1959–2012). In addition, mass balance data varied among glaciers in different mountain ranges. For example, glaciers shrank rapidly in the Hengduan Mountains, while the glaciers in Kunlun Mountains did not shrink much over the same period.

Glacial retreat in China was observed during the period 1930–2014, even though some glaciers advanced during that period. In addition, glacier advance/retreat varied among mountains in space and time. During the period 1942–1962, glaciers in the Tianshan Mountains advanced 500 m. During 1960s-2000s, most of glaciers retreated, except for those in the Karakoram Mountains, where the glaciers mean advanced 379 m during 1968–2000. There was relatively stable in the frontal position of the Pamir glacier during this period. The glaciers in the Tanggula Mountains appeared to be stable during the 1970s-2000s, but it is noted sample size of three glaciers. The most rapidly shrinking glaciers were located in the Hengduan Mountains, with as much as 1438 m of retreat during the period 1930–1959.

The glacier change is very important to understand the climate fluctuation and hydrological cycle in mountains, however, the number of monitored glaciers and meteorological stations in glacierized basins is very limited in western China. In addition, the time span of monitoring do not always coincide and the distribution of studied glaciers is heterogeneity in space. For example, more glaciers were studied in Tianshan and Qilian mountains and northwest Tibetan Plateau, while few glaciers in Altay Mountains and central Tibetan Plateau. This makes it difficult to quantitatively assess the regimes of glacier-climate and the uncertainty from glacier samples. Therefore, related key works will be addressed from now on: (1) continue and extend the long-term glaciological measurement, (2) assess and correct the glaciological mass balance using geodetic method, (3) improve and extend the dataset of glacier front variations based on the ground survey and remote sensing technology, (4) set up the meteorological network in those regions of climate anomaly, (5) model the response of mass balance and front variation of glacier to understand the regime between glacier and climate fluctuation, (6) establish a data sharing platform of glacier data to expediently exchange.

Acknowledgements

We sincerely thank the Cold and Arid Regions of Science Data Centre for providing the data of the second Chinese Glacier Inventory and meteorological data, and we thank China Meteorological Data Service Center for providing their meteorological data. This study was supported by the National Basic Research Programme of China (973 Program) (No. 2013CBA01801), the National Natural Science Foundation of China (No. 41301069 and 41641003), Foundation of State Key Laboratory of Cryospheric Sciences (No. SKLCS-OP-2017-04), and the Opening Foundation of Key Laboratory of Meteorological Disaster of Ministry of Education, Nanjing University of Information Science and Technology (No. KLME1416).

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.quaint.2017.07.003.

References

Ageta, Y., Fujita, K., 1996. Characteristics of mass balance of summer-accumulation type glaciers in the Himalayas and Tibetan Plateau. Z. Fürgletscherkd. Glazialgeol. 32, 61–65.

Andreassen, L.M., Elvehøy, H., Kjøllmoen, B., Engeset, R.V., 2016. Reanalysis of long-term series of glaciological and geodetic mass balance for 10 Norwegian glaciers. Cryosphere 10 (2), 535–552. http://dx.doi.org/10.5194/tc-10-535-2016.

Andreassen, L.M., Elvehøy, H., Kjøllmoen, B., Engeset, R.V., Haakensen, N., 2005.

Glacier mass-balance and length variation in Norway. Ann. Glaciol. 42 (1), 317–325. http://dx.doi.org/10.3189/172756405781812826.
Archer, D.R., Fowler, H.J., 2004. Spatial and temporal variations in precipitation in the Upper Indus Basin, global teleconnections and hydrological implications. Hydrol. Earth Syst. Sci. Discuss. 8 (1), 47–61.
Bhambri, R., Bolch, T., Kawishwar, P., Dobhal, D.P., Srivastava, D., Pratap, B., 2013. Heterogeneity in glacier response in the upper Shyok valley, northeast Karakoram. Cryosphere 7 (5), 1385–1398.
Bhutiyani, M.R., Kale, V.S., Pawar, N.J., 2010. Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006. Int. J. Climatol. 30 (4), 535–548.
Bishop, M.P., Olsenholler, J.A., Shroder, J.F., Barry, R.G., Raup, B.H., Bush, A.B.G., Copland, L., Dwyer, J.L., Fountain, A.G., Haeberli, W., Kääb, A., Paul, F., Hall, D.K., Kargel, J.S., Molnia, B.F., Trabant, D.C., Wessels, R., 2004. Global land ice measurements from space (GLIMS): remote sensing and GIS investigations of the Earth's cryosphere. Geocarto Int. 19 (2), 57–84. http://dx.doi.org/10.1080/10106040408542307.
Bocchiola, D., Diolaiuti, G., 2013. Recent (1980–2009) evidence of climate change in the upper Karakoram, Pakistan. Theor. Appl. Climatol. 113 (3), 611–641.
Bolch, T., Kulkarni, A., Kääb, A., Huggel, C., Paul, F., Cogley, J.G., Frey, H., Kargel, J.S., Fujita, K., Scheel, M., Bajracharya, S., Stoffel, M., 2012. The state and fate of himalayan glaciers. Science 336 (6079), 310–314.
Carturan, L., Baroni, C., Brunetti, M., Carton, A., Dalla Fontana, G., Salvatore, M.C., Zanoner, T., Zuecco, G., 2016. Analysis of the mass balance time series of glaciers in the Italian Alps. Cryosphere 10 (2), 695–712.
Clarke, G.C., Schmok, J.P., Ommanney, C.S.L., Collins, S.G., 1986. Characteristics of surge-type glaciers. J. Geophys. Res. 91 (B7), 7165–7180.
Cogley, J.G., 2011. Present and future states of Himalaya and Karakoram glaciers. Ann. Glaciol. 52 (59), 69–73.
Cogley, J.G., Hock, R., Rasmussen, L.A., Arendt, A.A., Bauder, A., Braithwaite, R.J., Jansson, P., Kaser, G., Möller, M., Nicholson, L., Zemp, M., 2011. Glossary of Glacier Mass Balance and Related Terms, IHP-VII Technical Documents in Hydrology No.86. IACS Contribution No.2. UNESCO-IHP, Paris, p. 114.
Cook, A.J., Fox, A.J., Vaughan, D.G., Ferrigno, J.G., 2005. Retreating glacier fronts on the antarctic peninsula over the past half-century. Science 308 (5721), 541–544. http://dx.doi.org/10.1126/science.1104235.
Copland, L., Sylvestre, T., Bishop, M.P., Shroder, J.F., Seong, Y.B., Owen, L.A., Bush, A., Kamp, U., 2011. Expanded and recently increased glacier surging in the Karakoram. Arct. Antarct. Alp. Res. 43 (4), 503–516.
Davies, B.J., Glasser, N.F., 2012. Accelerating shrinkage of patagonian glaciers from the Little ice Age (~AD 1870) to 2011. J. Glaciol. 58 (212), 1063–1084. http://dx.doi.org/10.3189/2012JoG12J026.
Ding, B., Yang, K., Qin, J., Wang, L., Chen, Y., He, X., 2014. The dependence of precipitation types on surface elevation and meteorological conditions and its parameterization. J. Hydrol. 513, 154–163.
Ding, Y., Xie, Z., 1991. A simple method on estimating glacial mass balance. J. Glaciol. Geocryol. 13 (3), 213–218 (in Chinese).
Dong, L., Zhang, M., Wang, S., Zhu, X., Ren, Z., Wang, Q., 2014. Extreme precipitation events in arid areas in northwest China based on gridded data. J. Nat. Resour. 29 (12), 2048–2057 (in Chinese).
Dong, Z., Qin, D., Ren, J., Li, K., Li, Z., 2013. Variations in the equilibrium line altitude of Urumqi Glacier No.1, Tianshan Mountains, over the past 50 years. Chin. Sci. Bull. 58 http://dx.doi.org/10.1007/s11434-012-5524-1.
Du, W., Qin, X., Liu, Y., Wang, X., 2008. Variation of the laohugou glacier No.12 in the qilian mountains. J. Glaciol. Geocryol. 30 (3), 373–379 (in Chinese).
Eisen, O., Harrison, W.D., Raymond, C.F., Echelmeyer, K.A., Bender, G.A., Gordeev, V.V., 2005. Variegated Glacier, Alaska, USA: a century of surges. J. Glaciol. 51 (174), 399–422.
Ferguson, R.I., Collins, D.N., Whalley, W.B., 1984. Techniques for investigating melt water runoff and erosion. In: Miller, K.J. (Ed.), International Karakoram Project. 2 Vols. Cambridge University Press, Cambridge, UK.
Fischer, A., 2010. Glaciers and climate change: interpretation of 50 years of direct mass balance of Hintereisferner. Glob. Planet. Change 71 (1–2), 13–26.
Fowler, A.C., Murray, T., Ng, F.S.L., 2001. Thermally controlled glacier surging. J. Glaciol. 47 (159), 527–538.
Fowler, H.J., Archer, D.R., 2006. Conflicting signals of climatic change in the upper indus basin. J. Clim. 19 (17), 4276–4293.
Gardelle, J., Berthier, E., Arnaud, Y., 2012. Slight mass gain of Karakoram glaciers in the early twenty-first century. Nat. Geosci. 5 (5), 322–325. http://dx.doi.org/10.1038/ngeo1450.
Gardner, A.S., Moholdt, G., Cogley, J.G., Wouters, B., Arendt, A.A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W.T., Kaser, G., Ligtenberg, S.R., Bolch, T., Sharp, M.J., Hagen, J.O., van den Broeke, M.R., Paul, F., 2013. A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009. Science 340 (6134), 852–857. http://dx.doi.org/10.1126/science.1234532.
Guo, L., Li, L., 2015. Variation of the proportion of precipitation occurring as snow in the Tian Shan Mountains, China. Int. J. Climatol. 35 (7), 1379–1393.
Guo, W., Xu, J., Liu, S., Shangguan, D., Wu, L., Yao, X., Zhao, J., Liu, Q., Jiang, Z., Li, P., Wei, J., Bao, W., Yu, P., Ding, L., Li, G., Ge, C., Wang, Y., 2014. The Second Glacier Inventory Dataset of China (Version 1.0). Cold and Arid Regions Science Data Center at Lanzhou. http://dx.doi.org/10.3972/glacier.001.2013.db.
Han, T., Liu, S., Ding, Y., Jiao, K., 2005. A characteristics mass balance of glacier No.1 at the headwaters of the Urumqi River, Tianshan Mountains. Adv. Earth Sci. 20 (3), 298–303 (in Chinese).
He, Y., Zhang, D., 2004. Climatic warming is the major reason for glacier retreat on Mt. Yulong, China. J. Glaciol. Geocryol. 26 (2), 230–231 (in Chinese).
He, Y., Zhang, Z., Yao, T., Chen, T., Pang, H., Zhang, D., 2003. Modern changes of the climate and glaciers in China's Monsoonal Temperate-Glacier region. Acta Geogr. Sin. 58 (4), 550–558 (in Chinese).
Hewitt, K., 2005. The Karakoram Anomaly? Glacier expansion and the 'elevation effect,' Karakoram Himalaya. Mt. Res. Dev. 25 (4), 332–340.
Hewitt, K., 2011. glacier change, concentration, and elevation effects in the Karakoram Himalaya, upper indus basin. Mt. Res. Dev. 31 (3), 188–200.
Hewitt, K., 2013. Glaciers of the Karakoram Himalaya: Glacial Environments, Processes, Hazards and Resources. Springer Science & Business Media.
Hewitt, K., 2014. Glacier Mass Balance Regimes, Glaciers of the Karakoram Himalaya: Glacial Environments, Processes, Hazards and Resources. Springer Netherlands, Dordrecht, pp. 143–162.
Hock, R., Jensen, H., 1999. Application of kriging interpolation for glacier mass balance computations. Geografiska annaler: series a. Phys. Geogr. 81 (4), 611–619.
Hoelzle, M., Haeberli, W., Dischl, M., Peschke, W., 2003. Secular glacier mass balances derived from cumulative glacier length changes. Glob. Planet. Change 36 (4), 295–306. http://dx.doi.org/10.1016/S0921-8181(02)00223-0.
Immerzeel, W., Petersen, L., Ragettli, S., Pellicciotti, F., 2014. The importance of observed gradients of air temperature and precipitation for modelling runoff from a glacierized watershed in the Nepalese Himalayas. Water Resour. Res. 50 (3), 2212–2226.
IPCC, 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, pp. 1–33.
IPCC, 2012. IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX). Cambridge University Press, Cambridge, pp. 1–21.
Jiao, K., Wang, C., Han, T., 2000. A strong negative mass balance recently appeared in the Glacier No.1 at the headwaters of the Urumqi River. J. Glaciol. Geocryol. 22 (1), 62–64 (in Chinese).
Jing, Z., Ye, B., Jiao, K., Yang, H., 2002. Surface velocity on the glacier No.51 at haxilegen of the kuytun river, tianshan mountains. J. Glaciol. Geocryol. 24 (5), 563–566 (in Chinese).
Jiskoot, H., 2011. Glacier surging. In: Singh, V.P., Singh, P., Haritashya, U.K. (Eds.), Encyclopedia of Snow, Ice and Glaciers. Springer Netherlands, Dordrecht, pp. 415–428.
Jiskoot, H., Murray, T., Boyle, P., 2000. Controls on the distribution of surge-type glaciers in Svalbard. J. Glaciol. 46 (154), 412–422.
Kääb, A., Berthier, E., Nuth, C., Gardelle, J., Arnaud, Y., 2012. Contrasting patterns of early twenty-first-century glacier mass change in the Himalayas. Nature 488 (7412), 495–498.
Kamb, B., 1987. Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. J. Geophys. Res. Solid Earth 92 (B9), 9083–9100.
Kang, S., Chen, F., Ye, Q., Jing, Z., Qin, D., Ren, J., 2007. Glacier retreating dramatically on the Mt. Nyainqentanglha during the last 40 Years. J. Glaciol. Geocryol. 29 (6), 869–873 (in Chinese).
Kendall, M.G., 1948. Rank Correlation Methods. Griffin, Oxford, England.
Li, J., Su, Z., 1996. Glaciers in Hengduan Mountains. Science Press, Beijing (in Chinese).
Li, Z., Li, H., Chen, Y., 2011. Mechanisms and simulation of accelerated shrinkage of continental glaciers: a case study of Urumqi Glacier No. 1 in eastern Tianshan, Central Asia. J. Earth Sci. 22 (4), 423–430. http://dx.doi.org/10.1007/s12583-011-0194-5.
Li, Z., Li, K., Wang, L., 2010. Study on recent glacier changes and their impact on water resuorces in Xinjiang, North Western China. Quat. Sci. 30 (1), 96–106 (in Chinese).
Li, Z., Wang, F., Zhu, G., Li, H., 2007. Basic features of the miaoergou flat topped glacier In east Tianshan mountains and its thickness change over the past 24 years. J. Glaciol. Geocryol. 29 (1), 61–65 (in Chinese).
LIGCCAS (Lanzhou Institute of Glaciology and Cryopedology, Chinese Academy of Sciences), 1980. A preliminary study on recent fluctuation of glaciers in the Qilian Shan. J. Glaciol. Geocryol. 35 (1), 48–57+99 (in Chinese).
Lin, H., You, Q., Jiao, Y., Min, J., 2015. Spatial and temporal characteristics of the precipitation over the tibetan plateau from 1961 to 2010 based on high resolution grid-observation dataset. J. Nat. Resour. 30 (2), 271–281 (in Chinese).
Liu, C., Kang, E., Liu, S., Chen, J., Liu, Z., 1999. Study on the glaciers variation and its runoff response in the arid region of Northwest China. Sci. China Ser. D Earth Sci. 29 (Suppl. 1 .1), 55–62 (in Chinese).
Liu, C., Xie, Z., Wang, C., 1997. A research on the mass balance processes of Glacier No.1 at the headwaters of the Urumqi River, Tianshan Mountains. J. Glaciol. Geocryol. 19 (1), 19–26 (in Chinese).
Liu, S., Lu, A., Ding, Y., Yao, T., Ding, L., Li, G., Hooke, R., 2002. Glacier fluctuations and the inferred climate changes in the A'Nyemaqen mountains in the source area of the yellow rive. J. Glaciol. Geocryol. 24 (6), 701–707 (in Chinese).
Liu, S., Shangguan, D., Ding, Y., Han, H., Xie, C., Zhang, Y., Li, J., Wang, J., Li, G., 2006. Glacier changes during the past century in the Gangrigabu mountains, southeast Qinghai-Xizang (Tibetan) Plateau, China. Ann. Glaciol. 43 (1), 187–193. http://dx.doi.org/10.3189/172756406781812348.
Liu, S., Yao, X., Guo, W., Xu, J., Shuangguan, D., Wei, J., Bao, W., Wu, L., 2015. The contemporary glaciers in China based on the Second Chinese Glacier Inventory. Acta Geogr. Sin. 70 (1), 3–16 (in Chinese).
Mackintosh, A.N., Anderson, B.M., Lorrey, A.M., Renwick, J.A., Frei, P., Dean, S.M., 2017. Regional cooling caused recent New Zealand glacier advances in a period

of global warming. Nat. Commun. 8, 14202.
Mann, H.B., 1945. Nonparametric tests against trend. Econometrica 13 (3), 245–259.
Mayewski, P.A., Jeschke, P.A., 1979. Himalayan and trans-Himalayan glacier fluctuations since AD 1812. Arct. Alp. Res. 11, 267–287.
Meierding, T.C., 1982. Late pleistocene glacial equilibrium-line altitudes in the Colorado Front Range: a comparison of methods. Quat. Res. 18 (3), 289–310.
Mukhopadhyay, B., Khan, A., 2017. Altitudinal variations of temperature, equilibrium line altitude, and accumulation-area ratio in Upper Indus Basin. Hydrol. Res. 48 (1), 214–230.
Murray, T., Strozzi, T., Luckman, A., Jiskoot, H., Christakos, P., 2003. Is there a single surge mechanism? Contrasts in dynamics between glacier surges in Svalbard and other regions. J. Geophys. Res. Solid Earth 108 (B5) n/a-n/a.
Oerlemans, J., 2000. Holocene glacier fluctuations: is the current rate of retreat exceptional? Ann. Glaciol. 31 (1), 39–44. http://dx.doi.org/10.3189/172756400781820246.
Oerlemans, J., 2001. Glaciers and Climate Change. CRC Press.
Oerlemans, J., 2005. Extracting a climate signal from 169 glacier records. Science 308 (5722), 675–677. http://dx.doi.org/10.1126/science.1107046.
Østby, T.I., Schuler, T.V., Hagen, J.O., Hock, R., Kohler, J., Reijmer, C.H., 2017. Diagnosing the decline in climatic mass balance of glaciers in Svalbard over 1957–2014. Cryosphere 11, 191–215.
Østrem, G., Brugman, M., 1991. Glacier Mass-balance Measurements. A Manual for Field and Office Work. Environment Canada. National Hydrology Research Institute, Saskatoon, Sask (NHRI Science Report 4.).
Porter, S.C., 1975. Equilibrium-line altitudes of late quaternary glaciers in the southern alps, New Zealand. Quat. Res. 5 (1), 27–47.
Pratap, B., Dobhal, D.P., Bhambri, R., Mehta, M., Tewari, V.C., 2016. Four decades of glacier mass balance observations in the Indian Himalaya. Reg. Environ. Change 16 (3), 643–658. http://dx.doi.org/10.1007/s10113-015-0791-4.
Pu, J., Yao, T., Tian, L., 2006. Change of the GurenhekouGlacier in yangbajain area, Nyainqentanglha range. J. Glaciol. Geocryol. 28 (6), 861–864 (in Chinese).
Pu, J., Yao, T., Wang, N., Su, Z., Shen, Y., 2004. Fluctuations of the glaciers on the qinghai-tibetan plateau during the past century. J. Glaciol. Geocryol. 26 (5), 517–522 (in Chinese).
Pu, J., Yao, T., Zhang, Y., Seko, K., Fujita, K., 1995. Mass balance on the Dongkemadi and Meikuang glaciers in 1992/1993. J. Glaciol. Geocryol. 17 (02), 138–143 (in Chinese).
Quincey, D.J., Braun, M., Glasser, N.F., Bishop, M.P., Hewitt, K., Luckman, A., 2011. Karakoram glacier surge dynamics. Geophys. Res. Lett. 38 (18) http://dx.doi.org/10.1029/2011 gl049004 n/a-n/a.
Qureshi, M.A., Yi, C., Xu, X., Li, Y., 2017. Glacier status during the period 1973–2014 in the hunza basin, western Karakoram. Quat. Int. 444 (Part A), 125–136. http://dx.doi.org/10.1016/j.quaint.2016.08.029.
Ren, J., Jing, Z., Pu, J., Qin, X., 2006. Glacier variations and climate change in the central Himalaya over the past few decades. Ann. Glaciol. 43 (1), 218–222. http://dx.doi.org/10.3189/172756406781812230.
Sagredo, E.A., Lowell, T.V., Kelly, M.A., Rupper, S., Aravena, J.C., Ward, D.J., Malone, A.G.O., 2016. Equilibrium line altitudes along the Andes during the Last millennium: paleoclimatic implications. Holocene. http://dx.doi.org/10.1177/0959683616678458.
Sakai, A., Nuimura, T., Fujita, K., Takenaka, S., Nagai, H., Lamsal, D., 2015. Climate regime of Asian glaciers revealed by GAMDAM glacier inventory. Cryosphere 9 (3), 865–880. http://dx.doi.org/10.5194/tc-9-865-2015.
Scherler, D., Bookhagen, B., Strecker, M.R., 2011. Spatially variable response of Himalayan glaciers to climate change affected by debris cover. Nat. Geosci. 4 (3), 156–159.
Scherler, D., Strecker, M.R., 2012. Large surface velocity fluctuations of Biafo Glacier, central Karakoram, at high spatial and temporal resolution from optical satellite images. J. Glaciol. 58 (209), 569–580.
Schmidt, S., Nüsser, M., 2009. Fluctuations of Raikot Glacier during the past 70 years: a case study from the Nanga Parbat massif, northern Pakistan. J. Glaciol. 55 (194), 949–959.
Sen, P.K., 1968. Estimates of the regression coefficient based on Kendall's tau. J. Am. Stat. Assoc. 63 (324), 1379–1389.
Shangguan, D., Liu, S., Ding, Y., Ding, L., 2004a. Monitoring results of glacier change in China Karakorum and Muztag Ata-Konggur Mountains by remote sensing. J. Glaciol. Geocryol. 26 (3), 374–375 (in Chinese).
Shangguan, D., Liu, S., Ding, Y., Ding, L., Li, G., 2004b. glacier changes at the head of yurungkax River in the west Kunlun mountains in the past 32 years. Acta Geogr. Sin. 59 (6), 855–862 (in Chinese).
Shen, X., Liu, B., Li, G., Zhou, D., 2015. Impact of Climate Change on Temperate and Alpine Grasslands in China during 1982-2006. Advances in Meteorology ID 180614, pp. 1–10.
Shi, P., Sun, S., Wang, M., Li, N., Wang, J., Jin, Y., Gu, X., Yin, W., 2014. Climate change regionalization in China (1961–2010). Sci. China Earth Sci. 44 (10), 2294–2306 (in Chinese).
Shi, Y., Liu, C., Kang, E., 2009. The Glacier inventory of China. Ann. Glaciol. 50 (53), 1–4. http://dx.doi.org/10.3189/172756410790595831.
Shi, Y., Liu, S., 2000. Estimation on the response of glaciers in China to the global warming in the 21st century. Chin. Sci. Bull. 45 (7), 668–672. http://dx.doi.org/10.1007/bf02886048.
Su, Z., Liu, Z., Wang, W., Yao, T., Shao, W., Pu, J., Liu, S., 1999. Glacier fluctuations responding to climate change and forecast of its tendency over the Qinghai-Tibet Plateau. Adv. Earth Sci. 14 (6), 607–612 (in Chinese).
Su, Z., Orlov, A.B., 1992. The preliminary report on the Sino-USSR joint glaciological expedition to Mt. Xixabangma region, 1991. J. Glaciol. Geocryol. 14 (2), 184–186 (in Chinese).
Su, Z., Pu, J., 1998. Glacier Fluctuations in Qinghai -Xizang (Tibetan) Plateau. Contemporary Climatic Variations over Qinghai-Xizang (Tibetan) Plateau and Their Influences on Environments. Guangdong Science and Technology Press, Guangzhou, pp. 223–236 (in Chinese).
Su, Z., Shi, Y., 2002. Response of monsoonal temperate glaciers to global warming since the Little Ice Age. Quat. Int. 97–98 (2), 123–131.
Sun, Z., Xie, Z., 1981. Variation of glacier and forecast of its tendency on No.12 glacier in Laohu valley over the Qianlian Mountains. Chin. Sci. Bull. 26 (6), 366–369 (in Chinese).
TGS (Tianshan Glaciological Station), 1981. The Annual Report. Cold and arid regions environmental and engineering research institute. Chin. Acad. Sci. 1 (in Chinese).
TGS (Tianshan Glaciological Station), 1991. The Annual Report. Cold and arid regions environmental and engineering research institute. Chin. Acad. Sci. 1 (in Chinese).
TGS (Tianshan Glaciological Station), 2016. The Annual Report. Cold and arid regions environmental and engineering research institute. Chin. Acad. Sci. 20–22 (in Chinese).
Wake, C.P., 1989. Glaciochemical investigations as a tool to determine the spatial variation of snow accumulation in the Central Karakoram, Northern Pakistan. Ann. Glaciol. 13, 279–284.
Wang, J., Zhang, M., Wang, S., Ren, Z., Che, Y., Zhang, F., 2016. Change of snowfall/rainfall ratio in the Tibetan Plateau based on a gridded dataset with high resolution during 1961-2013. J. Geogr. Sci. 26 (9), 1277–1288.
Wang, P., Li, Z., Li, H., Wang, W., Yao, H., 2014. Comparison of glaciological and geodetic mass balance at Urumqi Glacier No. 1, tian shan, central asia. Glob. Planet. Change 114, 14–22. http://dx.doi.org/10.1016/j.gloplacha.2014.01.001.
Wang, P., Li, Z., Li, H., Wu, L., Jin, S., Zhou, P., 2012. Changes of ice-thickness and volume for representative glaciers in Tianshan Mountains in the past 50 Years. J. Glaciol. Geocryol. 67 (7), 929–940 (in Chinese).
Wang, S., Ye, J., Gong, D., 1998. Climate in China during the Little ice Age. Quat. Sci. 18 (1), 54–64 (in Chinese).
Wang, Z., 1991. The Little ice Age of northwest China. J. Arid Land Resour. Environ. 5 (3), 64–74 (in Chinese).
WGMS (World Glacier Monitoring Service), 2008. Global glacier changes: facts and figures. UNEP, World Glacier Monitoring Service, Zürich. http://www.grid.unep.ch/glaciers/.
WGMS (World Glacier Monitoring Service), 2016. Fluctuations of Glaciers Database, Edited. World Glacier Monitoring Service, Zurich, Switzerland. http://dx.doi.org/10.5904/wgms-fog-2016-08.
Wiltshire, A.J., 2014. Climate change implications for the glaciers of the Hindu Kush, Karakoram and himalayan region. Cryosphere 8 (3), 941–958.
Winiger, M., Gumpert, M., Yamout, H., 2005. Karakorum–Hindukush–western Himalaya: assessing high-altitude water resources. Hydrol. Process. 19 (12), 2329–2338.
Xie, C., Ding, Y., Liu, S., Li, B., Zhu, G., 2006. Variation of keqikaer glacier terminus in tomur peak during last 30 years. J. Glaciol. Geocryol. 28 (5), 672–677 (in Chinese).
Xie, Z., Su, Z., Shen, Y., Feng, Q., 2001. Mass balance and water exchange of Hailuoguo glacier in Mount Gongga and their influence on glacial melt runoff. J. Glaciol. Geocryol. 23 (1), 7–15 (in Chinese).
Yao, T., Liu, S., Pu, J., Shen, Y., Lu, A., 2004. Recent glacial retreat in High Asia in China and its impact on water resource in Northwest China. Sci. China Ser. D Earth Sci. 34 (6), 535–543 (in Chinese).
Yao, T., Thompson, L., Yang, W., Yu, W., Gao, Y., Guo, X., Yang, X., Duan, K., Zhao, H., Xu, B., Pu, J., Lu, A., Xiang, Y., Kattel, D.B., Joswiak, D., 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. Nat. Clim. Change 2 (9), 663–667. http://dx.doi.org/10.1038/nclimate1580.
Yao, X., Liu, S., Guo, W., Huai, B., Sun, M., Xu, J., 2012. glacier change of Altay mountain in China from 1960 to 2009—based on the second Glacier Inventory of China. J. Nat. Resour. 27 (10), 1734–1745 (in Chinese).
Zecchetto, S., Serandrei-Barbero, R., Donnici, S., 2016. Temperature reconstruction from the length fluctuations of small glaciers in the eastern Alps (northeastern Italy). Clim. Dyn. 1–12. http://dx.doi.org/10.1007/s00382-016-3347-5.
Zemp, M., Frey, H., Gärtner-Roer, I., Nussbaumer, S.U., Hoelzle, M., Paul, F., Haeberli, W., Denzinger, F., Ahlstrøm, A.P., Anderson, B., Bajracharya, S., Baroni, C., Braun, L.N., Cáceres, B.E., Casassa, G., Cobos, G., Dávila, L.R., Delgado Granados, H., Demuth, M.N., Espizua, L., Fischer, A., Fujita, K., Gadek, B., Ghazanfar, A., Hagen, J.O., Holmlund, P., Karimi, N., Li, Z., Pelto, M., Pitte, P., Popovnin, V.V., Portocarrero, C.A., Prinz, R., Sangewar, C.V., Severskiy, I., Sigurðsson, O., Soruco, A., Usubaliev, R., Vincent, C., 2015. Historically unprecedented global glacier decline in the early 21st century. J. Glaciol. 61 (228), 745–762. http://dx.doi.org/10.3189/2015JoG15J017.
Zemp, M., Hoelzle, M., Haeberli, W., 2009. Six decades of glacier mass-balance observations: a review of the worldwide monitoring network. Ann. Glaciol. 50 (50), 101–111. http://dx.doi.org/10.3189/172756409787769591.
Zemp, M., Thibert, E., Huss, M., Stumm, D., Rolstad Denby, C., Nuth, C., Nussbaumer, S.U., Moholdt, G., Mercer, A., Mayer, C., Joerg, P.C., Jansson, P., Hynek, B., Fischer, A., Escher-Vetter, H., Elvehøy, H., Andreassen, L.M., 2013. Reanalysing glacier mass balance measurement series. Cryosphere 7 (4), 1227–1245. http://dx.doi.org/10.5194/tc-7-1227-2013.
Zhang, J., 1981. Mass balance studies on the No.1 glacier of Urumqi River in tianshan. J. Glaciol. Geocryol. 3 (2), 32–40.

Zhang, J., He, X., Ye, B., Wu, J., 2013. Recent variation of mass balance of the Xiao Dongkemadi glacier in the Tanggula range and its influencing factors. J. Glaciol. Geocryol. 35 (2), 263–271 (in Chinese).

Zheng, B., Zhao, X., Li, T., Wang, C., 1999. Features and fluctuation of the melang glacier In the mainri mountain. J. Glaciol. Geocryol. 21 (2), 145–146+417-150 (in Chinese).

Zhu, K., 1973. A preliminary study on climate change of China in recent five thousand years. Sci. China 16 (2), 168–189 (in Chinese).