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Responses of the Glacier Mass Balance to Climate Change in the Tibetan Plateau During 1975–2013

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Key Points:

- In this study, the long-term glacier mass balance from 1975 to 2013 for seven major glaciers in the Tibetan Plateau has been reconstructed
- Most mass balances are dominated by meltwater in the study area
- The western glacier mass balance changes strongly to moisture change, while the eastern glacier mass balance changes greatly to heat change

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Abstract Approximately 70% of the available water in the entire Tibetan Plateau is stored in glaciers. Understanding the impact of climate change on the glacier mass balance is crucial given that the Plateau is the "water tower" of East and Southeast Asia. However, the historical records of the glacier mass balance for the Tibetan Plateau are scattered and incomplete. In this study, we reconstructed the long-term glacier mass balance from 1975 to 2013 (the data can be downloaded at https://doi.org/10.11888/Glacio.tpdc.270382) using the field observations for seven major glaciers and corresponding meteorological data extracted from the GLDAS CLSM (Global Land Data Assimilation Systems based on the Catchment Land Surface Model) data set. The effects of refrozen water and snow depth on the glacier mass balance was examined. In addition, the response of glacier mass balance to climate change was investigated. The results indicate that most of the glaciers experienced a mass loss during the study period. Large mass loss occurred in glaciers in the southeastern part of the plateau. The glacier in the northwestern part of the plateau (the Muztagh No.15 Glacier) shows a small mass gain. Regarding the mass components of the glacier mass balance, most mass balances are dominated by meltwater, while the Muztagh No. 15 has a component offset. Further analysis manifests that mass balances in the western glaciers heavily change to the change of moisture factor (precipitation), while for the eastern glaciers, mass balance changes respond strongly to the changes of heat factors (air temperature and net radiation). The differences in the mass balance changes are closely related to the westerlies and Indian summer monsoon.

1. Introduction

One of the topics focused on globally these days is the changing climate, and the associated dramatic and worldwide glacier retreat (Benn et al., 2017; Bolch et al., 2012; Song et al., 2017). As the Asian "water tower," the Tibetan Plateau plays a significant role in the water supply for the downstream areas. The water volume stored in glaciers accounts for ~70% of the total water resources in the Tibetan Plateau (Yao et al., 2012). Based on the Second Chinese Glacier Inventory data set, the glacial area of the interior plateau and western China decreased by 9.5% (767 km^2) and 18% (~9,000 km^2), respectively, between 2004 and 2011 compared with the 1970s (Guo et al., 2014; Wei et al., 2014). However, most studies on the changes in the glacier mass balance and relevant influencing factors in the Tibetan Plateau were mainly carried out in situ (Liu et al., 2014; Wu et al., 2015) because of the serious scarcity of field measurements. Therefore, it is necessary to collect field data on glaciers and conduct large-scale studies. Because the observed glacier data are generally discontinuous, the reconstruction of long-term glacier data are important for understanding the changes over the years.

It has been widely acknowledged that continuous warming is the main driver of the glacier mass balance change. Specifically, rapid warming has occurred in the Tibetan Plateau in the recent decades, not only with respect to the air temperatures (+0.036°C/a during 2001–2012) but also related to the land surface temperature (+0.03°C/a; G. Zhang, Yao, Xie, Qin, et al., 2014). These rates represent approximately three times the global mean surface temperature increase from 1951 to 2012 (0.02°C/a; Field et al., 2014). The accelerated glacier retreat and enhanced precipitation based on the continuous regional warming have resulted in an increase in the lake numbers, expansion of lake areas (G. Zhang, Yao, Xie, K. Zhang, et al., 2014), and rising lake levels (Zhang et al., 2011, 2013). Therefore, the risk of dam failure floods due to the increasing temporary formation of glacier lakes has significantly increased (Phan et al., 2012). In addition, water vapor conditions in the Tibetan Plateau changes in the rainfall to snowfall, and evaporation caused by the weakening of the Indian summer monsoon and westerlies have also been of major concerns, especially regarding their impacts on the glacier mass balance (Immerzeel et al., 2010; Murari et al., 2014; Qiu, 2008; Sun et al., 2018; Yao et al., 2012). However, most studies of the relevant issues were primarily carried out in a qualitative way (Fujita, 2008; Murari et al., 2014), and the influences of the water vapor changes on the glacier mass balance were not quantified. This impedes the future prediction of the glacier mass balance under climate change. Therefore, a quantitative approach for the identification of the contributions of the two categories of variables related to water vapor (i.e., precipitation and evaporation) and heat (i.e., air temperature and solar radiation) to the glacier mass balance is needed.

The aim of this study is to quantify the impact of climate change on the glacial mass balance during 1975–2013 in the Tibetan Plateau. The detailed tasks are: (a) construction of long-term glacier data and investigation of the response of the glacier mass balance to different factors and (b) quantification of the contribution of mass components to the glacier mass balance. Seven monitored glaciers in the Tibetan Plateau were selected for this study.

2. Data

2.1. Glacier Mass Balance Data

Glacier mass balance data were collected from the World Glacier Inventory (https://nsidc.org/data/G10002/versions/1) (Dyurgerov et al., 2002, updated 2005) and Third Pole Environment Database (http://en.tpe-database.cn/). The data set includes the annual glacier mass balance (mm water equivalent [w.e.] from October to following September). Enough mass balance data are only available for seven of all 14 glaciers; therefore, these seven glaciers have been selected for the analyses. The seven selected glaciers roughly cover all glacier regions in the study area, except the southwestern Tibetan Plateau and thus reflect the general conditions of glaciers in the Tibetan Plateau. Figure 1 shows the spatial distribution of the glaciers, including the Hailuogou, Parlung No. 94, Qiyi, Xiaodongkemadi, Muztagh No.15, Meikuang, and NM551 glaciers.

2.2. Meteorological Data

The meteorological data include the daily precipitation flux (which is precipitation with the original unit of kg m^{-2} s^{-1}, and in the following application, the unit of precipitation is converted into mm w.e.), air temperature, evaporation, long- and short-wave radiation and snow depth of the entire Tibetan Plateau from 1975 to 2013 (study period of the above-mentioned glaciers). They have been obtained from the GLDAS CLSM 2.0 model outputs, which has been validated against previous studies over the study area (Bai et al., 2016; Zhong et al., 2011). It is worthy to note that daily evaporation and daily snow depth data for the Muztagh No.15 Glacier are missing in GLDAS data set. To compensate such a flaw, they are transplanted from the adjacent grid by the ratio of annual mean precipitation (the correlation coefficient of daily precipitation/air temperature between the grid in Muztagh No.15 Glacier and the selected adjacent grid is over 0.6 passing the 0.05 significance level by *t*-test [Cressie & Whitford, 1986]). The calculation was based on a mass balance year as above-mentioned (from October to following September). Accordingly, precipitation, evaporation, air temperature, and long-wave and short-wave radiation were the daily sums within balance years. The snow depths were the daily averages within mass balance years.

3. Methods

3.1. Glacier Mass Balance Equation

To investigate the glacier mass balance in the Tibetan Plateau in the study period, we combined the approaches introduced by Fujita et al. (1996) and Huss et al. (2008) for the central Tibetan Plateau. Fujita et al.'s (1996) approach has been used in many studies (Farinotti et al., 2012; Hock, 2005; Karner et al., 2013; Wadham & Nuttall, 2002). It accounts for the refrozen water as a mass component affecting the balance.

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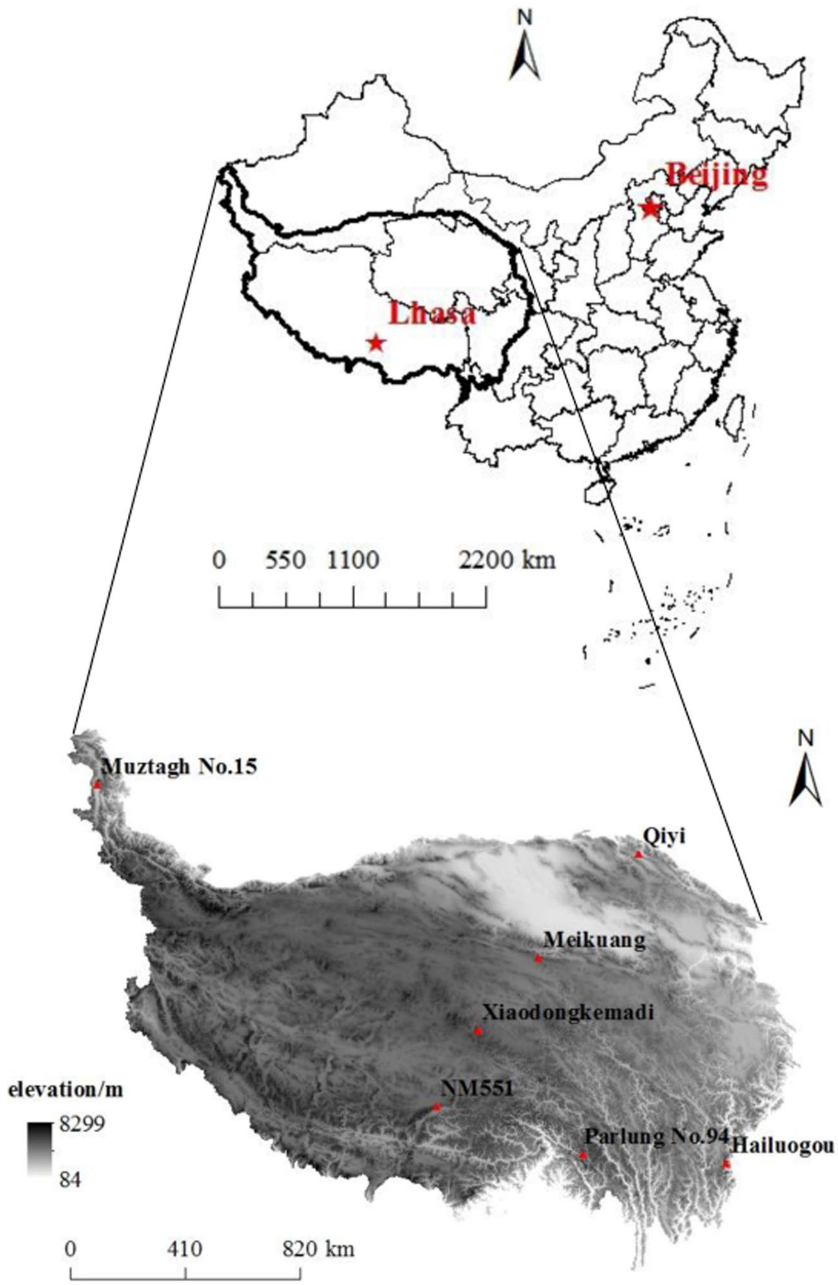

Figure 1. Spatial distribution of the selected seven glaciers in the Tibetan Plateau.

Huss et al.'s (2008) research only considered accumulation and ablation. We combined the two approaches and used the following equation for the mass balance calculation of glacier:

$$m = Acc - Melt - E + RW \tag{1}$$

where Acc is the glacier accumulation, which mainly comes from deposition of solid precipitation during a certain period, and Melt expresses corresponding glacier melt. E is actual evaporation on ice/snow surface, and RW represents refrozen water volume within the study duration.

$$\mathrm{Acc} = P \cdot D_{\mathrm{snow}} \cdot r_s \tag{2}$$

where D_{snow} is an adjustment coefficient reflecting the effect of spatial discrepancy in the snow distribution to accumulation ($D_{snow} = 1$ indicates no effect); r_s represents the fraction of solid precipitation, which linearly decreases from 1 to 0 corresponding to the air temperature ranging from ($T_{thr} - 1$) to ($T_{thr} + 1$)°C; and T_{thr} is the threshold air temperature used to distinguish snow from rainfall, the value of which is 0°C in this study (Hock, 1999).

The melt equation for glacier (Hock, 1999) is:

$$\text{Melt} = \begin{cases} \left(f_M + r_{snow/ice} \cdot I\right) \cdot T, & T > 0 \\ 0, & T \le 0 \end{cases} \tag{3}$$

where T is air temperature. f_M is the melt-rate factor [mm/(°C·d)], and $r_{snow/ice}$ is the factor reflecting radiation absorption for snow/ice [mm/(°C·d·W/m^2)]. Based on many previous studies (Arndt et al., 2017; Stamnes et al., 2011), the absorbed solar radiation into ice layer through snow surface increases with decreasing snow depth, causing larger glacier melt. In this study, the surface snow depth was considered in the fraction of the absorbed solar radiation for the underneath ice layer; r_{snow} was replaced by $r'_{snow}\frac{e}{S_d}$ (e is uniform snow of 1 mm; S_d illustrates snow depth with the unit mm). I refers to net short-wave radiation directed toward glacier surface minus net long-wave radiation directed away from glacier surface.

The refrozen water can be calculated using the following equation (Fujita et al., 1996):

$$RW = k \cdot \int_0^{z_c} \frac{\rho \cdot c}{L} \cdot \Delta T(z) dz \tag{4}$$

where c refers to the specific heat of ice fixed at 2,100 J/(kg·K), ρ indicates the density of ice and equals 900 kg/m^3, and ΔT(z) (°C) represents the increment of air temperature of snow/ice at depth z (m) during a given period. Several previous studies (Greuell & Thomas, 1994; Schwander et al., 1997) pointed out that $\Delta T(z)$ linearly varies with the depth z (m). The parameter z_c is the depth at which the mean air temperature is less than 0.1°C. In previous study (Fujita et al., 1996), the value of z_c was fixed at 20 m based on a thermal diffusivity for glacier ice (1.16×10^{-6} m^2/s). However, the previous study did not consider snow cover on glacier ice surface. Relevant studies (Kang et al., 2008; Li et al., 2011) suggested that snow temperature in the study area is generally lower than 0.1°C. Therefore, z_c is replaced by a sum of snow depth and 20 m in this study. The parameter k is the transfer coefficient from the potential refrozen water to the actual refrozen water volume, which is an empirical coefficient related to the water vapor condition over the study area obtained by Fujita et al. (1996). Moreover, when the calculated refrozen water is larger than the value of Melt in Equation 3, the value of refrozen water will be equal to Melt; otherwise, refrozen water is calculated by Equation 4.

It should be noted that the air temperature is determined at a constant lapse rate, and the precipitation is assumed to linearly increase with decreasing elevation (dP/dz). Among the above-mentioned parameters, r_{ice}, r'_{snow}, D_{snow}, f_M must be further determined by field data [the Shuffled Complex Evolution method developed at the University of Arizona (SCE-UA) was applied in the parameter determination of this case study (Duan et al., 1994), for which the Nash-Sutcliffe coefficient of efficiency (NSE), relative error (Er), correlation coefficient (r), and coefficient of determination (R^2) were used as the criteria for assessing the model performance Liu et al., 2015)]; the other parameters, including c_{ref}, P_{ref}, z_{ref}, dP/dz, dT/dz, and S_d can be predetermined. Because the parameter, S_d strongly depends on the air temperature state compared with zero, the routine study period of one year is divided into two periods based on air temperatures below and above 0°C, respectively.

3.2. The Response of Glacier Mass Balance to Climate Change

According to the above-mentioned description, mass balance can be denoted as the function expression of $m(P, T, I, \text{and } S_d)$. When precipitation, air temperature, net radiation and snow depth change at ΔP, ΔT, ΔI, and ΔS_d, respectively, the corresponding mass balances are $m(P+ \Delta P, T, I, S_d)$, $m(P, T+ \Delta T, I, S_d)$, $m(P, T, I+ \Delta I, S_d)$, and $m(P, T, I, S_d+ \Delta S_d)$. To explore the specific response of glacier mass balance change to

Table 1
Monitoring Years for Studied Glacier Stations

Glacier station	Monitoring years
Hailoguo	1989–1993
Parlung No.94	2005–2009
Qiyi	1975–1977, 1984–1985, 2005–2008
Xiaodongkemadi	1989–1998, 2005–2008
Muztagh No.15	2001–2002, 2005–2012
Meikuang	1989–1998
NM551	2005–2013

the actual changes of different meteorological factors, the expression as m(P+ΔP, T, I, S_d) − m(P, T, I, S_d) is calculated as the response of glacier mass balance change to change of precipitation for further analysis (Morris, 1991). Similar, the expressions as $m(P, T+\Delta T, I, S_d) - m(P, T, I, S_d)$, $m(P, T, I+\Delta I, S_d) - m(P, T, I, S_d)$, and $m(P, T, I, S_d+\Delta S_d) - m(P, T, I, S_d)$ are the response of glacier mass balance change to changes of air temperature, net radiation and snow depth, respectively.

4. Results

4.1. Parameters for the Glacier Mass Balance Equation

To reconstruct the long-term glacier mass balance of the selected glaciers, the corresponding parameters, including D_{snow}, f_M, r'_{snow}, and r_{ice}, were initially obtained by using SCE-UA method based on observations within the periods listed in Table 1. The results are shown in Table 2. The D_{snow} values for most glaciers including Hailuogou, Parlung No.94, Qiyi, Meikuang and NM551 glaciers are less than 1, indicating the spatial distribution of the snow cover is against glacier mass accumulating. The negative effects in the NM551 and Hailuogou glaciers among are strongest. However, the D_{snow} value for the Xiaodongkemadi and Muztagh No.15 Glacier are over 1, indicating that the distribution of the snow cover has a significant positive effect on its mass gain. In terms of the melt-rate factor f_M, the values of the Hailuogou and NM551 glaciers are highest of 19.85 and 15.6 mm/(°C·d), respectively. The melt-rate of the Qiyi, Meikuang and Parlung No.94 glaciers are inferior at 10.27, 8.96, and 7.39 mm/(°C·d), respectively. The Muztagh No.15 glacier has the lowest value of 3.23 mm/(°C·d).

To compare with the relevant studies, several degree-day factor results for the studied glaciers have been provided. For instance, Kayastha et al. (2003) found that in Xiaodongkemadi glacier, degree-day factor ranged from 5.5 to 14.2 mm/(d·°C) at different elevations, which has a similar result with the value of 7.39 mm/(d·°C) for the whole glacier in this study. The degree-day factor in Qiyi glacier was within 4.9–9.4 mm/(d·°C) in July and August before 2003, which being slightly lower than the result in this study with the value of 10.27 mm/(d·°C) for the entire glacier. Hailuogou was identified with the value of 5.0 mm/(d·°C) in degree-day factor at 3301 m in 1982, while this study gives the value of 19.85 mm/(d·°C). The difference might come from two aspects including the higher degree-day factor at a higher altitude and the melt-rate increasing during the recent three decades (Zhang et al., 2006).

The factor of radiation absorption on the ice surface is closely related to surface brightness. In particular, the ice with lower brightness has larger radiation absorption (Nolin & Payne, 2007; Schwikowski, 2011). The largest radiation absorption on ice surface appears in Meikuang Glacier with the value of 0.00249 mm/(°C·d·W/m^2), which may have the lowest surface brightness of ice. The values in Parlung No.94, Qiyi, Xiaodongkemadi and NM551 glaciers are weaker ranging from 0.00112 to 0.00183 mm/(°C·d·W/m^2). Moreover, in Hailuogou and Muztagh No.15 Glacier, the radiation absorptions on ice surface are lower than 0.001 mm/(°C·d·W/m^2) with comparably larger surface brightness of ice. Regarding the radiation absorption on the snow surface for the selected glaciers, the highest value was obtained for the Hailuogou Glacier (0.0351 mm/(°C·d·W/m^2), which may explain why the highest melt-rate factor is bound in this glacier as mentioned earlier). The weaker radiation absorption on the snow surface is found in the Xiaodongkemadi

Table 2
Calculated Parameters for the Selected Glaciers in the Tibetan Plateau

Parameter	Hailuogou	Parlung No.94	Qiyi	Xiaodongkemadi	Muztagh No.15	Meikuang	NM551
D_{snow}	0.45	0.82	0.90	1.25	1.22	0.85	0.37
f_M[mm/(°C·d)]	19.85	7.83	10.27	7.39	3.23	8.96	15.60
r'_{snow}	0.03510	0.00137	0.00192	0.01943	0.00984	0.00097	0.00073
r_{ice}	0.00087	0.00183	0.00140	0.00112	0.00055	0.00249	0.00125

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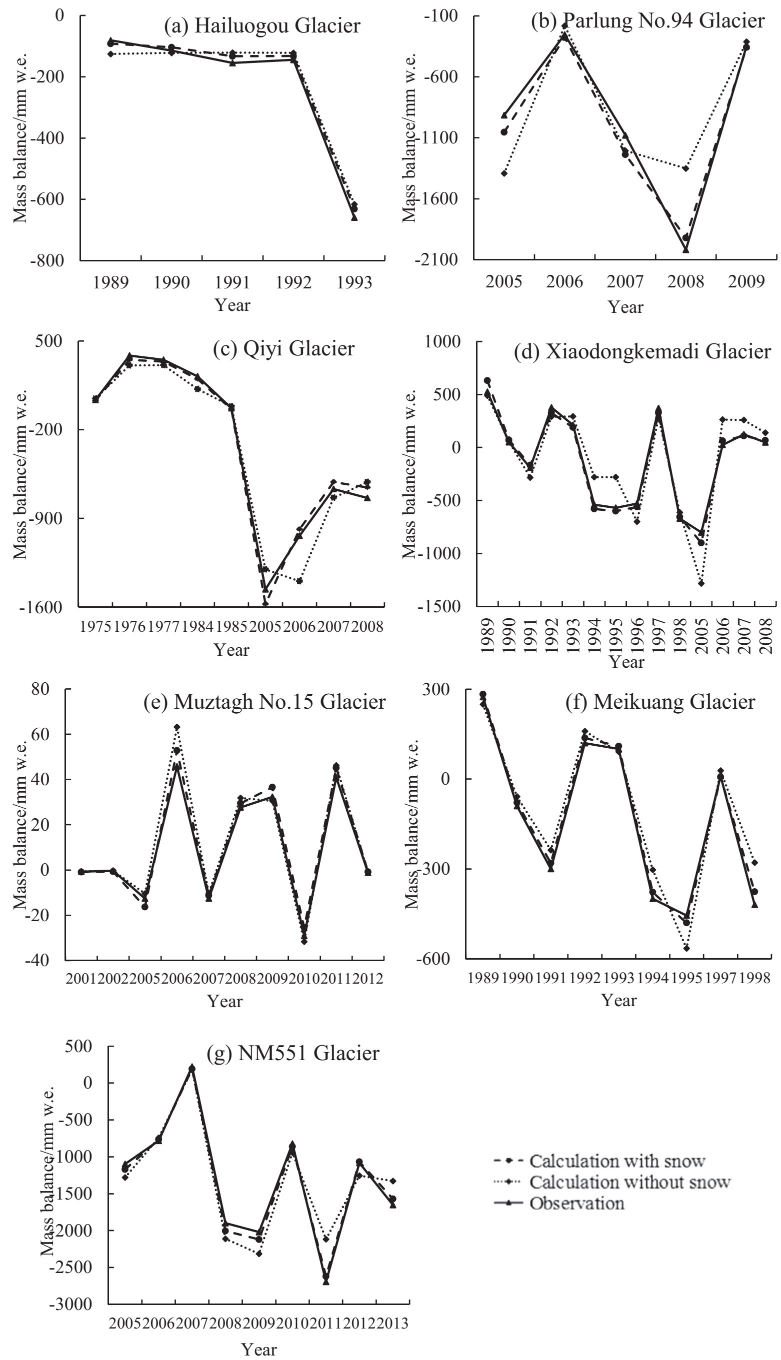

Figure 2. Mass balance calculation with and without consideration of snow depth over the selected seven glaciers.

Glacier with the value of 0.01943 mm/(°C·d·W/m^2). In addition, the values of radiation absorption on the snow surface for the other glaciers are in the range of 0.00073–0.00192 mm/(°C·d·W/m^2). Relevant studies (Marshall & Oglesby, 1994; Schwikowski, 2011) manifested that radiation absorption of snow mainly depends on the age of snow. Based on these results of the parameter r'_{snow} and r_{ice}, the comparison between the calculated and observed mass balances (listed in Table 1) is shown in Figure 2 (with and without considering the snow depth) and Figure 3 (with and without considering the refrozen water). The reconstructed mass balances are in good agreement with the measured data. The details will be shown in the following content.

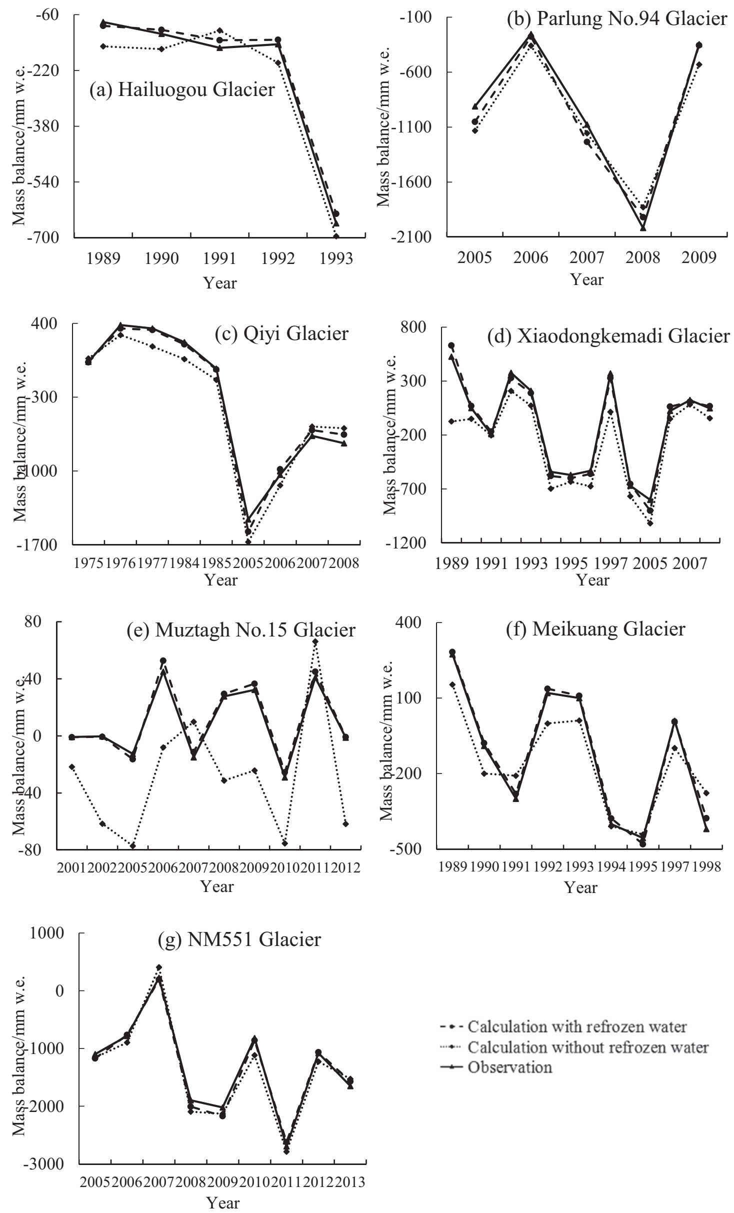

Figure 3. Mass balance calculation with and without refrozen water over the selected seven glaciers.

4.2. Influences of the Snow Depth and Refrozen Water on the Glacier Mass Balance

This study explicitly considers the influences of the snow depth on the radiation absorption on the snow cover in the calculation of the meltwater volume. To identify if this consideration improves the accuracy of the mass balance calculation, the calculated mass balance obtained with and without considering the snow depth were compared. The comparison results are shown in Figure 2. It is apparent that the measured and calculated mass balances obtained by considering the snow depth are in better agreement, especially for the Qiyi, Xiaodongkemadi and Meikuang glaciers. The coefficients of determination (Liu et al., 2015) for the Qiyi, Xiaodongkemadi, and Meikuang glaciers were improved to 0.97, 0.98, and 0.96 when considering the snow depth compared with values of 0.78, 0.80, and 0.83, respectively, obtained without considering the snow depth. The results suggest that the accuracy of the mass balance calculations for the selected glaciers in the Tibetan Plateau can be improved by considering the snow depth when calculating the meltwater volume. Hence, the following analyses are based on the inclusion of the snow depth.

To examine the importance of refrozen water for the net mass balance, calculations of the glacier mass balance with and without refrozen water were compared based on the field measurements for the seven selected glaciers, as shown in Figure 3. Similar to the consideration of snow depth in the mass balance calculation, the results obtained by considering refrozen water in the whole period for the studied glaciers are in better agreement with field measurements than the corresponding results ignoring the refrozen water, particularly for the Muztagh No.15 glacier. Specifically, the mass balance difference between the calculated values and field measurements for the Muztagh No.15 glacier was significantly reduced after considering the refrozen water with the coefficient of determination from 0.55 to 0.88. The value for the Meikuang Glacier has also been largely improved, which is from 0.69 without considering the refrozen water to 0.90 with the consideration of refrozen water. In addition, in the Qiyi, Hailuogou, and Xiaodongkemadi glaciers, the gaps between the calculated values and field measurements have also been reduced after considering the refrozen water with the coefficients of determination from 0.72, 0.75, and 0.76 to 0.87, 0.88 and 0.91, respectively. Furthermore, it is observed that most mass balances are underestimated without including the refrozen water. According to another investigation (Ageta & Kadota, 1992; Braithwaite & Zhang, 1999; Fujita, 2008), such underestimations always occur at the years of more precipitation and low temperature, in other words, mass balances in the years with climate conditions for having more refrozen water tend to be underestimated without considering the refrozen water. With regards to few overestimated glacier mass balances, they are caused by the underestimation of meltwater because of lower calculated radiation absorbption rate on both snow and ice surface. Therefore, further analysis will be based on the results with the consideration of refrozen water in the glacier mass balance calculation.

4.3. Reconstruction and Analyses of the Long-Term Glacier Mass Balance

The glacier mass balance is the combined result of the accumulation, meltwater, refrozen water volume and evaporation, and the reconstructed time series from 1975 to 2013. The annual means of the different mass components of the glacier mass balance for the seven selected glaciers are shown in Figure 4 and Table 3. All glacier mean annual mass balances during 1975–2013 are negative, except the Muztagh No.15 Glacier with the value of approximately 0.75 mm w.e. In the Muztagh No.15 Glacier, there is an obvious component offset between the mass gain components (accumulation and refrozen water) and the mass loss component (melt water). In other words, the mass gain components and the mass loss component tend to balance each other. This is consistent with the study by Holzer et al. (2015) who also pointed out that recent measurements performed at the Muztagh No.15 Glacier show a slight mass gain. In addition, the largest mass loss in annual mean mass balance appears at the NM551 Glacier with the value of −724.3 mm w.e., in which the meltwater (−1196.56 mm w.e.) plays a dominant role. The weaker mass loss happens in the Xiaodongkemadi Glacier with the value of −315.05 mm w.e. in the annual mean mass balance during the study period, in which the meltwater is also the main component. The Hailuogou and Parlung No.94 glaciers have the similar values in the annual mean mass balance with the values of −237.81 and −212.80 mm w.e., respectively. The annual mean mass balance in the Qiyi Glacier was found of −158.35 mm w.e. with the primary component of −503.84 mm w.e. in the meltwater. Moreover, the Meikuang Glacier was calculated of smaller mass loss with the value of −67.14 mm w.e. in the annual mean mass balance from 1975 to 2013, in which the component offset was also observed between the mass gain components (accumulation and refrozen water with the annual mean of 210.32 and 353.76 mm w.e., respectively) and the mass loss component (meltwater with the annual mean of −625.97 mm w.e.).

To analyze the trend in the annual glacier mass balance, accumulation, refrozen water, glacier melt, and evaporation of the selected glaciers, the Mann-Kendall method (Gocic & Trajkovic, 2013) was applied. The results are shown in Figure 5. The figure shows that the meltwater of all glaciers has a decreasing trend on an annual scale, especially that of the Qiyi, NM551, Hailuogou, Meikuang and Parlung No.94 glaciers. In the other two glaciers, including the Muztagh No.15 and Xiaodongkemadi glaciers, nonsignificant trend in mass balance may partly come from the strong component offset effect between the mass loss and gain components as above mentioned. Similar results have been obtained in other studies (e.g., Pu et al., 2005). Due the meltwater is the key component in the mass balance for all glaciers, the trends in the annual mass balances are consistent with the corresponding trends in the meltwater. With respect to the changes of the refrozen water of the selected glaciers, the trends for most glaciers are nonsignificant, while the NM551

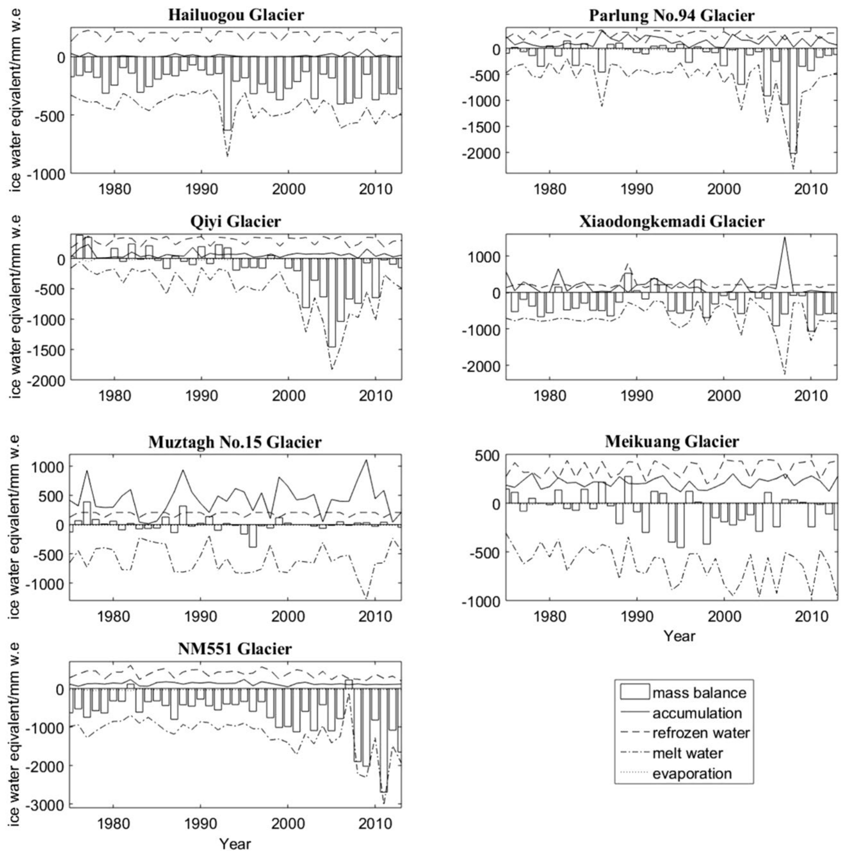

Figure 4. Reconstructed mass balance, accumulation, melt water and refrozen water volume and evaporation for the selected seven glaciers over the Tibetan Plateau from 1975 to 2013.

Glacier was found of significantly decreasing trend in the refrozen water from 1975 to 2013. Similarly, only the evaporation of the NM551 Glacier shows a significant increase.

4.4. The Response of the Glacier Mass Balance to Climate Change

To analyze the resultant mass balance changes, changes of meteorological factors are calculated at first. The results for all glaciers are shown in Table 4, in which the change of each meteorological factor within balance years from 1975 to 2013 is calculated from the product between the slope (mm/a) by the Mann-Kendall method (Atta-ur-Rahman & Dawood, 2017; Gocic & Trajkovic, 2013) and the number of year (39 a). As for precipitation, the Xiaodongkemadi and Muztagh No.15 Glacier have a decreasing trend with changes

Table 3
Different Mass Components of Glacier Mass Balance on Averages During 1975–2013 for the Selected Glaciers (unit: mm w.e.)

Glaciers	Mass balance	Accumulation	Refrozen water	Melt water	Evaporation
Hailuogou	−237.81	9.19	188.97	−435.99	−0.01
Parlung No.94	−212.80	127.90	268.08	−594.36	−14.42
Qiyi	−158.35	62.68	293.69	−503.84	−10.88
Xiaodongkemadi	−315.05	168.09	208.69	−691.76	−0.06
Muztagh No.15	0.75	432.61	184.89	−605.15	−11.60
Meikuang	−67.14	210.32	353.76	−625.97	−5.25
NM551	−724.30	124.85	377.64	−1196.56	−30.94

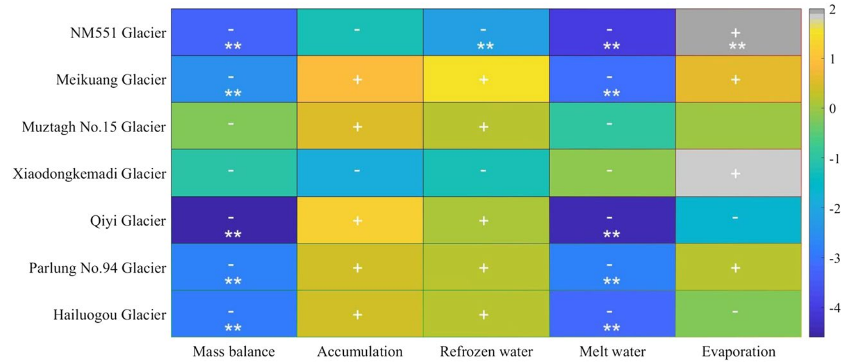

Figure 5. Trends of reconstructed mass balance and several mass components for the studied seven glaciers during 1975–2013. Note the color bar represents the statistical variable (Z) by Mann-Kendall nonparameter test (Gocic & Trajkovic, 2013), which are marked as "+," "+**," "−," and "−**" when $0 < Z < 1.96$, $Z > 1.96$, $-1.96 < Z < 0$, $Z < -1.96$ showing nonsignificant increasing tendency, significant increasing tendency, nonsignificant decreasing tendency and significant decreasing tendency, respectively.

of −30.186 and −325.806 mm, respectively, while in the other glaciers, precipitation increased during the study period. In particular, the Qiyi and Meikuang glacier have comparably larger increase with the changes of 29.874 and 58.695 mm, respectively. Changes of air temperature and net radiation for the studied glaciers are all positive. In terms of air temperature, the Muztagh No.15 Glacier has the highest change at 1.911°C. Besides, changes of the Hailuogou, Parlung No.94, Qiyi, Meikuang and NM551 Glacier are within 1.131–1.794°C. Similar to change of precipitation, air temperature of the Xiaodongkemadi also has the lowest change with the value of 0.585°C. Regarding change of radiation, comparably larger change occurs in Hailuogou and Muztagh No.15 Glacier with values of 1.443 and 1.326 W/m^2, respectively. The changes for the smaller two glaciers including the Meikuang Glacier and NM551 Glacier are lower at 0.546 and 0.429 W/m^2. Moreover, the Xiaodongkemadi and NM551 Glacier show a decreasing trend in snow depth within balance years from 1975 to 2013, while snow depths in the other glaciers are found of increasing trend. Specifically, the change of the Qiyi Glacier is the largest with the value of 2.262 m, while the changes of the other glaciers are within 0.117–0.624 m.

The response of the glacier mass balance of the studied glaciers to change of meteorological factors, including the precipitation, air temperature, net radiation and snow depth from 1975 to 2013 was analyzed based on the method in Section 3.2. The results are displayed in Table 5, from which the positive response of glacier mass balance change to change of precipitation and snow depth can be observed, vice versa for the other two factors. On the one hand, the mass balances in the Hailuogou, Qiyi, Xiaodongkemadi, Meikuang and NM551 Glacier show a decrease, so the increment of mass balances corresponding to their increasing precipitation/snow depth in the Hailuogou, Qiyi and Meikuang Glacier contribute comparably less than the decline of mass balances corresponding to the increasing air temperature/net radiation. The responses of mass balance change to changes of both air temperature and net radiation in the most western Muztagh No.15 Glacier are weakest, while the response of mass balance change to change of precipitation is strongest among the studied glaciers. However, the inferior smallest Meikuang Glacier has comparably higher response of mass balance change to changes of different meteorological factors, especially the increasing precipitation, air temperature, and snow depth. In the inferior largest Parlung No.94 Glacier, the responses of mass balance change to changes of air temperature and snow depth are highest among the selected glaciers with the values of −779.472 and 875.96 mm, respectively. In addition, the response of mass balance change to the change of net radiation is highest in the largest Hailuogou Glacier than the other selected glaciers. On the other hand, the responses of glacier mass balance change to changes of air temperature and snow depth are generally

Table 4
Change of Each Meteorological Factor During 1975–2013

Glaciers	Change of P (mm)	Change of T (°C)	Change of I (W/m^2)	Change of S_d (m)
Hailuogou	7.995	1.404	1.443	0.156
Parlung No.94	5.304	1.794	1.014	0.624
Qiyi	29.874	1.131	0.741	2.262
Xiaodongkemadi	−30.186	0.585	0.741	−0.624
Muztagh No.15	−325.806	1.911	1.326	0.117
Meikuang	58.695	1.248	0.546	0.273
NM551	17.043	1.794	0.429	−0.663

Note. P, T, I and S_d represent precipitation, air temperature, net radiation (short-wave radiation minus long-wave radiation) and snow depth, respectively.

Table 5
Response of Glacier Mass Balance to Change of Each Meteorological Factor During 1975–2013 (Unit: mm)

Glaciers	Mass balance change to P change	Mass balance change to T change	Mass balance change to I change	Mass balance change to S_d change	Total mass balance change
Hailuogou	0.69	−177.05	−163.12	287.30	−52.18
Parlung No.94	0.99	−779.472	−97.34	875.96	0.14
Qiyi	6.28	−604.16	−49.94	317.64	−330.18
Xiaodongkemadi	−12.55	−219.48	−24.42	−222.41	−478.86
Muztagh No.15	−132.76	−42.83	−16.35	200.88	8.94
Meikuang	15.21	−692.95	−28.74	706.45	−0.03
NM551	1.98	−190.72	−16.02	−188.57	−393.33

greater than the other two meteorological factors, except for the Muztagh No.15 Glacier. Liu and Liu (2015) found similar phenomenon in the Tianshan Mountains (on the north of Qinghai-Tibetan Plateau). In general, the response of glacier mass balance change to moisture factor (precipitation) increases from east to west and from south to north. In terms of the responses of glacier mass balance change to heat factors (air temperature, net radiation) are larger in the eastern glacier. Strangely, the spatial pattern in the response of glacier mass balance change to change of snow depth is similar to the two heat factors (air temperature, net radiation), which could be resulted in the significant influences of heat factors on the change of snow depth (Deng & Zhang, 2018).

5. Discussion

5.1. Importance of Including the Snow Depth and Refrozen Water in the Mass Balance Calculation

As Figure 2 shows, the snow depth affects the mass balance calculation. The albedo is one of the most important factors affecting the meltwater volume. Less albedo on the ice surface induces more glacier melt. Ignoring the snow depth can cause the overestimation of the glacier melt. Refrozen water also plays a role in the mass balance calculation, as shown in Figure 3. Fujita et al. (1996) also reported that refrozen water is very important for the mass balance of glaciers in the Tibetan Plateau. The refrozen water has two sources: refreezing of capillary water in the snow layer and water percolating from the snow layer into the cold snow. Ignoring the refrozen water can lead to underestimations of the mass balance.

5.2. Disparities in the Changes in the Mass Balance Among Different Glaciers

The responses of glacier melt to climatic conditions in the Tibetan Plateau are strongly related to the climatic zones, which are mainly influenced by the Indian summer monsoon and winter westerlies (He et al., 2003). The impact is based on the special geographic location and topographical conditions. For example, the Muztagh No.15 Glacier in the westernmost part of the Tibetan Plateau is mainly influenced by the westerlies and is partly influenced by Asian summer wind, which could be one of the dominant reasons for the component offset resulting in a mass gain. In general, the responses of glacier mass balance change to moisture factor (precipitation) and heat factors (air temperature, net radiation) behave differently. Stronger response of glacier mass balance change to change of moisture factor is bound in the western glacier, while the responses of glacier mass balance change to heat factors show greater for the eastern glaciers. The potential causation is the spatial pattern of water moisture and heat energy formed by the surrounding atmospheric circulations (Zhu et al., 2018). In addition, the negative response of mass balance to precipitation increase may be resulted from the changing precipitation seasonality (Yang et al., 2013). However, the spatial distribution in the response of glacier mass balance change to change of snow depth is similar to the two heat factors (air temperature, net radiation), which could be resulted in the significant effects of heat factors on the change of snow depth (Deng & Zhang, 2018).

5.3. Limitations of the Study

The biggest limitation of this study is the small amount of observed data, which does not allow the proper calibration of the parameters necessary for the mass balance equations. This may to some extent affect the accuracy of the reconstructed mass balance series. The data available for the validation are also inconsistent, complicating the evaluation of the mass balance reconstructed for several glaciers. Another limitation related to the data scarcity is that the period have not been divided into different periods in this study to explore the responses of the mass balance to climatic factors. In addition, the limited data also lead to an uneven distribution of the selected glaciers; no glacier in the southwestern Tibetan Plateau was selected for this study. Hence, more field observation data should be collected and remote sensing images should be used in future studies to obtain the required information and improve the accuracies of glacier mass balance quantifications.

6. Conclusions

The long-term mass balance from 1975 to 2013 has been reconstructed for seven glaciers in the Tibetan Plateau and the effects of the snow depth and refrozen water on the mass balance calculation were analyzed. In addition, the response of the mass balance to different meteorological factors at the seven studied glaciers was analyzed and the internal patterns were further explored. The major findings can be summarized as follows:

(1) Most of the studied glaciers experienced a mass loss during the past 4 decades. However, a slight mass gain was determined in the Muztagh No.15 Glacier with a strong component offset between mass gain and loss components. Regarding the mass components of the mass balance for the residual glaciers, meltwater is the dominant component
(2) Regarding the changes in the glacier mass balance and mass components, the mass balance and meltwater are significantly decreasing excluding the Muztagh No.15 and Xiaodongkemadi glaciers with a strong component offset. In the smallest NM551 Glacier, the significantly decreasing and increasing trends in refrozen water and evaporation also made a big contribution to the decreasing mass balance
(3) In terms of the response of the glacier mass balance to climate change, the greater response of mass balance change to change of moisture factor (precipitation) is found in the western glaciers, while for the eastern glaciers, mass balances change largely to the changes of heat factors (air temperature, net radiation)

Conflict of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data are available at 10.11888/Glacio.tpdc.270382

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