



Glacier Mass Loss Simulation Based on Remote Sensing Data: A Case Study of the Yala Glacier and the Qiyi Glacier in the Third Pole

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Abstract: The climate warming over the Third Pole is twice as large as that in other regions and glacier mass loss is considered to be more intensive in the region. However, due to the vast geographical differences, the characteristics of glacier mass loss might be very different between different parts of the Third Pole, such as between the southern and northern Third Pole. It is, therefore, very important to clarify the characteristics of glacier mass loss between different parts of the Third Pole, particularly between the southern and northern Third Pole. We selected the Yala Glacier in the Central Himalayas and the Qiyi Glacier in the Qilian Mountains to study the different characteristics of glacier mass loss between the southern and northern Third Pole using remote sensing data and in situ data. Based on the results, we found that the Yala Glacier has not only been in a status of mass loss but also in a status of intensive and accelerating mass loss. Our analysis showed that the average multi-year mass loss of the Yala Glacier is $-736 \text{ mm w.e.a}^{-1}$, with a maximum of $-1815 \text{ mm w.e.a}^{-1}$. At the same time, the Qiyi Glacier has experienced a mild glacier mass loss process compared with the Yala Glacier. The Qiyi Glacier's mass loss is $-567 \text{ mm w.e.a}^{-1}$ with a maximum of $-1516 \text{ mm w.e.a}^{-1}$. Our results indicate that the mass loss of the Yala Glacier is much stronger than that of the Qiyi Glacier. The major cause of the stronger mass loss of the Yala Glacier is from the decrease of glacier accumulation associated with precipitation decrease under the weakening Indian monsoon. Other factors have also contributed to the more intensive mass loss of the Yala Glacier.

Keywords: Third Pole; in-situ and remote sensing data; modeling; glacier mass



Citation: Yao, R.; Shi, J. Glacier Mass Loss Simulation Based on Remote Sensing Data: A Case Study of the Yala Glacier and the Qiyi Glacier in the Third Pole. *Remote Sens.* **2022**, *14*, 5190. <https://doi.org/10.3390/rs14205190>

Academic Editors: Massimo Menenti, Yaoming Ma, Li Jia and Lei Zhong

Received: 4 September 2022

Accepted: 13 October 2022

Published: 17 October 2022

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1. Introduction

Glaciers are important water resources for the whole world [1,2]. The Third Pole (TP) stores the world's largest glacier mass outside Antarctica and the Arctic [2–4]. Abnormal climate warming over the TP is twice as large as that in other regions [5–7]. Under the background of the intensive glacier melt at global scale caused by global warming [8,9], the glacier melt in the TP is more intensive because of abnormal warming [10–15]. The intensive glacier melt in the TP causes runoff increase in the short term, benefiting water resources supply in the downstream areas [16–19]. However, on a longer time scale, glacier melt ultimately causes substantial runoff decrease and impacts the water supply, and more than 2 billion people living in the region would face water shortage [16]. The direct impact of glacier melt on water resource is its close relationship to the rivers of the Asian Water Tower such as the Yangtze, Yellow, Mekong, Ganges and Indus Rivers, as well as large inland rivers such as the Tarim, Amu Darya, and SYR Darya. Glacier melt also causes global sea level rising [4,20] through river discharge contribution. Intensive glacier melt is also directly related to emerging disasters such as ice collapse, which is a new serious phenomenon of intensive glacier mass loss [20–22]. It is, therefore, very important to know the status of glacier mass loss in the TP and to clarify the mass loss difference between

the southern and northern TP for a comprehensive understanding of its water resource supplying capability and for the hazard risk management of the societies.

A previous study pointed out spatial heterogeneity of glacier mass loss in the TP [23]. Remote-sensing monitoring showed that glaciers experienced intense mass loss and area shrinkage in the southern TP, particularly in the Himalayas, with glacier mass loss from 0.21 to 0.38 m w.e. a^{-1} in different periods [24–27], with glacier area reduction of $-0.18 \pm 0.07\% \text{ a}^{-1}$ [28] during the 1970s–2010s. In the Central Himalayas, the mass loss was $-0.40 \pm 0.09 \text{ m w.e. a}^{-1}$ in 2011–2013 for the Yala Glacier [29], and $-0.20 \pm 0.30 \text{ m w.e. a}^{-1}$ for the other four glaciers in 2014 [30]. In the Qilian Mountains located in the northern TP, the average mass loss was $-0.24 \pm 0.03 \text{ m w.e. a}^{-1}$ during 1961–2010 [31]. The accelerated melt in the Qilian Mountains began in the early 1990s, as was confirmed by the observations [3,32]. The mass loss in the Qiyi Glacier reached $-0.29 \pm 0.22 \text{ m w.e. a}^{-1}$ during 2000–2009 [33]. In the Qilian Mountains, there was rapid glacier mass loss in the eastern but slow glacier mass loss in the central and in the western [31,34]. Recently, more intensive mass loss of $-0.43 \pm 0.03 \text{ m w.e. a}^{-1}$ was estimated for glaciers in the Lenglongling Mountains in the very eastern of the Qilian Mountains during 1972–2016, whereas less mass loss of -0.27 ± 0.07 and $-0.28 \pm 0.03 \text{ m w.e. a}^{-1}$ was estimated for glaciers in the Beida River basin in the central and Shule River basin in the western [35–38].

The differences in glacier regimes are very important for understanding the differences of mass loss between the southern TP. In the southern TP, most glaciers are maritime temperate glaciers. However, most glaciers are continental cold glaciers in the northern TP. The characteristics of the glacier regimes are determined by both the different temperature and precipitation characteristics associated with atmospheric circulation processes over the TP [3,23]. Generally speaking, glaciers in the southern TP are more sensitive to temperature variations than those in the northern TP since ice temperature is higher in the glaciers in the southern TP. Furthermore, the southern TP is dominated by the Indian monsoon, while the northern TP is dominated by the westerly. In the central Himalayas, more annual precipitation fell in summer [30] compared with that in the Qilian Mountains [39]. Due to the vast territory of the TP, different geographical zones have different climate conditions under the dominance of different atmospheric circulation processes, resulting in great differences in the characteristics of glacier mass loss. Therefore, an important scientific question is how we can clarify the major difference of the characteristics of glacier mass loss between the northern and southern TP.

In order to quantitatively study the differences in the characteristics of glacier mass loss between the northern and southern TP, we selected two representative glaciers, the Yala Glacier in the southern TP and the Qiyi Glacier in the northern TP and used remote sensing data, combined with the in situ data, to model the different characteristics of glacier mass loss shown by the two different types of glaciers, and the potential mechanisms causing differences in glacier mass loss. Our study will help improve the understanding of glacier mass loss in the TP under the background of the abnormal climate warming, and deepens the understanding of the impact mechanism of climate change on glacier fluctuations over the TP.

2. Methods

2.1. Selection for the Representative Glaciers in the Southern and Northern Third Pole

The Yala Glacier ($28^{\circ}14'N$, $85^{\circ}37'E$), lying on the south slope of the central Nepal Himalayas and representing maritime temperate glacier, is selected as the representative glacier for the southern TP (Figure 1). It is a summer accumulation glacier without debris, with area and length of 1.37 km^2 and 1.5 km , respectively. The total area of all the glaciers in the region is 87.2 km^2 . The glacier flows southwest from the elevation of 5681 to 5143 m a.s.l. [40]. The Yala Glacier belongs to the Indian monsoon climate, with the highest precipitation in summer months (June to September) and a rather dry winter. At the same time, glacier mass loss reaches the maximum in summer. Based on in situ measurement, the Yala Glacier has been thinning at rates of -0.69 ± 0.25 during 1982–1996 and

$-0.75 \pm 0.24 \text{ m a}^{-1}$ during 1996–2009, with an accelerated mass loss since 1990s [41,42]. The glacier mass loss increased from -0.36 m w.e. in 1996 [41] to $-0.81 \pm 0.27 \text{ m w.e.}$ in 2009 [40,43]. The total glacier mass loss is about 40% over the 27 years.

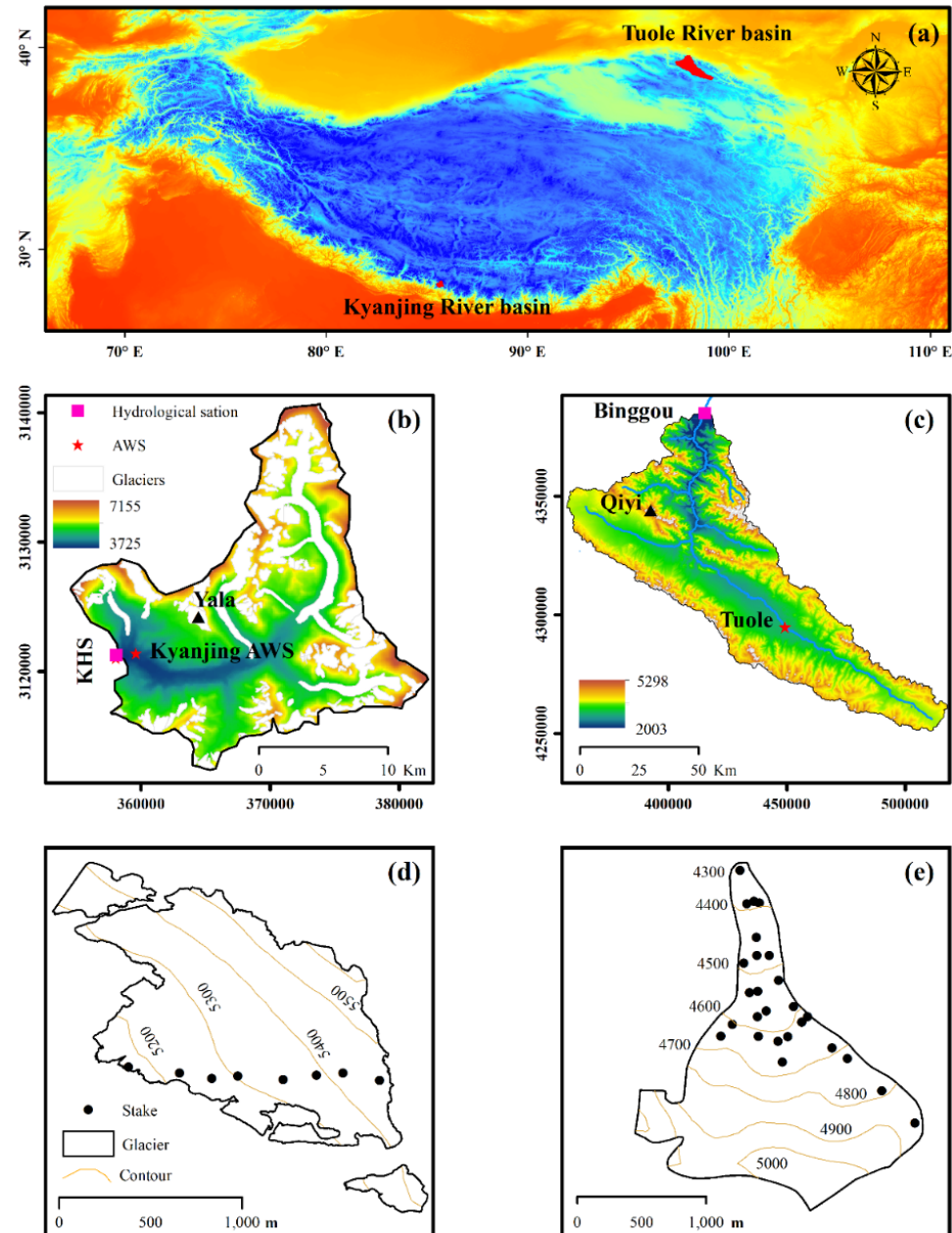


Figure 1. Locations of the Yala Glacier and Qiyi Glacier. In the figure, (a) is for the locations of the Yala Glacier and Qiyi Glacier, (b,d) are for the river basin where the Yala Glacier is located and the contour map of the Yala Glacier, (c,e) for the river basin where the Qiyi Glacier is located and the contour map of the Qiyi Glacier.

The Qiyi Glacier ($39^{\circ}15'N$, $97^{\circ}45'E$), lying on the north slope of the Tuolai Mountains in the Qilian Mountain, representing continental cold glacier, is selected as a representative glacier for the northern TP (Figure 1). The Qiyi Glacier is also a summer accumulation glacier and is debris free. It flows northward from an elevation of 5159 to 4304 m a.s.l., with an area of 2.76 km^2 and a length of 3.8 km [3]. The total area of all the glaciers in the region is 136 km^2 . The Qiyi Glacier is located in the westerly dominated area in the northern TP and the eastern margin is affected by the East Asian monsoon. The area is mainly the

continental climate and dominant by the cold air mass in winter, but occasionally affected by the East Asian monsoon in summer. Based on the in situ measurement, the equilibrium line altitude (ELA) was respectively 4600 m a.s.l. in 1970s, 4708 m a.s.l. in 1980s, 4935 m a.s.l. in 2000s [44] and 4941 m a.s.l. in 2010s [45]. In addition, the glacier mass was positive before 1980s (+0.26 m w.e. in 1970s, 0.004 m w.e. in 1980s). Glacier mass loss began after the 1990s (−0.47 m w.e. in 2000s and −0.50 m w.e. in 2010s [3,32,46]).

2.2. MODIS Temperature Data and TRMM Precipitation Data Acquisition

MODIS is the abbreviation of Moderate Resolution Imaging Spectroradiometer. There are many sensors used to acquire MODIS temperature data. The MODIS temperature data for the present study is from the Terra-MOD11A1 which provides observed results four times a day, 1:30 a.m., 10:30 a.m., 1:30 p.m., 10:30 p.m., through optical and infrared sensors. We used the Data Interpolating Empirical Orthogonal Functions (abbreviated as DINEOF method), proposed by Zhou et al. [47], to get accurate remote sensing MODIS temperature data. The MODIS temperature data we have obtained are satisfactory with RMSE of 2.91 °C and bias of −1.19 °C. Based on the interpolation in the DINEOF method, the data are still satisfactory with RMSE of 1.77 °C and bias of −0.52 °C Even under the condition of cloud day.

TRMM is the abbreviation of Tropical Rainfall Measuring Mission. TRMM sensor consists of a precipitation scanning radar (PR), a passive microwave imager (TRMM TMI) and an infrared imager (VIRS). TMI provides water vapor and the intensity of precipitation, which is therefore the core sensor for the TRMM data. The TRMM precipitation data for the present study are from TRMM 3B43. The time resolution of the TRMM 3B43 is one day and the spatial resolution is 0.25°. We used the method proposed by Zhang et al. [48] to obtain the accurate TRMM precipitation data.

2.3. Model Principle

2.3.1. Model Setup

The glacier mass loss was computed using degree day model [49].

$$M = \begin{cases} DDF_{snow/ice} T & T > T_t \\ 0 & T < T_t \end{cases} \quad (1)$$

where M is the meltwater (mm w.e.a^{−1}); $DDF_{snow/ice}$ is the degree day factor for snow and ice melting; T is the temperature; T_t is the temperature threshold, when $T > T_t$, the melting started.

Total daily precipitation at certain elevation is calculated using P_r observed at automatic weather station (AWS) and a vertical gradient of precipitation (ΔP). Then, rainfall and snowfall were separated from total precipitation by linear interpolation using two temperature thresholds for rain (T_{rain}) and snow (T_{snow}).

In order to use the remote-sensing data to simulate glacier mass loss, we assembled four sub-models. The four sub-models driven by four different driving data sets to get different glacier mass loss: Sub-model1 was driven by the combined data set of in situ temperature and precipitation data; sub-model2 was driven by the combined data set of in situ temperature and precipitation data associated with the lapse rate calculated from the MODIS temperature data from different elevations in the Yala Glacier and Qiyi Glacier; sub-model3 was driven by the combined data set of MODIS temperature and TRMM precipitation data; sub-model4 was driven by the combined data set of in situ temperature data and TRMM precipitation data associated with the lapse rate calculated from the MODIS temperature data from different elevations in the Yala Glacier and Qiyi Glacier.

2.3.2. Model Input Data

The main inputs that the model requires are as follows: (1) The glacier outlines of the Yala and Qiyi glacier obtained from the second glacier inventory dataset of China [50] and the Randolph Glacier Inventory V6.0 (RGI6.0) [51], and the SRTM DEM (90m) is used as the glacier surface; (2) observed daily data at two AWSs are used as driving data to drive the model. In addition, MODIS temperature and MODIS temperature lapse rate were computed from MOD11A1 and MYD11A1 production, TRMM precipitation were withdraw from TRMM production; T_a , and P_{rec} are linear interpolated to each grid cell by using their vertical gradients; (3) The initial snow depth on the glacier is computed using the linear relationship between measured snow depth and elevations; (4) The density of ice and fresh snowfall are assumed to be 900 and 200 kg m⁻³, respectively.

2.3.3. Model Calibration and Validation

The parameter ranges are summarized in Table 1. Monte Carlo simulation method is used to obtain the optimal combination of parameters for glacier mass loss simulation. The model results, with the lowest root mean square error (RMSE) between modeled glacier mass loss and observed ones and between modeled annual point mass loss and observed ones, are acceptable for selecting the optimal combination of parameters.

Table 1. List of model parameters, their initial ranges.

Symbol	Parameter	Range
ΔP	Gradient of precipitation	0–0.2 m ⁻¹
T_{LR}	Lapse rate of temperature	0.2–0.9 °C/100 m
T_{snow}	Phase threshold for snow	2–6 °C
T_{rain}	Phase threshold for rain	−4–2 °C
DDF_{snow}	Degree day factor of fresh snow	1–5 mm w.e./°C
DDF_{ice}	Degree day factor of ice	1–10 mm w.e./°C

We divided the total observations into two periods: one period (2010–2015 for the Yala Glacier and 2001–2012 for the Qiyi Glacier) was used to calibrate the model, and the other period (2016–2019 for the Yala Glacier and 2013–2018 for the Qiyi Glacier) was used to validated the models. The optimal driving data parameters of sub-models 1–4 for the Yala and Qiyi Glacier are shown in Tables 2 and 3.

Table 2. The optimal driving data parameters of the sub-models 1–4 for the Yala Glacier.

Parameters	Sub-Model 1	Sub-Model 2	Sub-Model 3	Sub-Model 4
T _{LR}	0.46 °C	0.41 °C	0.51 °C	0.42 °C
T _{snow}	1.78 °C	2.97 °C	0.20 °C	2.87 °C
T _{rain}	3.72 °C	3.0 °C	3.49 °C	3.64 °C
DDF _{ice}	6.46 °C	5.36 °C	7.95 °C	6.45 °C
DDF _{snow}	5.08 °C	3.11 °C	5.79 °C	3.33 °C

Table 3. The optimal driving data parameters of the sub-models 1–4 for the Qiyi Glacier.

Parameters	Sub-Model 1	Sub-Model 2	Sub-Model 3	Sub-Model 4
T _{LR}	0.78 °C		0.94 °C	
T _{snow}	1.61 °C	2.70 °C	0.55 °C	2.84 °C
T _{rain}	3.10 °C	5.62 °C	5.13 °C	5.71 °C
DDF _{ice}	4.04 °C	3.05 °C	11.10 °C	2.48 °C
DDF _{snow}	1.64 °C	0.78 °C	2.93 °C	1.25 °C

In the above two tables, temperature lapse rate (TLR) is based on MODIS temperature data, phase threshold for snow (T_{snow}), phase threshold for rain (T_{rain}), degree day factor for ice (DDF_{ice}), degree day factor for snow (DDF_{snow}) were also calculated and shown.

3. Data

In this study, we used two sets of data: remote sensing data and in situ data.

3.1. Remote Sensing Data

The remote sensing data in the study include land surface temperature based on MODIS and precipitation based on TRMM, °C.

MODIS Temperature Data

The most important parameter for glacier mass loss study is temperature. We have used the MODIS temperature data to study glacier mass loss for the Yala Glacier and Qiyi Glacier. Since MODIS land surface temperature product has already been widely validated by scientific community, such as Wan et al. [52], Wan et al. [53] and Hu et al. [54], it can be concluded that MODIS land surface temperature can be used to study glacier mass loss in this study although some errors exist. The daily mean, minimum and maximum temperatures data from 2000 to 2008 are calculated from MODIS for the Yala Glacier and Qiyi Glacier. All the MODIS temperature data were calculated for the whole glacier rather than pixel temperature. Figure 2 shows the daily mean, minimum and maximum temperatures from 2000 to 2008 for the Yala Glacier. The MODIS temperature data indicate obvious diurnal and seasonal changes, reflecting the basic characteristics of temperature change from 2000 to 2008. The averaged minimum temperature is -4.42°C , the averaged maximum temperature is 18.86°C , and the mean temperature is 9.83°C .

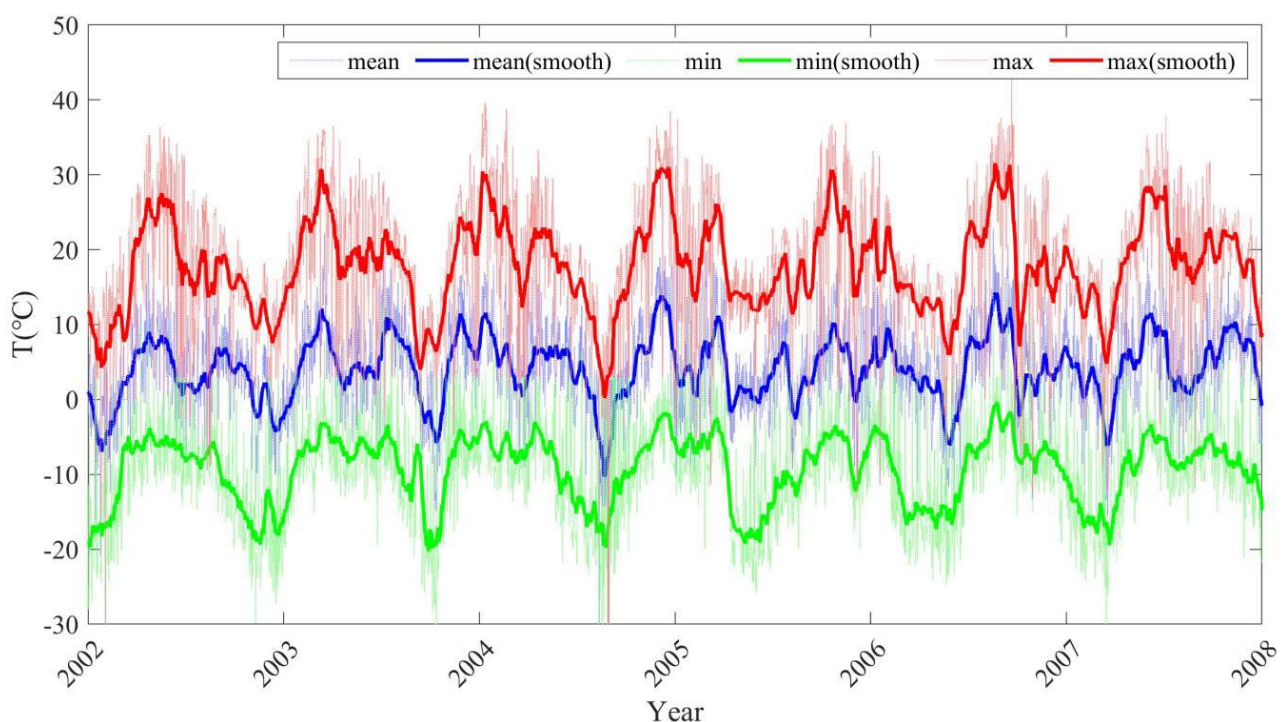


Figure 2. The glacier surface temperature data for the Yala Glacier. In the figure, we have shown the daily mean, minimum and maximum temperatures from MOD11A1 and MYD11A1 products.

Figure 3 shows the daily mean, minimum and maximum MODIS temperature data from 2000 to 2013 for the Qiyi Glacier. The MODIS temperature data indicate obvious diurnal and seasonal changes, reflecting the basic characteristics of temperature change. The MODIS temperature data clearly indicated the temperature increase from 2000 to 2013. The averaged minimum temperature is 3.11°C , the averaged maximum temperature is 20.25°C , and the mean temperature is 7.93°C .

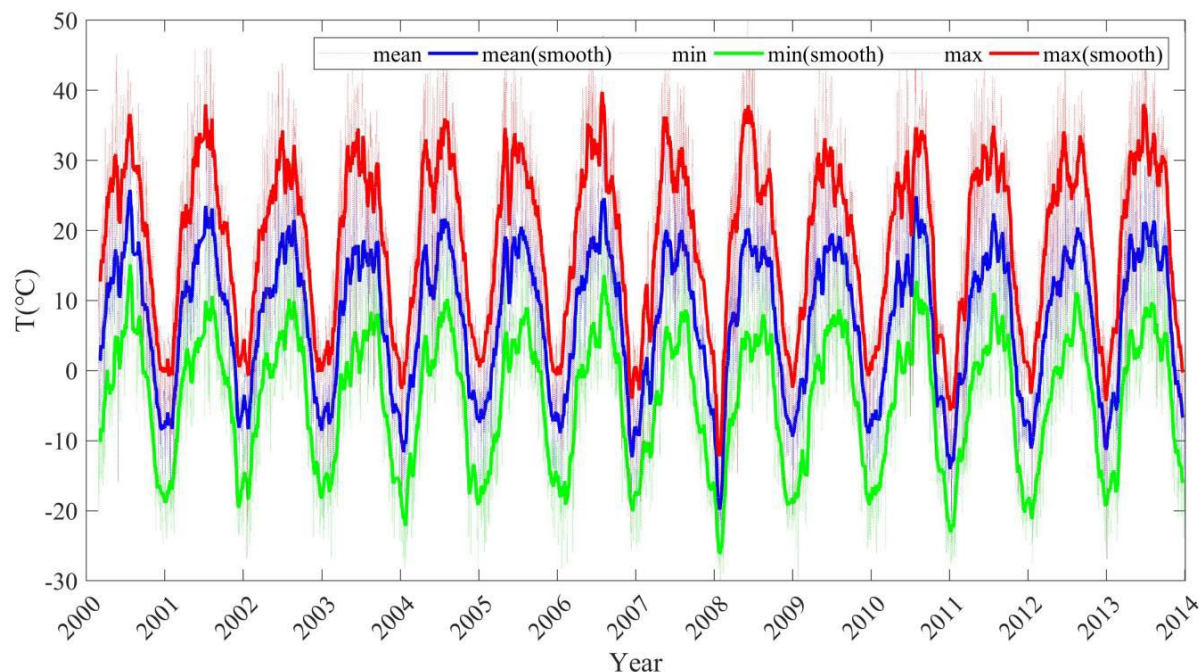


Figure 3. The glacier surface temperature data for the Qiyi Glacier. In the figure, we have shown the daily mean, minimum and maximum temperatures from MOD11A1 and MYD11A1 products.

3.2. TRMM Precipitation Data

The TRMM precipitation data for the Yala Glacier and Qiyi Glacier were obtained by: firstly, the in situ data were used to verify and correct the TRMM data from the seasonal distribution to ensure that the relative proportions of the average monthly precipitation of the two data sites in a year are stable; then, precipitation are considered with the assumption that the amount of occurrence and the amount of accumulative precipitation are proportional to the deviation correction of TRMM data.

By evaluating the daily mean, monthly mean, and annual mean precipitation and by calculating the root mean square error of the accumulated precipitation and the difference of the accumulated precipitation times, the TRMM precipitation data were calibrated. The missing data were supplemented by interpolation to ensure the completeness and consistency of the data.

In Situ Data

The in situ air temperature data were from the records of the AWS and the fixed long-term observing station. The AWS (Figure 1d) for the Yala Glacier is located at the terminus of the Yala Glacier (5058 m a.s.l.), and the fixed observing station (Kyanging, 2821 m a.s.l., Figure 1b) in the middle reaches of the Langtang River basin. The AWS (Figure 1e) for the Qiyi Glacier is located at the tongue (4408 m a.s.l.) of the Qiyi Glacier. The fixed observing station (Tuole station, 3367 m a.s.l., Figure 1c) is located in the upper reaches of the Tuole River basin. The meteorological data, including temperature, precipitation, humidity, air pressure, wind velocity and direction, were measured synchronously with glacier mass balance. In addition to the observation data by AWS, some data are from Chinese Meteorological Agency (CMA) (<http://data.cma.cn/> (accessed on 20 March 2020)) and TPE data (data.tpdc.ac.cn (accessed on March 21 2020)). The discontinuous in situ measurements for the two glaciers were carried out since 1970s. The glacier mass balance was measured by measuring stakes installed in the two glaciers. The observing system included 8 stakes for the Yala Glacier (Figure 1d) and 26 stakes for the Qiyi Glacier (Figure 1e), respectively. The observations of the Yala Glacier were carried out by Fujita et al. [41,55], Racoviteanu et al. [56], ICIMOD and Acharya and Kayastha [40], and a recent observation

was performed by Li (unpublished). The observations of the Qiyi Glacier were carried out by Guo et al. [57], Wang et al. [45,58], and Pu et al. [32].

4. Results and Discussions

Figure 4 shows the simulations of mass loss for the Yala Glacier by the four sub-models. It can be seen from the figure that the simulation of the sub-model3 is the best to simulate glacier mass loss and stake measured point mass loss, compared with the other sub-models in the calibration period. Although the sub-model4 is improved after adding calibrating data in the validation period, the sub-model3 is still the best. The above analyses indicate that the sub-model using MODIS temperature data and TRMM Precipitation data at the same time has the highest simulation accuracy. Under some particular conditions, the use of MODIS temperature lapse rate might also help improve the outcomes of the sub-models.

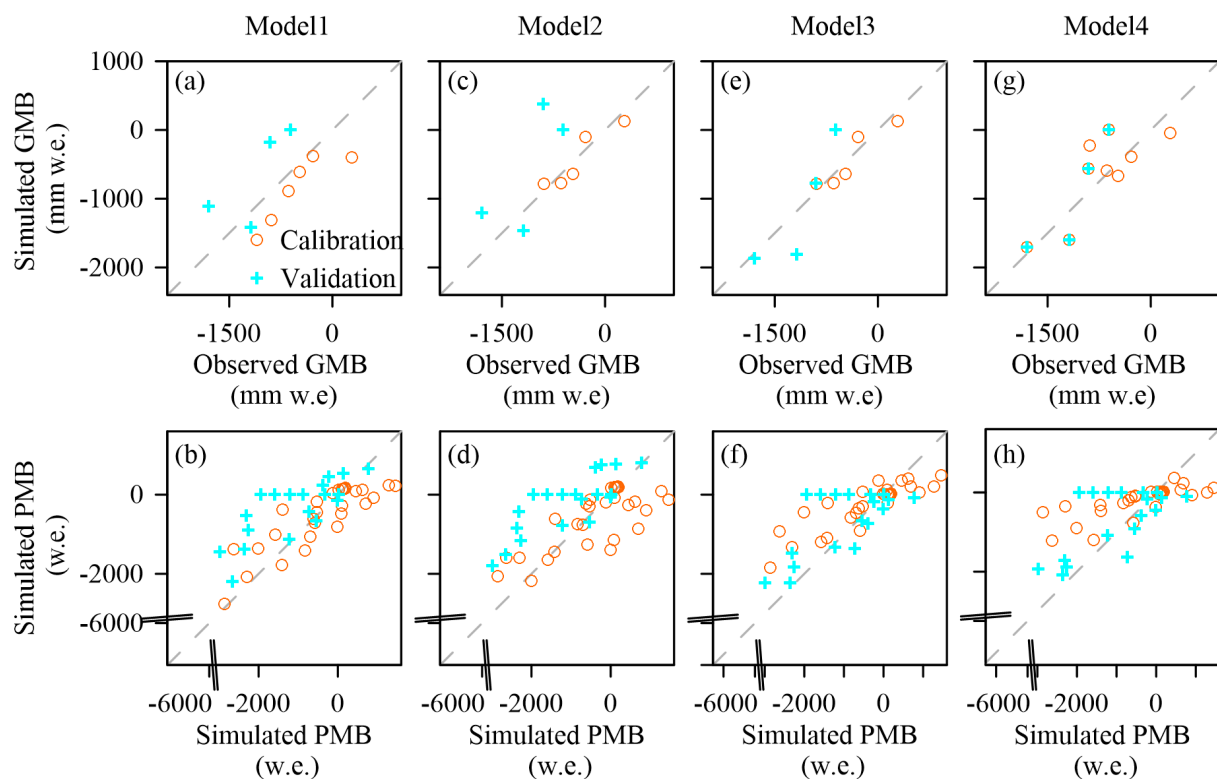


Figure 4. The modeled glacier mass loss and the stake measured mass loss as well as point mass loss of the Yala Glacier by the four sub-models. In the figure, the red circles are the data of calibration period and the blue crosses are the data of validation period; (a,c,e,g) are the simulated GMB (Glacier Mass Balance for the whole glacier) results of the four sub-models; (b,d,f,h) are the simulated PMB (Point Mass Balance of the glacier).

Figure 5 shows the results of the mass loss for the Qiyi Glacier simulated by four sub-models. It can be seen from the figure that the sub-model2 is better than the other sub-models in simulating glacier mass loss and stake measured point mass loss. The sub-model3 and sub-model4 overestimated the in situ measurement of glacier mass loss during the calibration period and underestimated the glacier mass loss during the validation period, showing the inter-annual instability of TRMM precipitation data. Similar to the Yala Glacier, the Qiyi Glacier also reflects the importance of precipitation data accuracy to glacier mass loss simulation.

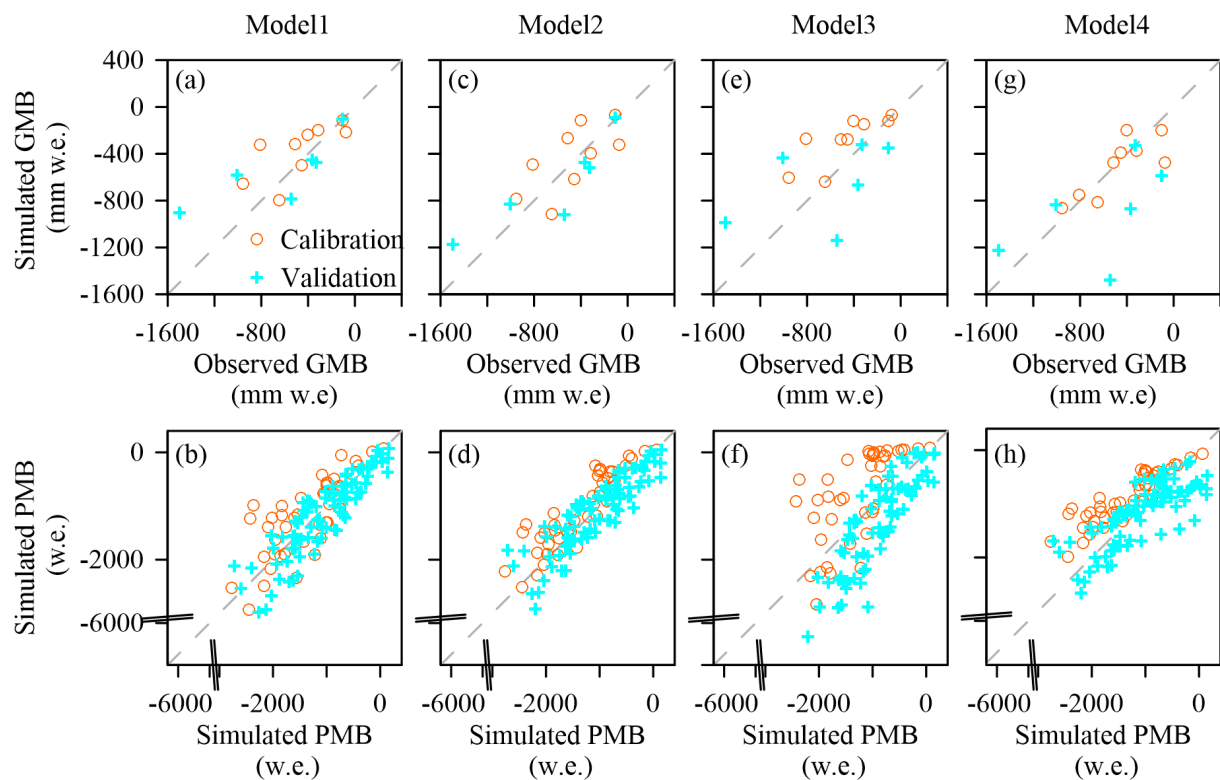


Figure 5. The modeled glacier mass loss and stake measured mass loss as well as point mass loss of the Qiyi Glacier by using the four sub-models. In the figure, the red circles are the data of calibration period and the blue crosses are the data of validation period; (a,c,e,g) are the simulated GMB (Glacier Mass Balance for the whole glacier) results of the four sub-models; (b,d,f,h) are the simulated PMB (Point Mass Balance of the glacier).

Using the best sub-model for the Yala Glacier driven by the combined data set of MODIS temperature and TRMM precipitation data, we have made a regression to get the mass balance results for the Yala Glacier, which is shown as Figure 6a:

$$MB = -16788.91 + 3177.81 \times T_y + 1.98 \times P_y - 867.86 \times T_s - 1521.92 \times T_w - 0.92 \times P_w \quad (2)$$

In the regression, T_y is annuan mean temperature, P_y annual precipitation, T_s summer temperature, T_w winter temperature, P_w winter precipitation, R^2 0.90 and RMSE 128.8 mm w.e.

Similarly, using the best sub-model for the Qiyi Glacier driven by the combined data set of in situ temperature and precipitation data associated with the lapse rate calculated from the MODIS temperature data from different elevations, we have made a regression to get the mass balance results for the Qiyi Glacier, which is shown as Figure 6b:

$$MB = -124.63 - 14606.2 \times T_y + 193.62 \times P_y + 4642.50 \times T_s - 191.84 \times P_s + 9566.3 \times T_w - 189.22 \times P_w \quad (3)$$

In the regression, T_y is annuan mean temperature, P_y annual precipitation, T_s summer temperature, T_w winter temperature, P_w winter precipitation, R^2 0.82 and RMSE 226.6 mm w.e.a⁻¹.

Based on the analyses of the remote sensing data and the in situ data as well as the results through modeling using four sub-models, we have analyzed the characteristics of glacier mass loss for both the Yala Glacier located in the southern TP and the Qiyi Glacier located in the northern TP.

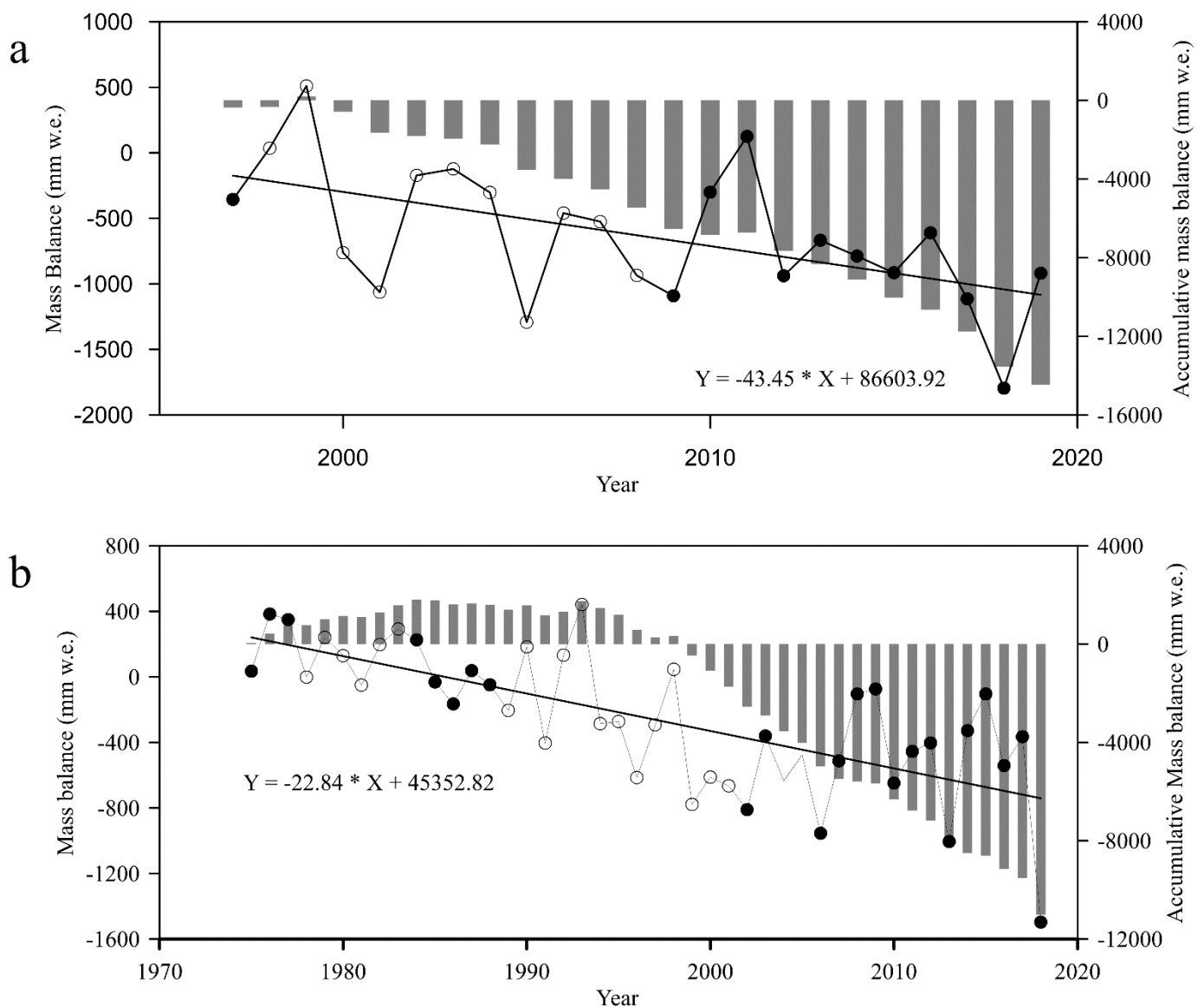


Figure 6. The modeled glacier mass balance changes of the of the Yala Glacier and Qiyi Glacier. In the figure, (a) is for the modeled glacier mass balance changes of the Yala Glacier and the (b) for the modeled glacier mass balance changes of the Qiyi Glacier.

The average multi-year mass loss of the Yala Glacier is $-736 \text{ mm w.e.a}^{-1}$, while that of the Qiyi Glacier is $-567 \text{ mm w.e.a}^{-1}$; the maximum mass loss is $-1815 \text{ mm w.e.a}^{-1}$ for the Yala Glacier and $-1516 \text{ mm w.e.a}^{-1}$ for the Qiyi Glacier. Based on a statistics of glacier mass loss comparison of the two glaciers in the same year, the mass loss of the Yala Glacier is much stronger than that of the Qiyi Glacier. From 2000 to 20018, the mass loss of the Yala Glacier is keeping at a rate $-43.8 \text{ mm w.e.a}^{-1}$, while that of Qiyi glacier is keeping at a rate of $-9.4 \text{ mm w.e.a}^{-1}$. The glacier mass loss of the Yala Glacier is significantly faster than that of the Qiyi Glacier on a longer time scale. The glacier mass loss of the Yala Glacier was low before 1996. It was only -357 mm w.e. in 1996, but entered into a rapid mass loss period in the 21st century, particularly after 2011, except 2012/13. At the same time, the Qiyi Glacier showed mild melt status compared with the Yala Glacier.

The major cause why the mass loss of the Yala Glacier is more intensive than that of the Qiyi Glacier is from the decrease of glacier accumulation associated with precipitation decrease under the weakening Indian monsoon and from the more intensified glacier ablation. In addition, the precipitation increases under the dominance of the westerly

enhancing reduced the glacier ablation in the Qiyi Glacier. The more intensive glacier mass loss of the Yala Glacier than that of the Qiyi glacier is also related to the low latitude where glaciers receive more solar radiation, which will result in more intensive melt.

5. Conclusions

Remote sensing data and in situ data were obtained to study the glacier mass loss in the two glaciers, the Yala Glacier in the Central Himalayas in the southern TP and the Qiyi Glacier in the Qilian Mountains in the northern TP. By obtaining the remote sensing data including MODIS land surface temperature and TRMM precipitation data, with calibration and validation with in situ data, the glacier mass loss were simulated. Based on the study of glacier mass loss together with the changes of temperature and precipitation, the climatological factors that resulted in the differences in the two glacier were analyzed. We concluded from the analyses that the remote sensing data are useful in the glacier mass loss study on the TP. When the remote sensing data are used to model the glacier mass loss parameters, they show that the MODIS temperature and TRMM precipitation, after a simply adjustment, can be used to drive effective models and get accurate mass loss results. The modeled results show different characteristics of glacier mass loss between the southern and northern parts of the TP. The Yala Glacier has not only been in a state of mass loss, but also in a status of intensive and accelerating mass loss. Our analyses have also shown that the average multi-year mass loss of the Yala Glacier is $-736 \text{ mm w.e.a}^{-1}$, with a maximum of $-1815 \text{ mm w.e.a}^{-1}$. At the same time, the Qiyi Glacier has experienced a mild glacier mass loss process compared with the Yala Glacier. The Qiyi Glacier's mass loss is -567 mm with a maximum of $-1516 \text{ mm w.e.a}^{-1}$. Our results indicate that the mass loss of the Yala Glacier is much stronger and faster than that of the Qiyi Glacier.

Author Contributions: R.Y. has obtained the data, made the analyses and the figures, and written the text. J.S. has proposed the idea and designed the structure of the paper. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Ministry of Science and Technology of China through the Second Tibetan Plateau Scientific Expedition and Research (STEP) program [grant no. 2019QZKK0206].

Conflicts of Interest: The authors declare no conflict of interest.

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