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Three-stage Linear Model Simulation of Midui Glacier since Little Ice Age (LIA)

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Abstract Studying the past glacier fluctuations during the Little Ice Age (LIA) is crucial for interpretation of climate-induced glacier changes. Thickness, flux and length changes are particularly vital, as they are the sequential changes on the glacier with changes in mass balance. In the past, the studies regarding long-term glacier fluctuations were particularly based on moraine dating in the southeastern Tibetan Plateau. However, arrays of glacier changes for each time step were not well understood. Based on the dominant role of warming temperature in glacier retreat, we hypothesized that during LIA, low temperature could have mediated the glacier fluctuation compared to precipitation. To test this hypothesis, we used three-stage linear model and simulated thickness, flux and length of the Midui glacier since 1385 CE. Our results showed that the glacier advanced during the LIA (1550-1780 CE) was controlled by temperature rather than precipitation. The simulated changes were more comparable with moraine records when both the climatic factors were considered as forcing. In the light of these findings, we concluded that the three-stage linear model was important tool to emulate the past climate driven glacier fluctuations in the southeastern Tibetan Plateau. This study may help to advance our understanding of variation in glacier behavior under ongoing warming climate.

Keywords: *precipitation, response time, temperature, Tibetan Plateau*

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1. Introduction

Mountain glaciers are important sources of water for agriculture, hydropower, aquatic life, and basic water supply [1,2]. The timing and magnitude of glacier changes are sensitive to climate change, hence, understanding the past changes in glacier are crucial to conserve water resources for future [3]. The high mountains of Asia constitute the highest reservoir of glaciers after Polar Regions [4]. Majority of these glaciers are identified as a source of sustenance for hydro-economic nations. Global warming aggravated drought intensity and water shortages, especially in arid and semi-arid regions, which suffered socio-economic impact through decline in agriculture production and insufficient power supply for industries, across the Asia [5]. However, studies suggested that glaciers could mitigate the extreme water shortages by enabling sustained water supply during the drought periods [5,6,7]. Moreover, despite an overarching role of glaciers in the sustainable conservation of biodiversity, glacier retreat due to warming have also contributed to rise in sea level, local natural hazards such as glacial lake outburst floods (GLOFs) and migration of vulnerable mountain communities [8,9,10,11].

The glaciers in the Southeastern Tibetan Plateau showed periods of advancing and retreating in the past due to occurrence of cold and warm climatic periods, respectively [12]. The Little Ice Age (LIA), a recent cold period (1400-1800 CE), in the Tibetan Plateau was in agreement with the climatic variability in Northern Hemisphere [13]. During the LIA, the global temperature dropped considerably, which resulted in the expansion of ice masses globally [14]. The maximum LIA glacier extent based on moraine dating occurred during the late 1700 CE and early 1800 CE in the southeastern Tibetan Plateau [15,16,17]. These records from moraine dating however, only provides a definitive position of glacier on particular time rather than arrays of changes.

The scientific approach to achieve the continuous temporal array of changes are glacier models. Previously, the linear glacier models had been successfully used to simulate glacier response to climate in the form of arrays. Different models were used to simulate past glacier fluctuations and to project for future, for example, by calibrating models from historical glacier length records [18], varying Ablation Area Ratio (AAR) and melt factor [19] and varying time of attending response time [20]. The simple linear models provided dependency of numerical solutions on glacier geometry, and could be used to estimate the response of glacier across a wider range of parameter uncertainty [21]. Various dynamic and linear glacier models have been used to simulate the evolution of glaciers and prediction of glacier response to changing climate, which further highlights the impact of temperature and precipitation on the Tibetan Plateau [22,23].

Based on the rationale presented above, we used the three-stage linear model to simulate the historical changes driven by climate on Midui glacier, southeastern Tibetan Plateau. This study intended to assess the response of Midui glacier to mass balance change due to change in climate during the LIA by generating arrays of past fluctuations of this glacier. We selected the LIA as the simulation period because maximum glacier advance during the LIA portrayed the last major turning point from an advancing to a retreating glacier [24]. The simulations were carried out for change in mass balance mainly accounting for the sole effect of temperature, the sole effect of precipitation and the effect of both temperature and precipitation. Currently, glacier retreat is largely dominated by warming temperatures across the globe, therefore, we hypothesized that low temperature rather than precipitation, during LIA, regulated the response of Midui glacier. Our simulation of glacier evolution on LIA are forced by reconstructed past climates rather than probable climatic conditions.

2. Materials and Methods

2.1. Study Area

The Midui glacier (29.41°N, 95.50°E) is located in Linzhi area of the southeastern Tibetan Plateau (Figure 1). The area is represented by Himalayas, Nyainqêntanglha Mountains, and the Hengduan Mountains. A ridge separated the glacier into two tributaries, each with an icefall creating ogives, which merged later terminates into a proglacial lake. The glacier has an area of 26.88 km^2 with mean elevation of 5108 m.a.s.l [25]. Based on the nearest grid of Climate Research Unit Time series (CRU TS) 4.01 datasets (1901-2017) [26] , this region revealed a significant warming of 0.3°C (Figure 2a) and a change in the glacier accumulation of -0.0004 m a^{-1} (Figure 2b).

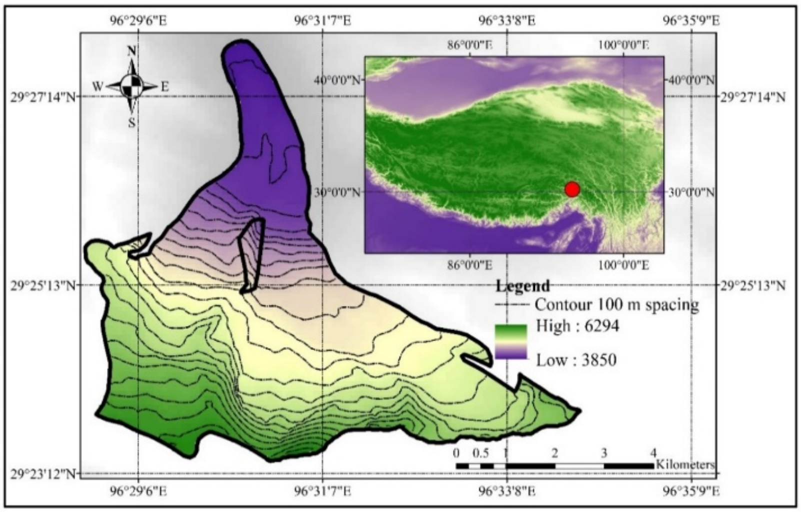

Figure 1. Contour map of the Midui glacier of year 2005 and its location in the southeastern Tibetan Plateau. The contour was constructed on the spacing of 100 m

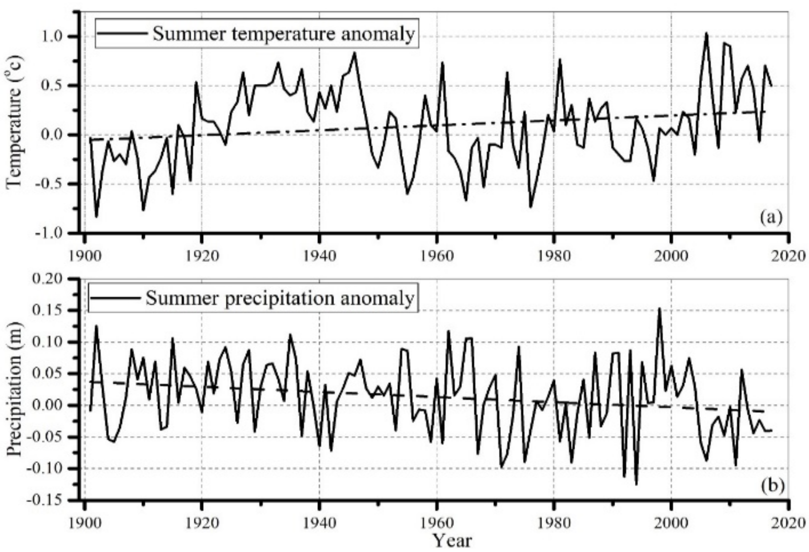

Figure 2. (a) Long-term trend of summer temperature fluctuation, (b) long-term trend of summer precipitation fluctuation. Both temperature and precipitation were retrieved from CRU datasets of the nearest grid point 29.25 °N, 96.75 °E

2.2. The Glacier Model

There are very few observations related to this glacier over the past few decades, so available map of 2005 (Figure 1) was considered to define glacier geometry for linear modelling [25]. A three-stage linear model, removes uncertainties associated with one-stage model, was used to study glacier length fluctuation around prescribed mean state [21]. This model effectively emulates the behavior of numerical flow line model under wide range of parameter choices [21]. The model was based on the glacier adjustment-taking place in three stages as;

- Change in mass balance first causes change in interior glacier thickness;
- Thickness change drove change in flux at terminus; and
- Finally, flux change causes change in glacier length.

The simple third-order differential equation could explain the three-stage flow of glacier.

$$\frac{dL'}{dt} + \frac{L'}{\check{T}} = \alpha T' + \beta P \qquad (1)$$

Where, $\in = 1/\sqrt{3} = 0.58$, is a constant. The equation (1) elaborated the idea of change in the length of glacier on changing mass balance of glacier. The changes were made on steady state glacier and were represented in terms of anomalies. The geometry of glacier formed after the selection of model parameters is zero position of glacier, a hypothetical steady state of glacier.

Sensitivity ratio was very important property of the linear model as it evaluates the relative sensitivity of the glacier length to accumulation and melt-season temperature. The change in glacier length on step change of precipitation and temperature was given by;

$$Rano = \frac{\sigma L_T}{\sigma L_P} \qquad (2)$$

Where, σL_T and σL_P are deviation in glacier length further on sole forcing of temperature and precipitation respectively and these changes were based on geometry of glacier and are calculated as;

$$\sigma L_T = (A_t * \mu * \sigma_T) \qquad (2a)$$

$$\sigma L_P = (A_{tot} * \sigma_P) \qquad (2b)$$

Where, σ_T and σ_P represented the deviation in temperature and precipitation respectively.

The simulation of Midui glacier fluctuation was validated using the past moraine records [16] and historical imageries [27]. Tree-ring based moraine dating of the Midui glacier showed advancements during 1767, 1875, 1924 and 1963. Furthermore, the historical satellite imagery between 2001 and 2017 were used to create a fine series of glacier length observation for validation of glacier length simulation. The initial perturbation length at the LIA maxima (1767 CE) for the glacier model was a free parameter and was chosen to be of some desired value to produce best fit with the historical moraine records [28].

2.3. Parameter Setup

The parameter value 'x' was presented with uncertainty as a standard deviation 'σx' in this section. The value of environmental factors melt rate and lapse rate are 0.5 and 6.5°C km^{-1} respectively [1,29]. The AAR had large spatial variability from 40% to 70%, based on a large data set and a fixed AAR value should not be applied to different regions [30]. So, the accurate value for melt factor and AAR with in this range were represented with some uncertainties. The parameters melt factor based on Roe and Neal (2009) [28] and thickness of glacier from empirical relation between glacier thickness and area by Kulkarni (2006) [31] were calculated using following equations,

$$\text{Melt area} = \text{Aabl} + \frac{\text{Precipitation*width}}{\text{Melt factor*Lapse rate*slope}} \qquad (3)$$

$$\text{Mean thickness} = -11.32 + 53.21 * A^{0.3}. \qquad (4)$$

Using equation 3, the melt area of glacier was calculated 16 km^2. The mean thickness of glacier was 131.51 m, which was calculated using empirical relation between total area and glacier thickness (Equation 4). Further, the characteristics width of glacier was 900 m, which was calculated by measuring contour at the glacier terminus region (Figure 1). The assumed glacier bed slope was considered 0.1 after simulation under multiple possibilities (Figure 4).

The glaciers were simulated using three-stage linear model under mass balance due to a) temperature and precipitation b) sole effect of temperature and c) sole effect of precipitation. The mass balance forcing was calculated using simple mass balance model (Equation 5). The reconstructed climatic anomalies for glacier region were used to calculate mass balance forcing.

$$\beta b' = \beta P' - \alpha T'. \qquad (5)$$

In scenarios like mass balance due to sole effect of only precipitation or only temperature, the effect of ablation or accumulation were removed, and equations were developed as;

$$\beta b' = \beta P' \qquad (5a)$$

$$\beta b' = -\alpha T' \qquad (5b)$$

Where, P' and T' are precipitation and temperature anomalies and α and β are model coefficients. The coefficients α and β were calculated as;

$$\alpha = -\frac{\mu A_t}{\omega H}, \beta = \frac{A_{tot}}{\omega H} \qquad (6)$$

Where, A_{tot} was the total area, A_t was the area over which melting occurs; w and H were the characteristic width and thickness of the glacier in the terminus zone, and μ was the melt factor. The timescale 'τ' was given by,

$$\tau = \frac{\omega H}{\mu r \tan\Phi A_{abl}} \qquad (7)$$

where, τ was the time of glacier to attain its steady state, A_{abl} was ablation area where mass balance was negative, r was atmospheric lapse rate and $tan\Phi$ represented slope of bedrock on which the glacier was located.

Table 1. Input values of parameters for simulation with standard deviation

Parameters	Value	Unit
Total area (A)	26.88	km^2
Ablation area (A_{abl})	15.05 (2.9)	km^2
Melt factor area (A_t)	8 (1.4)*10^6	$m^3 yr^{-1}$ °C
Mean thickness of glacier (h)	131.51	m
Characteristics width of terminus (w)	900	m
Lapse rate (r)	6.5	°C km^{-1}
Time step (t)	1	year
Assumed slope (tanΦ)	0.1	-
Model Coefficients		
Alpha (α)	28.05 (6)	-
Beta (β)	227.1	-
Response time (τ)	24.19 (7.31)	year

2.4. Temperature and Precipitation Anomalies

The past climate reconstructions have always sighted present context of climate. In this study, reconstructed temperature and precipitation were used to modulate the past changes of glaciers in the southeastern Tibetan Plateau (TP). For the temperature forcing, the summer (August) temperature reconstruction over the period 1385–2002 based on a tree-ring width chronology of Balfour spruce (*Picea likiangensis var. balfouriana*) on the southeastern TP (Figure 3a) was used [32]. The reconstructed precipitation forcing was based on correlations between climate data and the tree-ring d^{18}O of high-elevation junipers, where annually resolved oxygen isotope series reflects the long-term variations in summer monsoon activity in the southern TP (Figure 3b) [33]. The temperature trend showed the overall rise since 1385 with cooler period during 1600-1800. However, no general trend of precipitation was observed despite the increased precipitation from 1550 to 1850 in TP.

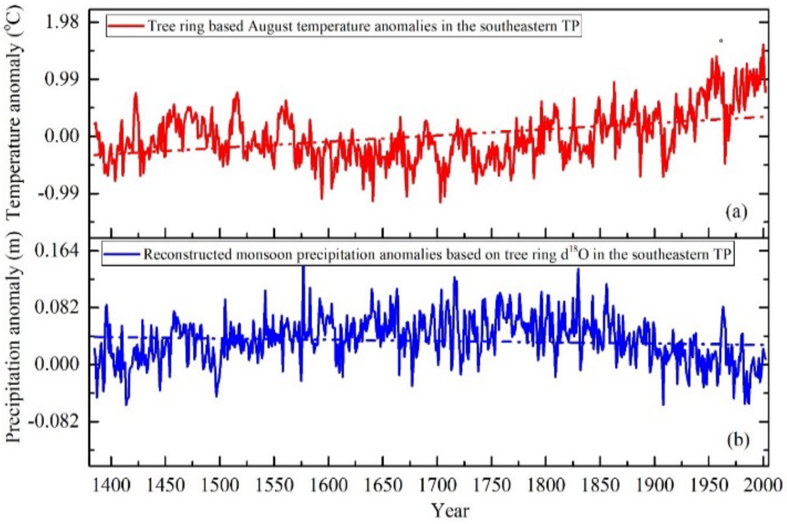

Figure 3. Reconstructed climate forcing (solid), and their respective trends (dotted) (a) August temperature anomaly [32] and (b) Monsoon precipitation anomaly [33] in the southeastern Tibetan Plateau during 1385-2002 CE

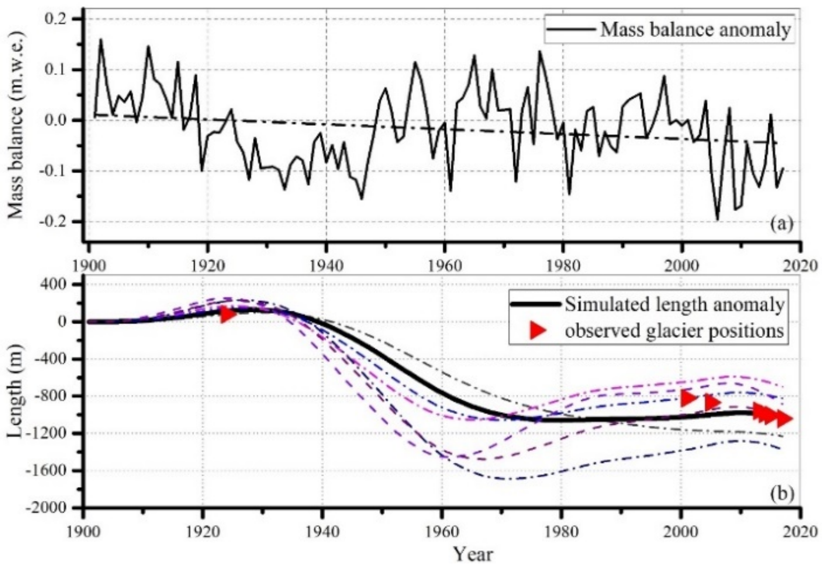

Figure 4. (a) Mass balance deducted using temperature and precipitation forcing with glacier geometry. (b) Glacier length observations (black dots) together with model calibration using anomalies and calibrated parameter values (solid black line); dotted lines representing various possibilities of Ablation Area Ratio (AAR) and melt factor-causing uncertainty on response time and alpha

3. Results

The mass balance is a forcing agent, which shapes glacier geometry under variation of input parameters for validation was calculated using temperature and precipitation [26] (Figure 3a). Figure 3b shows length observations at Midui glacier (black dots) with a best estimate model simulation (black line) using mass balance forcing. The uncertainty on AAR, melt factor and melt area simulated glacier length under various span of response time. The length under lower values of τ resulted in a speedy response but are less sensitive whereas larger τ cased a lengthier response, but were ultimately more sensitive to provided climate anomalies. The calculated response time used for simulation was 24.19± 7.31 years (Table 1). The model coefficients alpha and beta were calculated to be 28.05 and 227.1 respectively (Table 1).

Table 2. Correlation (ρ) and Lag Correlation (ρ^1) of simulated glacier length with temperature and precipitation along with Root mean square error (RMSE) and Relative sensitivity (c)

Forcing Factor	ρ	ρ^1	RMSE	c
Temperature	-0.6	0.45	144.1m	1.5
Precipitation	-0.73 (-0.87 τ)	0.53 (+0.95 τ)	345.5m	

The temperature showed good indication of historical fluctuation compared to length change anomaly with negative correlation of -0.60 (Table 2). The higher correlation occurred at lag of -0.87 tau (-21 years) for the length with temperature. The RMSE for the Midui glacier for sole effect of temperature was 144.1 m and for sole effect of precipitation was 345.5 m. The glacier advanced until 1780 CE and retreated sharply afterwards. The glacier advanced by 324 m until 1780 with the balance rise of 0.0002 m.w.e/yr. (Figure 5a). Furthermore, the thickness increased by 0.048 m/yr. and flux also rose by $1.8e^8$ m^2/yr. As the LIA ended, the glacier receded by -0.0008 m.w.e. /yr. with negative flux rate of $-7.8e^8$ m^2/yr. The glacier thinned by -0.21 m/yr. and retreated by rate of -4.27 m/yr. reaching the final length of -712.97 m (Figure 5a).

The precipitation, however, did not influence high advances in case of the Midui glacier. There was a positive correlation (+0.45) between precipitation and glacier length anomaly (Table 2). Similarly, the precipitation driven changes in the length showed better correlation if temperature series was used from period after +0.95 tau (+23 years). The RMSE for the Midui glacier for sole effect of precipitation was 345.5 m. The glacier advanced with the rate of 0.0001 m.w.e./yr. until 1800 (Figure 5b). The geometry change in glacier was thickness rise in 0.033 m/yr. with advance of 2.83 m/yr. with flux of $1.3e^8$ m^2/yr. After 1800 CE, precipitation declined which resulted the glacier to retreat by -1.38m/yr. with mass loss of -0.0003 m.w.e. /yr. The glacier thinned by -0.077 m/yr. with change in flux of $-2.7e^8$ m^2/yr. (Figure 5b). There were minimal changes in glacier thickness, flux and length in the end of simulation compared to 1385.

The simulation under the effect of both temperature and precipitation (Figure 6) matched with the simulation under sole effect of temperature (Figure 5a). For the effect of temperature and precipitation (Figure 6), the glacier advanced until 1780 CE and retreated sharply afterwards. The glacier advanced by 338 m until 1780 with the balance rise of 0.0003m.w.e./yr. Furthermore, the thickness increased by 0.052 m/yr. and flux also rose by $1.9e^8$ m^2/yr. As the LIA ended, the glacier receded by -0.0007m.w.e. /yr. with negative flux rate of $-6.8e^8$ m^2/yr. The glacier thinned by -0.18 m/yr. and retreated by rate of -3.7 m/yr. reaching final length of -680.18 m (Figure 6). The RMSE for forcing of both climatic parameters was 138.2 m. The relative sensitivity of temperature-forced length fluctuation to precipitation-forced fluctuation was calculated to be 1.5 (Table 2). This means the glacier was more sensitive to temperature by factor of 1.5.

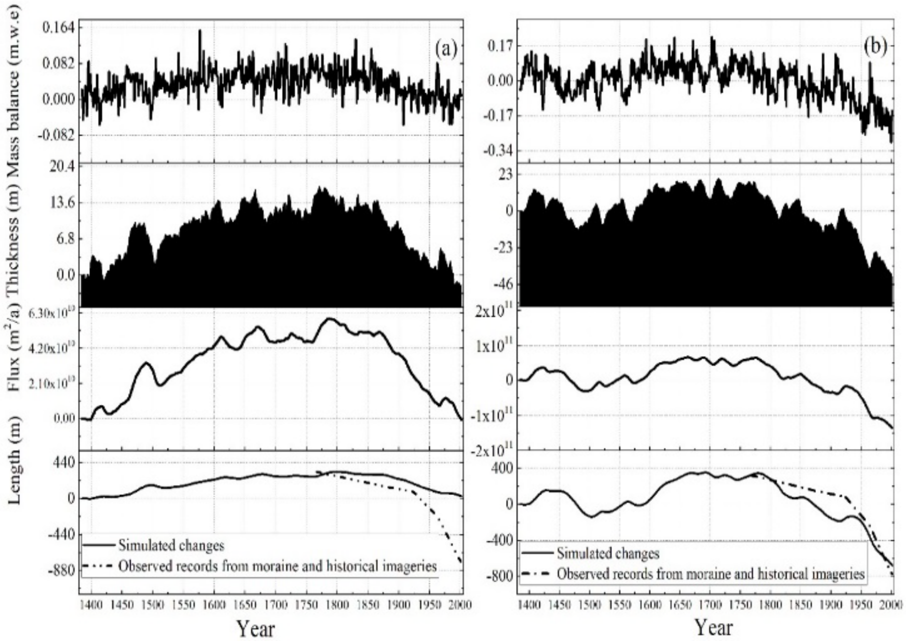

Figure 5. Simulated outputs of three-stage linear model for the Midui glacier based on (a) sole effect of precipitation and (b) sole effect of temperature on glacier changes. The gradual changes in the form of anomaly were presented as simulation of mass balance, thickness change, flux change, and length (solid as simulated and dotted as observed) from 1385 to 2017 in both (a) and (b)

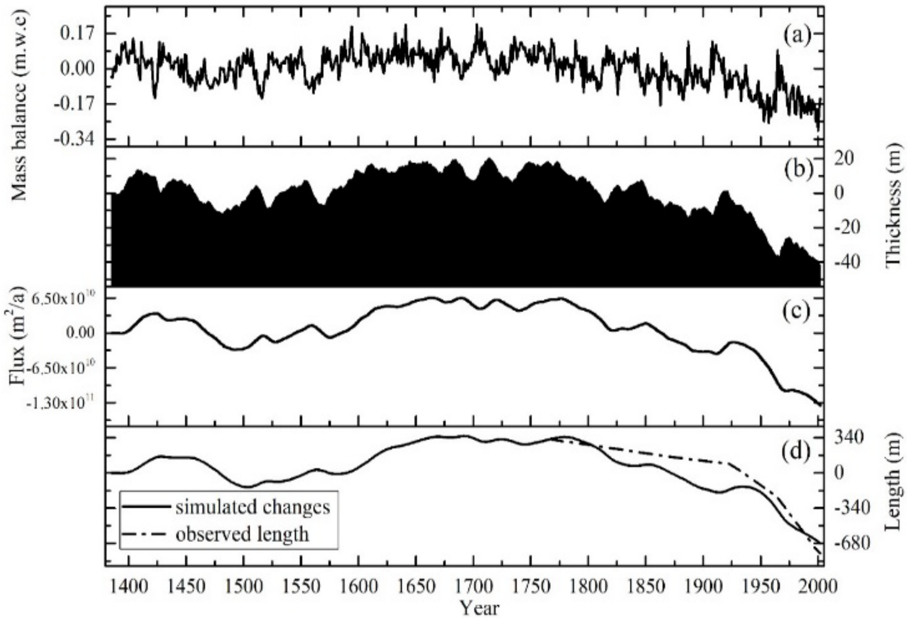

Figure 6. Simulated outputs of three-stage linear model for the Midui glacier based on effect of both temperature and precipitation. The gradual changes in the form of anomaly were presented as simulation of mass balance, thickness change, flux change, and length (solid as simulated and dotted as observed) from 1385 to 2017 in sections (a), (b), (c) and (d)

4. Discussion

The three-stage linear model was able to simulate and interpret the influence of climate factors in different combinations on glacier fluctuations during the LIA. The advancement of glaciers, which occurred between the periods from 1600 to 1850 CE in the southeastern Tibetan Plateau, confirmed the LIA conditions, are consistent with previous studies [15,34,35,36,37]. The LIA maxima timing of the Midui glacier was slightly inconsistent to tree ring based moraine dating record by the margin of 13 years. This could be due to high summer accumulation in glacier [38] as summer snow in the ablation zone over a larger area may have a significant effect on the rate of retreat on a timescale of decades, which promotes slow sensitivity of glaciers to climatic factors [39]. In addition, the use of tree ring technique for determining long gone past could be inaccurate as the success of cross dating depends upon the longevity of local trees, which often fail to exceed 300–400 years in many subalpine locations [40]. The rare and minor glacier advances after the LIA were in agreement with moraine records of Midui glacier [16] and neighboring glaciers in the Tibetan plateau [15,41] and Karakoram glaciers [4,42]. This further supports that the three-stage linear model was able to capture advances in close approximation to the observation.

Our results demonstrated that the glacier retreats in the southeastern Tibetan Plateau could be explained by forcing of both temperature and precipitation. The approach of modelling with both climatic forcing factors have been accurate to define changes in glacier [20,28,43,44]. The regional change in precipitation and temperature affected the glaciers in the southeastern TP [45,46]. Though the glaciers changes were due to forcing mechanisms of both temperature and precipitation, the temperature was found to be the controlling factor of the historical glacier fluctuations. While the RMSE value between all simulations and observations was quite high, the temperature driven glacier length changes had less error in comparison with precipitation driven length changes. Our findings were in agreement with previous study that the temperature change was the fundamental factor underlying changes observed in glacier [47]. On both centennial and decadal timescale, temperature was the main controlling factor for glacier fluctuations rather than precipitation variations. The summer temperature was the dominant control on annual mass balance ultimately affecting glacier fluctuation in most of the glacial regions [48,49]. The previous approaches of glacier modelling in the TP also suggested that steady warming was more adequete factor on evolution of glaciers during various time periods [22,23]. The reason might be that the temperature is spatially more stable or homogeneous, less affected by topographic variations as compared to precipitation [50]. In addition, as we have shown that precipitation in the TP was declining while the temperature was ascending (Figure 3), this could also be the potential reason behind the superiority of temperature. In contrast, the temperature was not always dominant factor of glacier control. The precipitation was also prime factor controlling glacier fluctuation in various region. The glacier advances was driven by high winter precipitation in coastal areas of Scandinavia, SE Alaska, Kamchatka, New Zealand and western Patagonia glaciers [51,52]. The fluctuations in Midui glacier region are mainly affected by circulation of westerlies, the South Asian monsoon, and the East Asian monsoon [53]. The nearby Karakoram glaciers and high altitude glaciers are also mostly influenced by high summer and winter precipitation and cooler summer conditions [54]. This justifies the more crucial role of summer or monsoon seasonality, especially temperature, in the glacier evolution, which determined the fate of the glacier through retreat and advance.

Our finding suggested the driving effect of temperature over precipitation in the southeastern Tibetan plateau. While the solid precipitation acted to nourish the glacier as an accumulator, the effect of temperature was more vigorous on glacier evolution [12]. The increase in summer temperature would result in more positive degree days, which caused more ablation controlling annual mass balance [55]. The formation of the glacier was a gradual process; where the solid precipitation compile for extended years to form glacier ice. Similar phenomenon of nourishing and accumulating prevail during snow fall to form glacier [56]. However, ablation of glacier is rather the immediate effect of temperature with instant effect on ice masses through severe melt [12]. Therefore, the changes in air temperature was more impactful for glacier changes rather than change in precipitation.

5. Conclusion

In conclusion, the three-stage linear model was capable to simulate the past fluctuation of glacier in the southeastern Tibetan Plateau. The series of simulation from the start of the LIA to recent period suggest that temperature can solely define the history of glacier fluctuation indicating the overriding effect of summer temperature over summer precipitation in defining ice melting and the snow accumulation fraction. The glacier fluctuations since LIA was well represented when both climatic factors were used to define mass balance changes. The model can act as suitable alternative for higher order approaches, especially while modeling numerous ensembles of the glaciers. Although improvements were needed in future research, the model can be coupled with other climatic models to create arrays of datasets. The environment factors like melt factor and lapse rate vary from topographic, geographic and climatic settings of the locality, so field-based data can further minimize the uncertainties.

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Source Code

(https://earthweb.ess.washington.edu/roe/GerardWeb/Home.html).

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