

Article

Numerical Reconstruction of Three Holocene Glacial Events in Qiangyong Valley, Southern Tibetan Plateau and Their Implication for Holocene Climate Changes

Yong Sun ^{1,2}, Xiangke Xu ^{1,3,*}, Lianqing Zhang ^{1,2}, Jinhua Liu ⁴, Xiaolong Zhang ¹, Jiule Li ¹ and Baolin Pan ⁵

¹ Key Laboratory of Tibetan Environment Changes and Land Surface Processes, Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100101, China; sunyong@itpcas.ac.cn (Y.S.); zhanglianqing@itpcas.ac.cn (L.Z.); zxl1986@itpcas.ac.cn (X.Z.); jlli@itpcas.ac.cn (J.L.)

² University of Chinese Academy of Sciences, Beijing 100049, China

³ CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing 100101, China

⁴ School of Earth Sciences, East China University of Technology, Nanchang 330013, China; hua1991212@sina.com

⁵ College of Resource Environment and Tourism, Capital Normal University, Beijing 100048, China; blpan@cnu.edu.cn

* Correspondence: xkxu@itpcas.ac.cn

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Abstract: The dating of well-preserved Holocene moraines in the Qiangyong Valley, southern Tibetan Plateau (TP), offers great potential for reconstructing Holocene glacier extents and examining climate changes in the region. Guided by Holocene moraine features, this study used Geographic Information System (GIS) model tools to reconstruct paleo-glacier surfaces and glacier equilibrium line altitude (ELA) depressions for three Holocene glacial stages in the valley. The GIS-based models showed that the Qiangyong Valley contained ice volumes of 8.1×10^8 , 6.2×10^8 , and 4.6×10^8 m³ during the early Holocene, Neoglacial, and Little Ice Age (LIA) glacial stages, and that the ELA was decreased by $\sim 230 \pm 25$, $\sim 210 \pm 25$, and $\sim 165 \pm 25$ m, respectively, compared to modern conditions. Furthermore, the summer temperatures were estimated to be 1.56–1.79, 1.37–1.64, and 1.29–1.32 °C cooler than present to support the three Holocene glacier extents, based on the evidence that the respective precipitation increased by 20–98, 13–109, and 0.9–11 mm relative to the present, which were derived from the lacustrine pollen data for the southern TP. By comparison, this study found that the amplitudes of the ELA-based summer temperature depressions were much larger than the pollen-based counterparts for the three glacial stages, although the two proxies both showed increasing trends in the reconstructed summer temperatures.

Keywords: paleo-glacier reconstruction; equilibrium line altitude; Holocene glacial stages; Qiangyong Valley

1. Introduction

Glacier changes over time provide clear evidence of climate variations [1]. Specifically, former glacier extents indicated by moraines and trimlines reflect temporal changes in glacier mass balance that were mainly controlled by past annual solid precipitation (snow) and summer temperature [2]. Therefore, paleoclimatic information can be inferred from glacial geomorphologic features by reconstructing the age of past mountain glacier extents [3,4]. The geomorphology-derived paleoclimate can provide an independent check on fidelity of other nearby terrestrial climate reconstructions and can help to assess the quality of climate model simulations. This is particularly true for the areas

where we have very few observational and proxy climate records at high elevation or in remote areas of the world. In addition, reconstructing the paleo-glacier parameters, especially volumes, helps in evaluating glacier water resources available for downstream communities and in understanding the variability of water resources and their relationship with climate changes in mountain areas.

Throughout the Tibetan Plateau (TP), Holocene glacial geomorphologic features are generally better preserved than older glaciation successions, and thus offer great potential to derive a detailed record for Holocene climate change [5,6]. Holocene glacier histories have been extensively documented aided by different dating methods, especially by the cosmogenic ^{10}Be exposure dating method over recent years. For example, Zhou et al. (1991) [7] reviewed ^{14}C data of the Holocene glacial chronology on the TP to show that the TP continental glaciers advanced with a 2500-year cycle at ~8300, 5700, 3000 and 200 years ago, while the maritime glaciers advanced with a ~1000-year cycle at ~3000, 2000, 1000, and 200 years ago. Based on 53 ^{14}C ages from Holocene moraines on the whole TP, Yi et al. (2008) [8] argued that the glaciers advanced at 9.4–8.8, 3.5–1.4, and 1.0–0.13 ka, thus suggesting that the Holocene glacial events correlated well with cooling periods in the Guliya ice core [9]. Moreover, Seong et al. (2009) [10] showed that the Holocene glaciers had stillstands at ~11.2, 10.2, 8.4, 6.7, 4.2, 3.3, 1.4 ka, and at a few hundred years ago in the Mustah Ata and Kongur Shan, northwestern TP. Furthermore, Owen (2009) [6] suggested that eight Holocene glacial events should have occurred on the TP, supported by the ice core data, which show millennial-scale abrupt climate oscillations throughout the Holocene [9,11,12]. Overall, millennial-scale glacier advance events have been reported as occurring during different periods of the Holocene on the TP, including the early Holocene e.g., [8,13,14] and the mid-late Holocene e.g., [10,13,15–17]. Even though these studies provide chronological information about the Holocene glacier fluctuations on the TP, little attention has been paid to reconstructing glaciological parameters such as glacier area, ice volume, and glacier equilibrium line altitude (ELA), which are essential to recognize water resource evolution and glacier response to climate change in a mountain region.

This study, as a case study, aimed to reconstruct paleo-glacier surfaces and ELAs for the Holocene glacial events in the Qiangyong Valley, southern TP, and then inferred possible climate conditions that could have sustained the Holocene glacial expansions. The paleo-glacier surfaces were reconstructed by estimating the distributed ice thicknesses on the basis of an iterative solution to the perfect plasticity assumption for glacier rheology; and the paleo-glacier ELAs were retrieved on the paleo-glacier surfaces, and then used to infer paleoclimatic conditions by analyzing the regional temperature and precipitation gradients with elevation. We built this study on the chronological frame of the cosmogenic ^{10}Be exposure dating by Owen et al. (2005) [18] and Liu et al. (2017) [19].

2. Study Area

The Qiangyong Valley originates from the Mt. Kaluxung (28.8° N, 90.3° E), 6674 m above sea level (m asl), and drains northward to the Kaluxiong River on the northern slope of the Himalaya (Figure 1). The valley occupies an area of 28 km², with elevation ranging from 4800 m asl at the confluence with the Kaluxiong River to 6674 m at the summit. In the valley, the contemporary Qiangyong glacier, with an area of ~6.25 km², flows down along a ~4.9 km-long flow path and terminates at an elevation of 5000 m asl. Based on the field observation at the end of Qiangyong Glacier, the annual precipitation in 1975 was ~489 mm [20,21]. Downstream of the modern glacier, three sets of latero-frontal moraines can be seen near the mouth of the valley (Figure 2) [18,22]. The outermost moraine complex extends ~4 km from the valley mouth and terminates at an altitude of 4810 m asl where some hummocks are enclosed by the latero-frontal moraine. The second moraine complex comprises distinct sharp-crested lateral ridges which lie 20–30 m above the present river on both sides of the valley. The moraine encloses the Daqiangyong Lake at 4900 m asl and stretches up for ~3 km from the valley mouth to an elevation of 5000 m asl. The innermost latero-frontal moraine is relatively small, with its ridges lying 10–15 m above the valley floor. This moraine is about 1 km downstream of the modern glacier front and encloses the Xiaoqiangyong Lake at 4950 m asl. Using the cosmogenic ^{10}Be exposure dating method,

Owen et al. (2005) [18] dated the outermost and the second moraine complexes to between 9.17 ± 0.22 and 10.63 ± 0.26 ka and between 2.09 ± 0.14 and 3.48 ± 0.32 ka, respectively. Although no direct ages are assigned to the innermost moraine, a morpho-stratigraphically similar moraine (M1) was dated by Liu et al. (2017) [19] to between 0.13 ± 0.02 and 0.36 ± 0.09 ka in the Karola West Valley, Noijin Kangsang peak (Figure 1b), no more than 10 km north of the Qiangyong Valley. The outermost and second moraines also respectively correlate to the moraines of M3 (between 8.2 ± 0.4 and 9.7 ± 0.4 ka) in the Karola West Valley and M2 (between 2.2 ± 0.2 and 2.6 ± 0.1 ka) in the Gangbu Valley, Noijin Kangsang peak (Figure 1b) [19]. These ^{10}Be ages suggest that the three moraine sets correspond well to the early Holocene, Neoglacial and Little Ice Age (LIA) glacial stages, respectively [18,19]. This provides a reliable chronological framework to estimate the Holocene glacier parameters and then to infer the climates that sustained the paleo-glacier extents.

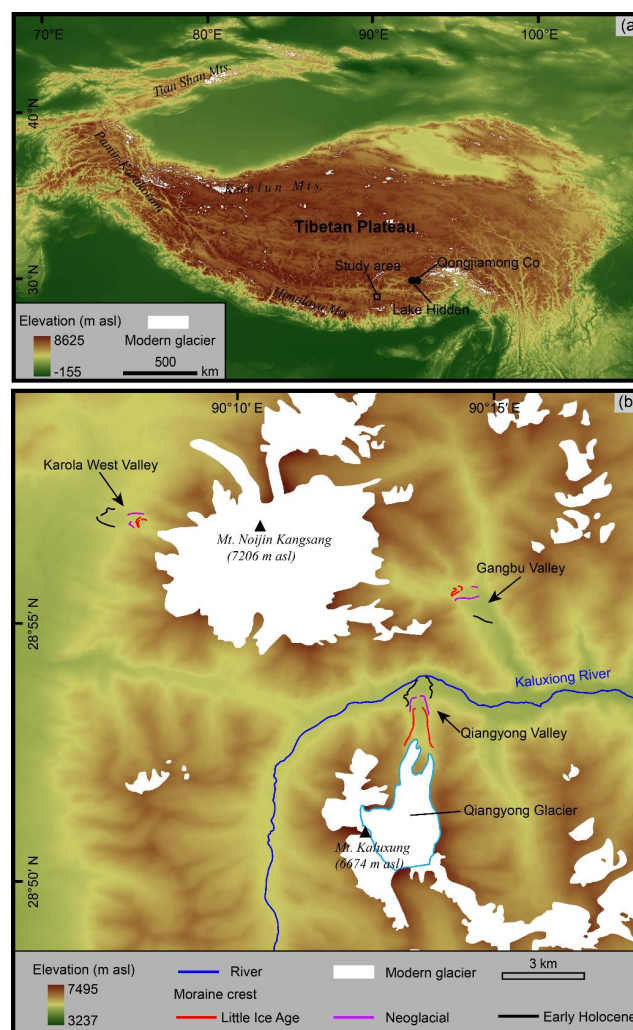


Figure 1. (a) Map showing the location of the study area (black box). The background map was drawn using the 30 m ASTER Global Digital Elevation Model V2 (<http://www.gscloud.cn/>). (b) Map showing the location of the dated moraines around the study area. Moraines in Qiangyong Valley were dated by Owen et al. (2005) [18], while moraines in Gangbu Valley and Karola West Valley were dated by Liu et al. (2017) [19]. The Kaluxiong River and moraine crests were delineated from Google Earth image.

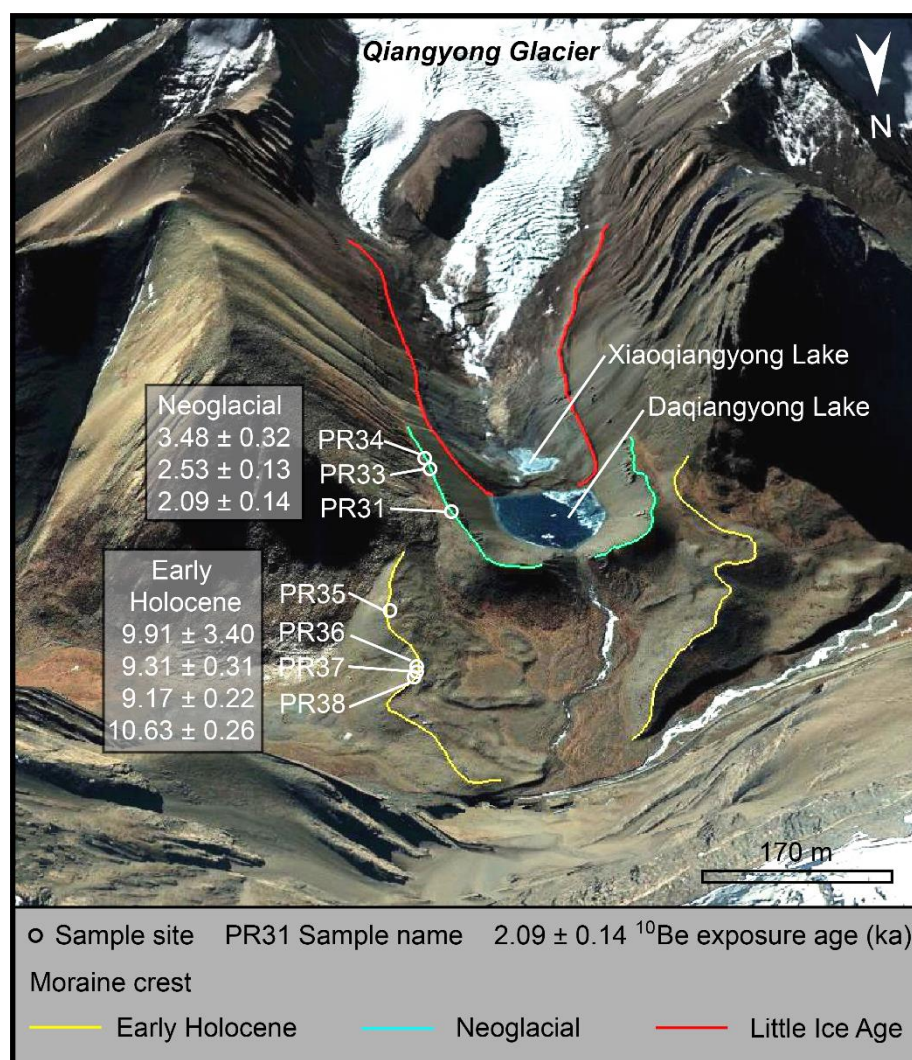


Figure 2. Oblique Google Earth image (vertical exaggeration = 1) showing lateral and frontal moraines in front of the Qiangyong Glacier. Age dating sample sites and ^{10}Be exposure ages from Owen et al. (2005) [18] were marked in the image.

3. Materials and Methods

3.1. Derivation of Glacier Bed Topography

Reconstruction of the paleo-glacier surface requires knowledge of past glacier basal topography. Thus, evidence of post-glacial geomorphologic activities, which would change the glacier bed topography, should be considered when tailoring present-day topography to the real paleo-glacier bed conditions. The ASTER Global Digital Elevation Model V2 (GDEM V2), with 30×30 m spatial resolution (downloaded from Geospatial Data Cloud, <http://www.gscloud.cn/>, and then trimmed slightly beyond the watershed of the Qiangyong Valley), was corrected to represent the paleo-glacier basal topography. In the study area, the thickness of the contemporary glacier and the depth of the two lakes, enclosed by the Neoglacial and LIA moraines, had to be subtracted from the GDEM V2 data to obtain the basal topography of reconstructed paleo-glaciers.

We calculated the contemporary glacier bed topography starting from the current surface topography given by the GDEM V2, and subtracting from it the current glacier thickness, as calculated applying the VOLTA model developed by James and Carrivick (2016) [23]. We used the glacier boundary of the glacier reported in the Randolph Glacier Inventory (RGI) version 6.0 [24]. In the

calculation, we used the VOLTA default method to assign the basal shear stress (τ_b) value on the flow line. The τ_b was calculated using the method proposed by Driedger and Kennard (1986) [25], who suggested separating the glacier in elevation bands with areas (A_i) and mean slopes (α_i) as follows:

$$\tau_b = 2.7 \times 10^4 \sum_{i=1}^n \left(\frac{A_i}{\cos \alpha_i} \right)^{0.106} \quad (1)$$

where the A_i is in m^2 and the τ_b is in Pa. The basal shear stress obtained for the modern glacier is 162 kPa.

To measure the depth of the two lakes, we used a sonar detection system with Global Navigation Satellite System that was carried on an unmanned surface vehicle. The measuring precision is of ± 1 cm, and the retrieved average depth of the two lakes was 3.90 m and 14.67 m for the Xiaoqiangyong and Daqiangyong lakes, respectively.

3.2. Reconstruction of Paleo-Glacier Surface

Paleo-glacier geometry reconstructions rely highly on morphologic evidence of former glacier extent (e.g., lateral and terminal moraines, glacier trimlines on bedrock). However, in reality, these glacial morphologic features are fragmentary and even totally missing, and often become degraded with time. In addition, these landforms often provide information exclusively along the margins of the paleo-glaciers, and the accuracy in reconstructing the surface topography sharply decreases with increasing distance from the margins, especially on the accumulation area. The best alternative is to use the available geomorphic evidence as constraints for numerical reconstructions of glacier thickness based on the mechanics of glacier flow [26,27]. The GlaRe, a GIS tool based on an iterative solution to the perfect plasticity assumption for glacier rheology [28], was utilized to numerically estimate the ice thickness distribution and paleo-glacier geometry for the three Holocene glacial events in the Qiangyong Valley. This tool first generates ice thicknesses along flow lines and then interpolate them towards the limits of the glacier. Specifically, the numerical approach iteratively solves the Equation (2) as a quadratic equation along the central glacier flowline.

$$h_{i+1}^2 - h_{i+1}(b_i + b_{i+1}) + h_i(b_{i+1} - H_i) - \frac{2\Delta x \tau_{av}}{Fg} = 0 \quad (2)$$

where h is ice surface elevation, b is glacier bed elevation, H is ice thickness (in meters), Δx is step length (in meters), τ_{av} is average basal shear stress over an interval (in Pa), F is shape factor of cross-section, g is gravity acceleration (9.81 ms^{-2}), and i is iteration step number. This is a derivation from the perfect plasticity assumption formula ($\tau = \rho g H \sin \alpha$) for the calculation of basal shear stress (τ) at the glacier bed [27], with ρ and α being ice density ($\sim 900 \text{ kgm}^{-3}$) and ice surface slope, respectively. Details and explanations on the derivation of Equation (2) can be found in Benn and Hulton (2010) [29] and Van Der Veen (2013) [30]. For the reconstruction of paleo-glacier surfaces, we manually drew the flowlines according to the convex and concave directions on topographic contours of the valley. To calculate the F , we made cross-sections orthogonal to the flowlines at an interval of 50 m.

For each paleo-glacier surface reconstruction, we applied the GlaRe tool using the catchment divide of the Qiangyong Valley, the lower point of the glacier as constrained by the frontal moraine, and the bedrock topography calculated by the VOLTA model as inputs. The glacier basal shear stress (τ_{av}), as a primary input to the GlaRe, makes the first-order control on the glacier surface elevation. Its values usually lie in the 50–150 kPa range for valley glaciers, indicated by field observational and experimental data [2,27]. Because the latero-frontal moraines of the three Holocene events can be clearly traced up to the contemporary glacier tongue, we tuned the τ_{av} on cross sections (with a 50 m step length) along the flow line, until the modeled ice thicknesses matched the heights of the lateral and frontal moraines. For the middle and upper parts of the paleo-glacier during each glacial stage, we used the basal shear stress value obtained at the upper end of the lateral moraine [29]. The shear

stress values that have been assigned along the flowlines of the three paleo-glaciers are shown in Figure 3.

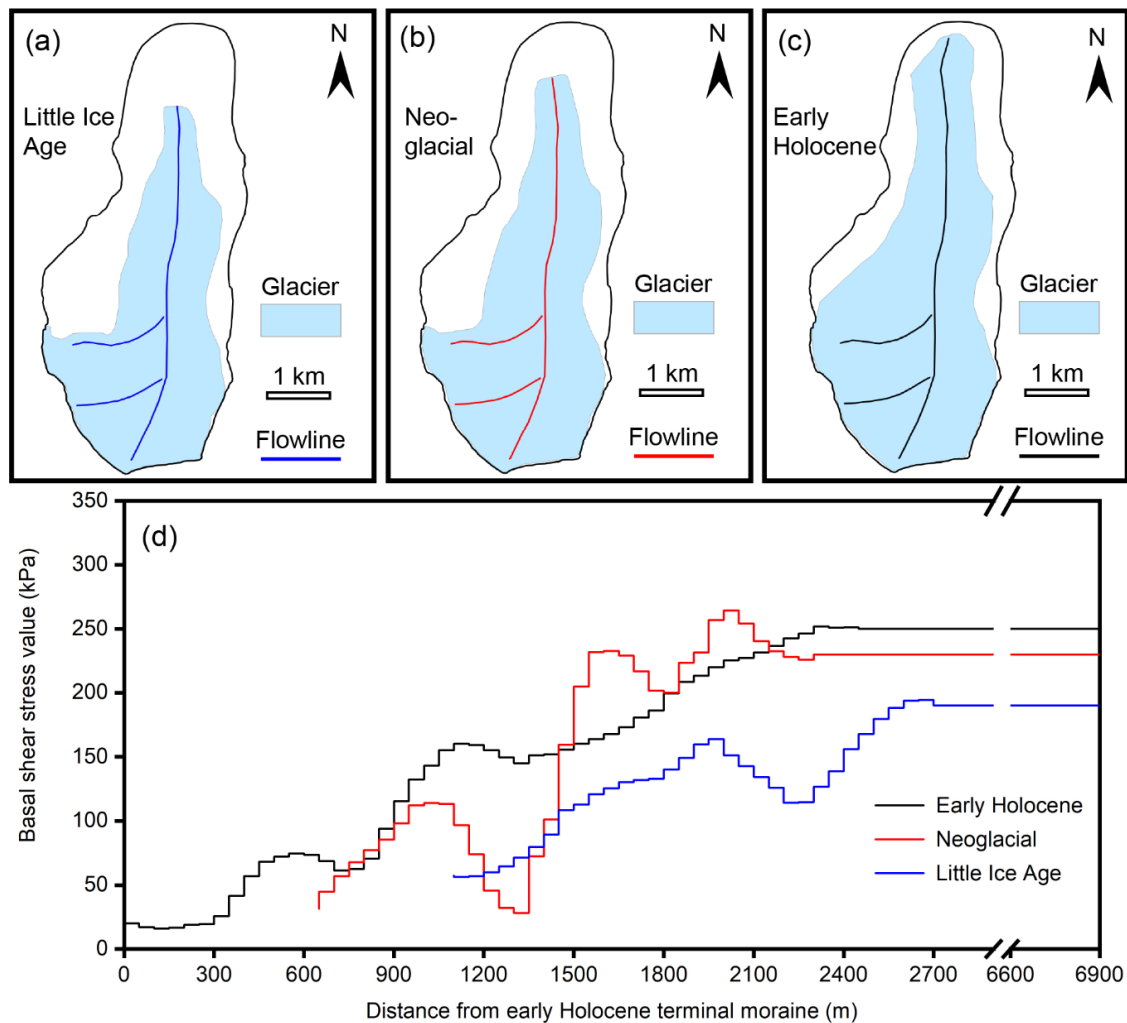


Figure 3. Glacier flowlines (a–c) and basal shear stress values along the glacier flowlines (d) of the three Holocene glaciers. The basal shear stress is kept unchanged above 2700 m.

For topographically constrained glaciers, such as valley glaciers, not all the glacier driving stress is supported by the basal shear stress, because significant resistance to flow is also provided by lateral drag effect. To consider this effect in the basal shear stress formula ($\tau = \rho g H \sin \alpha$), the F factor (shape friction factor) was incorporated into the formula to obtain the adjusted basal shear stress (τ_a)

$$\tau_a = \rho g F H \sin \alpha \quad (3)$$

$$F = \frac{A}{Hp} \quad (4)$$

where A is area of glacier cross-section (m^2) and p is perimeter of the cross-section (m) [2].

The GlaRe calculated the F factor on defined cross-sections and propagated values up the glacier until the next cross-section or the end of the flow line was reached. This tool automatically generated additional ice thickness points along the defined cross-sections, and thus helped to improve the interpolation accuracy, as errors in interpolation naturally increase with distance from an input point (on the flow line).

3.3. Reconstruction of Paleoglacier ELA and Paleoclimate

Reconstruction of ELA is a simple technique to reconstruct past climatic conditions from geomorphologic evidence of paleo-glacier extent, which is based on the fact that accumulation above the ELA must be compensated by equal ablation below the ELA in a steady state glacier condition. Since the study of Porter (1975) [31], the method has often been used and became a traditional method to assess climate during Quaternary glaciations. Benn et al. (2005) [32] reviewed the methods of ELA reconstruction for former glaciers. In this study, we use the accumulation area ratio (AAR) and area-altitude balance ratio (AABR) methods on the reconstructed glacier surfaces to estimate the ELAs for the three Holocene glacier events in the Qiangyong Valley. For the AAR method, we assumed that the zero-balance AAR ranges between 0.5 and 0.8, as suggested by Benn et al. (2005) [32], Osmaston (2005) [33], and Dyurgerov et al. (2009) [34]. For the AABR method, we used a balance ratio of 1.75 ± 0.71 , which is the average value provided by Rea (2009) [35]. These methods have been implemented for the paleo-glacier in the Qiangyong Valley using the GIS-based tool developed by Pellitero et al. (2015) [36].

The differences in ELA (ΔELA) between these Holocene and modern glaciers represent the climate shifts associated with the changes in the Holocene glacier geometry. Specifically, Ohmura et al. (1992) [37], using linear perturbation analytic mathematics, derived a formula to relate the ΔELA to changes in temperature (ΔT) and precipitation (ΔP) at the ELA

$$\Delta ELA = \frac{\Delta T - \Delta P \left(\frac{\partial P}{\partial T} \right)_{ELA}^{-1}}{\frac{\partial P}{\partial z} \left(\frac{\partial P}{\partial T} \right)_{ELA}^{-1} - \frac{\partial T}{\partial z}} \quad (5)$$

where $(\partial P / \partial T)_{ELA}$ is the gradient of the empirical function $f(P, T) = 0$ that formulates the relationship between annual precipitation and summer temperature at the glacier ELA, $\partial P / \partial z$ is the gradient of precipitation with elevation, and $\partial T / \partial z$ is the temperature lapse rate in a specific area. Ohmura et al. (1992) [37] suggested the $(\partial P / \partial T)_{ELA}^{-1}$ ranges from 2.5×10^{-3} to 3.3×10^{-3} °C/mm on the basis of the best-fit polynomial regression curve ($P = 645 + 296T + 9T^2$) for 70 globally-distributed glaciers. Using weather station records in the Kaluxiong River catchment, Zhang et al. (2015) [21] estimated the annual $\partial T / \partial z$ and $\partial P / \partial z$ to be -0.72 °C/100 m and 28 mm/year/100 m, respectively, using one year observation data on the glacier in 1975. We assumed that these parameters have not changed during the Holocene, and used the values reported by Zhang et al. (2015) [21] for calculating air temperature changes relative to the year of 1975 for the three Holocene paleo-glaciers, using Equation (5).

4. Results and Discussion

4.1. Glacier Extents of the Three Holocene Glacial Periods

The modern glacier thickness derived from the VOLTA model is shown in Figure 4. The VOLTA model estimated the modern glacier volume to be 3.0×10^8 m³, with maximum and average ice thickness being ~155 and ~47 m, respectively (Table 1).

Table 1. Reconstructed glacial extent parameters for the Qiangyong Glacier at different Holocene stages.

Glacial Stage	Area (km ²)	Volume (m ³)	Length (km)	Maximum Ice Thickness (m)	Average Ice Thickness (m)
Modern	6.25	3.0×10^8	4.7	~155	~47
Little Ice Age	7.68	4.6×10^8	5.7	~223	~60
Neoglacial	8.45	6.2×10^8	6.1	~246	~73
Early Holocene	10.00	8.1×10^8	6.8	~268	~83

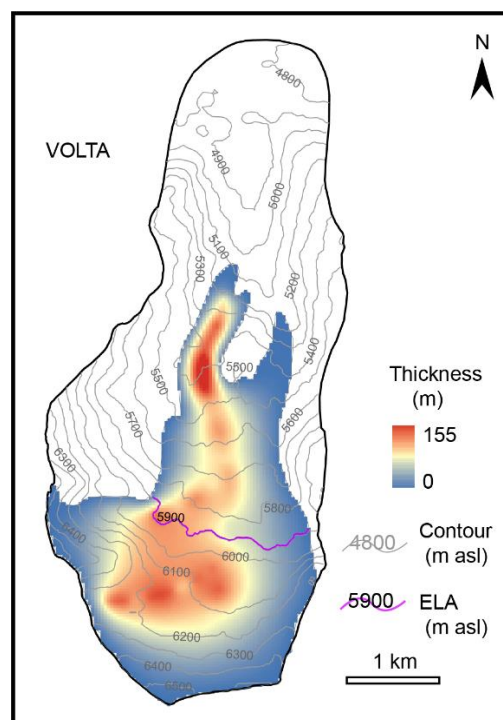


Figure 4. Modern glacier thickness derived from the VOLTA model and the reconstructed modern equilibrium line altitude (ELA) (accumulation area ratio (AAR) = 0.65, area-altitude balance ratio (AABR) = 1.75).

To evaluate the validity of the AAR and AABR methods in calculating ELAs, we compared the modern glacier ELAs, calculated by using the GIS-based tool, with the ELAs estimated by using mass balance field observations. By locating at which elevation belt the observed annual mass balances was zero, we found that the zero-balance elevations in 2005/2006 and 2007/2008 on Qiangyong Glacier were 6250–6300 and 5750–5800 m, respectively [38,39]. The specific mass balance was −478 mm in 2005/2006 (negative), and 443 mm in 2007/2008 (positive) on the whole glacier [38,39], indicating that the two years did certainly not show specific balanced-budget conditions. We believe that the modern balanced-budget ELA lies somewhere between the zero-balance elevations of the two years (5800 and 6250 m asl). Using the AAR and AABR methods, we estimated the modern ELAs to be between 5700–6100 m (Table 2), overlapping with the range of 5800–6250 m asl. This suggest that the AAR and AABR methods can be used to estimate the ELA changes in the Qiangyong Valley.

Table 2. Estimated equilibrium line altitude (ELA, in meters) using different AAR and AABR values.

Method	R/BR Value	Modern	Little Ice Age	Neoglacial	Early Holocene	Error #
AAR	0.50	6100	5935	5927	5919	±25
	0.60	5950	5835	5777	5769	±25
	0.65	5900	5735	5677	5669	±25
	0.70	5850	5635	5577	5519	±25
	0.80	5700	5435	5377	5319	±25
AABR	1.04	6000	5835	5827	5769	±25
	1.75	5900	5735	5687	5669	±25
	2.46	5850	5685	5637	5569	±25

Contour interval was 50 m in calculation of the ELAs, ±25 m was automatically assigned to the calculation error according to Pellitero et al. (2015) [36].

Figure 5 shows the reconstructed paleo-glacier surface elevations of the three Holocene paleo-glaciers. Based on the paleo-glacier surface elevations, the paleo-glacier parameters are estimated

and listed in Table 1. The early Holocene glacier occupied an area of 10.0 km² and had a volume of 8.1×10^8 m³. Relative to the early Holocene glacier, the Neoglacial glacier decreased to an area of 8.45 km², and the volume of this period decreased to 6.2×10^8 m³. The LIA glacier area continued to decrease to 7.68 km², and the ice volume was 4.6×10^8 m³. The estimated average ice thickness values range from 47 to 83 m between the reconstructed glaciers, while the maximum values vary widely from 223 to 268 m.

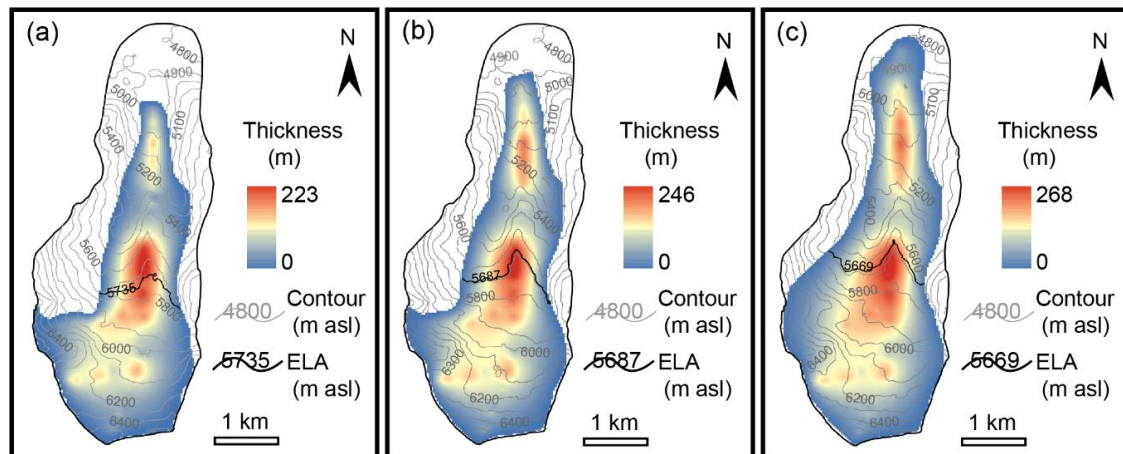


Figure 5. Reconstructed surfaces, ELAs (AABR = 1.75) and thicknesses of paleo-glaciers during Little Ice Age (a), Neoglacial (b) and early Holocene (c).

The estimated ELAs using different AAR and AABR values are listed in Table 2. Obviously, the ELA obtained with the AAR method for AAR varying between 0.5–0.8 ranges between a large elevation interval, 500–600 m on average. Considering the AAR of 0.65, the ELAs of the three paleo-glaciers are 5669, 5677, and 5735 m asl, respectively. Under the worldwide average AABR value of 1.75 [35], the ELAs for the three glacier periods are 5669, 5687, and 5735 m asl, respectively, which are comparable to the values from the AAR of 0.65. Compared to the modern glacier ELA of 5900 m asl (AAR = 0.65 or AABR = 1.75), the ELAs of the three paleo-glaciers were 230 ± 25 , 210 ± 25 , and 165 ± 25 m lower, respectively. The AABR method explicitly accounts for glacier surface hypsometry and uses glacier mass balance gradients with altitude below and above glacier ELA (BR value), thus yielding more reliable ELA reconstruction than the AAR method [33]. Considering an uncertainty (± 0.71) of the global-wide AABR value [35], the ELAs differ by 150–200 m, less than the ELAs difference (500–600 m) derived by the AAR (0.5–0.8) for each of the three glacier periods (Table 2). Therefore, we chose the AABR-derived ELA values to discuss the climate implications.

4.2. Climate Implications of the Three Glacial Events

To establish the climate scenarios for the three glacial events using Equation (5), we set the ΔP to be from -100 to 100 mm relatively to the modern annual mean precipitation (with an incremental change of 25 mm), and found the corresponding ΔT values for the respective paleo-glacier ELAs (Figure 6). Without precipitation change, the respective ELA changes required temperatures of 1.82–1.87, 1.66–1.71, and 1.30–1.34 °C lower than present for the three glacial events, with a range that depends on the $(\partial P / \partial T)_{ELA}^{-1}$ range of 2.5×10^{-3} – 3.3×10^{-3} °C/mm. If the annual precipitation were set to increase (decrease) by 100 mm, the summer temperature would be 1.54–1.57 (2.07–2.20), 1.38–1.41 (1.91–2.04), and 1.01–1.05 (1.55–1.67) °C lower than present to sustain the three glacial events. Therefore, the ELA shift is highly controlled by the summer temperature, as can be expected by the different coefficients for ΔT and ΔP in Equation (5).

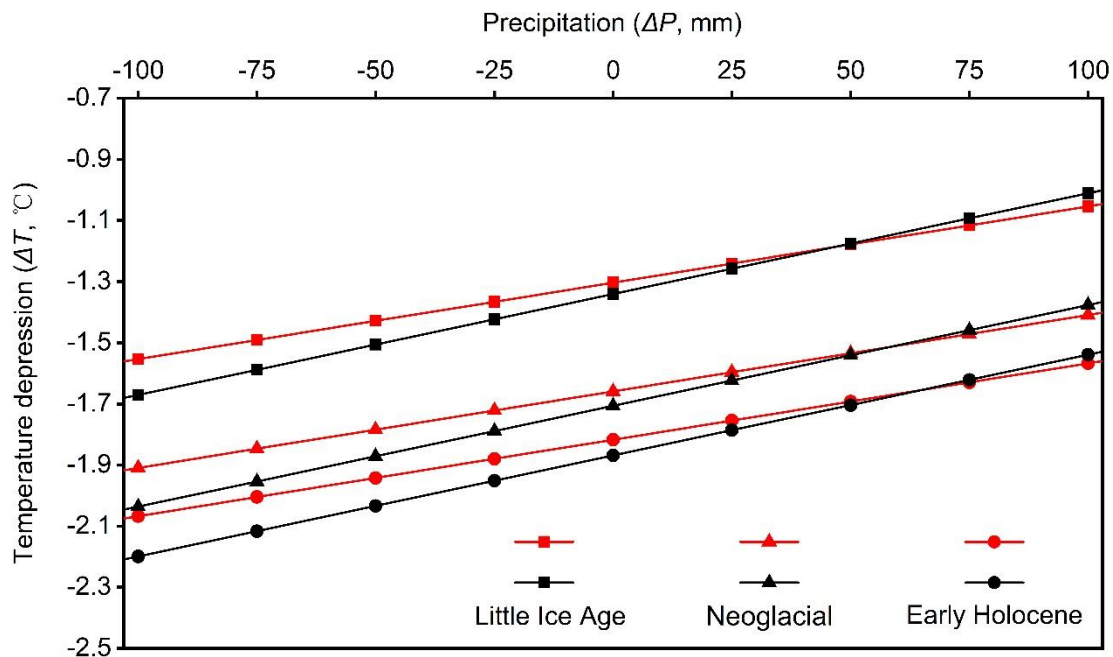


Figure 6. Plots of the temperature and precipitation combinations that yield Little Ice Age, Neoglacial and Early Holocene glacial extents in model simulations. Note that the red lines were plotted by using $(\partial P / \partial T)_{ELA}^{-1}$ value of $2.5 \times 10^{-3} \text{ }^{\circ}\text{C}/\text{mm}$, the black lines by $3.3 \times 10^{-3} \text{ }^{\circ}\text{C}/\text{mm}$. See the text for details.

The uncertainties of calculated ΔT and ΔP for the three Holocene glacial stages are determined by the errors in ELA, temperature lapse rate and precipitation gradient (Equation (5)). According to Pellitero et al. (2015) [36], the uncertainty in the estimated ELA mainly derives from the delineation of the paleo-glacier boundaries. Pellitero et al. (2015) [36] also suggested that the calculation error (i.e., the minimum error) is equal to the chosen contour interval. In calculation of the ELA, we used the contour interval of 50 m, so the uncertainty of the reconstructed ELA is about ± 25 m. Using Equation (5), we tested the sensitivity of the inferred paleoclimate to the uncertainties related to the ELA, temperature lapse rate and the precipitation gradient. The ± 25 m error in the ELA results in an uncertainty of $\pm 0.2 \text{ }^{\circ}\text{C}$ for the inferred temperature. Varying the temperature lapse rate of $\pm 0.10 \text{ }^{\circ}\text{C}/100 \text{ m}$ makes the inferred temperature change by $\pm 0.23 \text{ }^{\circ}\text{C}$; similarly, varying the precipitation gradient by $\pm 10 \text{ mm/year}/100 \text{ m}$, leads to variations in the inferred temperature of $\pm 0.06 \text{ }^{\circ}\text{C}$. We therefore suggest that the uncertainty in the inferred summer temperature change (ΔT) for each of the Holocene glacial stages is of about $\pm 0.53 \text{ }^{\circ}\text{C}$.

Equation (5) gives no unique paleoclimate solution for each of the three glacial events. The estimates of $\Delta T - \Delta P$ combinations shown in Figure 6 are just possible climatic scenarios. However, these solutions for $\Delta T - \Delta P$ combinations are valuable in assessing other quantitative climatic-proxy-based reconstructions. Using pollen assemblage data from lake and peat sediments, Chen et al. (2020) [40] quantitatively reconstructed the summer temperature changes and annual precipitation variations during the Holocene period at different parts of the TP. For the southern TP and nearest to our study area, the Lake Hidden and Qongjiamong Co were chosen by Chen et al. (2020) [40] to reconstruct the Holocene summer temperature and annual precipitation changes. The pollen-based climate reconstructions from Lake Hidden showed that the average annual precipitation was 98, 109, and 11 mm higher than the present during the early Holocene (10.8–8.9 ka), Neoglacial (3.7–1.9 ka) and LIA (0.4–0.1 ka), respectively; from Qongjiamong Co, the corresponding values were 20, 13, 0.9 mm higher than the present, respectively. If these values were correct, the model of Equation (5) would predict that the summer temperature was 1.56–1.79, 1.37–1.64, 1.29–1.32 $^{\circ}\text{C}$ lower than the present during the three Holocene glacial stages, respectively. This suggests an increasing temperature trend between the three Holocene glacial periods. The summer temperature in the Hidden Lake

area was averagely 0.90, 0.38, 0.13 °C lower than present in the three Holocene glacial periods, respectively; and in the Qongjiamong Co area, it was averagely 0.11, 0.59 °C higher than present in the early Holocene and Neoglacial periods, but slightly lower (0.03 °C) than present in the LIA. Therefore, the lake pollen-based summer temperature reconstructions, especially from Lake Hidden, also indicate an increasing temperature trend between the three Holocene glacial periods (Figure 7). Despite this increasing trend in both of the reconstructions, the amplitudes of the ELA-based summer temperature depressions relative to the present are much larger than the pollen-based counterparts (0.90, 0.38, 0.13 °C at Lake Hidden site) during the three glacial stages. Such difference between the ELA-based and pollen-based reconstructions may partly result from the accuracy of the ^{10}Be exposure ages for the three glacial stages. For example, the ^{10}Be ages frame, provided by Owen et al. (2005) [18] and Liu et al. (2017) [19], can be estimated to be systematically older than published ones (Table S1), when recalculated with the updated ^{10}Be production scaling models in the online calculator of CRONUS-Earth V3 [41]. Specifically, the recalculated sample ages for the LIA, Neoglacial and early Holocene stages respectively become a few decades, about 1000 years and 3000 years older than the corresponding ages published by Owen et al. (2005) [18] and Liu et al. (2017) [19]. This is caused by different ^{10}Be production scaling models. Until now, there is no consensus about which scaling model is the best [42]. Moreover, when establishing the pollen-climate functions, the inherent “edge effects” within weighted averaging partial least squares (WA-PLS) method would overestimate the target climatic variable (temperature or precipitation) at its low-gradient end and underestimate it at the high-gradient end [40,43]. These factors may all contribute to the difference between the ELA-based and pollen-based reconstructions. Therefore, more investigations are encouraged to understand the possible reasons for the detected discrepancies between the glacier-model based and pollen-based temperature reconstructions.

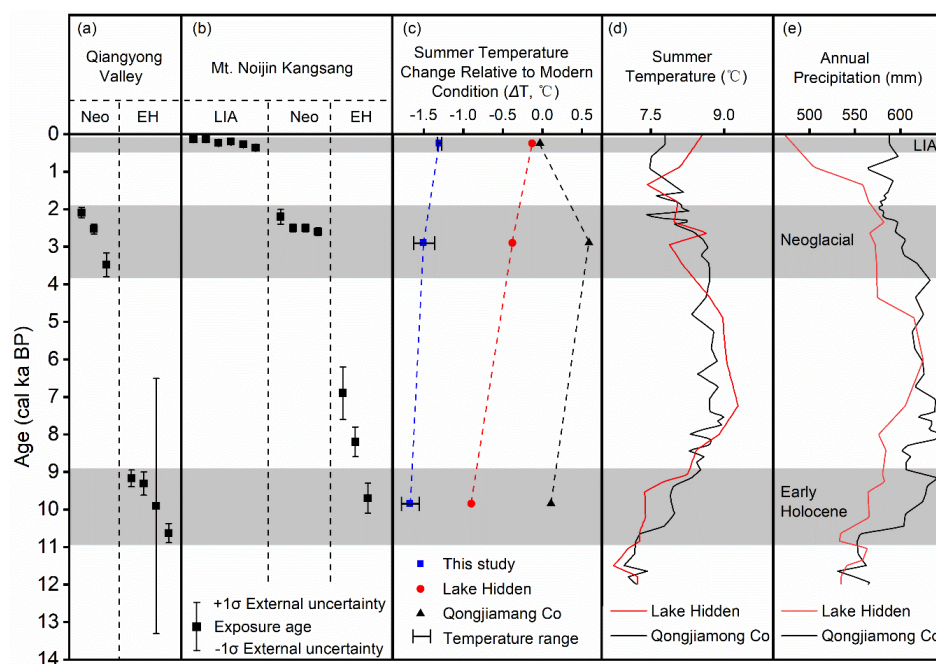


Figure 7. Plots showing the published ^{10}Be exposure ages (with 1σ external uncertainties) from Qiangyong Valley (a, Data from Owen et al. (2005) [18]) and Mt. Noijin Kangsang (b, Data from Liu et al. (2017) [19]), Neo—Neoglacial, EH—Early Holocene, LIA—Little Ice Age; comparison of the ELA-based with the pollen-based summer temperature changes relative to the modern conditions for the three Holocene glacial periods, with the red dots and black triangulars being the respective average values of these changes in Lake Hidden and Qongjiamong Co areas (c); and the pollen-based summer temperature (d) and annual precipitation (e) during the Holocene period from Lake Hidden and Qongjiamong Co (Data from Chen et al. (2020) [40]).

5. Conclusions

On the basis of ^{10}Be exposure age frame for Holocene moraines [18,19], we have reconstructed paleo-glacier surfaces for three Holocene glacial stages in the Qiangyong Valley, southern TP, using the GIS tool GlaRe [28]. On the reconstructed paleo-glacier surfaces, the ELAs were derived using the AAR ($0.5\text{--}0.8$) and AABR (1.75 ± 0.71) methods for the three glacial stages. Constrained by the Holocene moraine positions, the model results suggested that the Qiangyong Valley contained ice volumes of 8.1×10^8 , 6.2×10^8 , and $4.6 \times 10^8 \text{ m}^3$ with glacier areas of 10.0, 8.45, and 7.68 km^2 during the early Holocene, Neoglacial, and LIA glacial stages, respectively. The ELA depressions compared to current glacier geometry were 230 ± 25 , 210 ± 25 , and $165 \pm 25 \text{ m}$ during the three Holocene glacial stages, respectively. Without precipitation changes relative to the present, these ELA depressions would have required temperature of $1.82\text{--}1.87$, $1.66\text{--}1.71$, and $1.30\text{--}1.34 \text{ }^\circ\text{C}$ lower than at present for the three glacial stages. Lower temperature depressions ($1.56\text{--}1.79$, $1.37\text{--}1.64$, and $1.29\text{--}1.32 \text{ }^\circ\text{C}$) would have been required to support the three reconstructed glacial stages when using precipitation anomalies inferred from pollen data, which suggests higher precipitation in the past compared to current conditions. By testing the sensitivity of the inferred temperature change (ΔT) to the ELA, temperature lapse rate and precipitation gradient, we suggested that the uncertainty in the ΔT for each of the Holocene glacial stages is of about $\pm 0.53 \text{ }^\circ\text{C}$. Moreover, we found that the amplitudes of the ELA-based summer temperature depressions were much larger than the pollen-based counterparts during the three glacial stages, although the summer temperature reconstructions from the two methods both showed an increasing trend between the three Holocene glacial stages. Therefore, we highlight that the glacier ELA-climate model is valuable for quantitatively assessing other independent proxy-based climate reconstructions.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4441/12/11/3205/s1>, Table S1: Recalculated previously published ^{10}Be surface exposure ages near the Qiangyong Valley.

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References

1. IPCC. *The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2013. [CrossRef]
2. Cuffey, K.M.; Paterson, W.S.B. *The Physics of Glaciers*, 4th ed.; Butterworth-Heinemann/Elsevier: Boston, MA, USA, 2010.
3. Shi, Y. Characteristics of late Quaternary monsoonal glaciation on the Tibetan Plateau and in East Asia. *Quatern. Int.* **2002**, *97–98*, 79–91. [CrossRef]
4. Thackray, G.D.; Owen, L.A.; Yi, C. Timing and nature of late Quaternary mountain glaciation. *J. Quat. Sci.* **2008**, *23*, 503–508. [CrossRef]
5. Owen, L.A.; Caffee, M.W.; Finkel, R.C.; Seong, Y.B. Quaternary glaciation of the Himalayan-Tibetan orogen. *J. Quat. Sci.* **2008**, *23*, 513–531. [CrossRef]
6. Owen, L.A. Latest Pleistocene and Holocene glacier fluctuations in the Himalaya and Tibet. *Quat. Sci. Rev.* **2009**, *28*, 2150–2164. [CrossRef]

7. Zhou, S.; Chen, F.; Pan, B.; Cao, J.; Li, J.; Derbyshire, E. Environmental change during the Holocene in western China on a millennial timescale. *Holocene* **1991**, *1*, 151–156. [[CrossRef](#)]
8. Yi, C.; Chen, H.; Yang, J.; Liu, B.; Fu, P.; Liu, K.; Li, S. Review of Holocene glacial chronologies based on radiocarbon dating in Tibet and its surrounding mountains. *J. Quat. Sci.* **2008**, *23*, 533–543. [[CrossRef](#)]
9. Thompson, L.G.; Yao, T.; Davis, M.E.; Henderson, K.A.; Mosley-Thompson, E.; Lin, P.-N.; Beer, J.; Synal, H.-A.; Cole-Dai, J.; Bolzan, J.F. Tropical Climate Instability, The Last Glacial Cycle from a Qinghai-Tibetan Ice Core. *Science* **1997**, *276*, 1821–1825. [[CrossRef](#)]
10. Seong, Y.B.; Owen, L.A.; Yi, C.; Finkel, R.C. Quaternary glaciation of Muztag Ata and Kongur Shan: Evidence for glacier response to rapid climate changes throughout the Late Glacial and Holocene in westernmost Tibet. *Geol. Soc. Am. Bull.* **2009**, *121*, 348–365. [[CrossRef](#)]
11. Bond, G.; Kromer, B.; Beer, J.; Muscheler, R.; Evans, M.N.; Showers, W.; Hoffmann, S.; Lotti-Bond, R.; Hajdas, I.; Bonani, G. Persistent solar influence on North Atlantic climate during the Holocene. *Science* **2001**, *294*, 2130–2136. [[CrossRef](#)]
12. Thompson, L.G.; Mosley-Thompson, E.; Davis, M.E.; Bolzan, J.F.; Dai, J.; Klein, L.; Yao, T.; Wu, X.; Xie, Z.; Gundestrup, N. Holocene–late pleistocene climatic ice core records from qinghai-tibetan plateau. *Science* **1989**, *246*, 474–477. [[CrossRef](#)]
13. Owen, L.A.; Dortch, J.M. Nature and timing of Quaternary glaciation in the Himalayan–Tibetan orogen. *Quat. Sci. Rev.* **2014**, *88*, 14–54. [[CrossRef](#)]
14. Finkel, R.C.; Owen, L.A.; Barnard, P.L.; Caffee, M.W. Beryllium-10 dating of Mount Everest moraines indicates a strong monsoon influence and glacial synchronicity throughout the Himalaya. *Geology* **2003**, *31*, 561–564. [[CrossRef](#)]
15. Yang, J.; Zhang, W.; Cui, Z.; Yi, C.; Liu, K.; Ju, Y.; Zhang, X. Late Pleistocene glaciation of the Diancang and Gongwang Mountains, southeast margin of the Tibetan plateau. *Quatern. Int.* **2006**, *154–155*, 52–62. [[CrossRef](#)]
16. Xu, X.; Yi, C. Little Ice Age on the Tibetan Plateau and its bordering mountains: Evidence from moraine chronologies. *Glob. Planet Chang.* **2014**, *116*, 41–53. [[CrossRef](#)]
17. Saha, S.; Owen, L.A.; Orr, E.N.; Caffee, M.W. High-frequency Holocene glacier fluctuations in the Himalayan–Tibetan orogen. *Quat. Sci. Rev.* **2019**, *220*, 372–400. [[CrossRef](#)]
18. Owen, L.A.; Finkel, R.C.; Barnard, P.L.; Ma, H.; Asahi, K.; Caffee, M.W.; Derbyshire, E. Climatic and topographic controls on the style and timing of Late Quaternary glaciation throughout Tibet and the Himalaya defined by ^{10}Be cosmogenic radionuclide surface exposure dating. *Quat. Sci. Rev.* **2005**, *24*, 1391–1411. [[CrossRef](#)]
19. Liu, J.; Yi, C.; Li, Y.; Bi, W.; Zhang, Q.; Hu, G. Glacial fluctuations around the Karola Pass, eastern Lhagoi Kangri Range, since the Last Glacial Maximum. *J. Quat. Sci.* **2017**, *32*, 516–527. [[CrossRef](#)]
20. Li, J.; Zheng, B.; Yang, X. *Glaciers in Tibet*; Science Press: Beijing, China, 1986.
21. Zhang, F.; Zhang, H.; Hagen, S.C.; Ye, M.; Wang, D.; Gui, D.; Zeng, C.; Tian, L.; Liu, J. Snow cover and runoff modelling in a high mountain catchment with scarce data: Effects of temperature and precipitation parameters. *Hydrol. Process* **2015**, *29*, 52–65. [[CrossRef](#)]
22. Zheng, B. The influence of Himalayan uplift on the development of Quaternary glaciers. *Z. Geomorphol.* **1989**, *76*, 89–115.
23. James, W.H.M.; Carrivick, J.L. Automated modelling of spatially-distributed glacier ice thickness and volume. *Comput. Geosci-UK* **2016**, *92*, 90–103. [[CrossRef](#)]
24. RGI Consortium. Randolph Glacier Inventory—A Dataset of Global Glacier Outlines: Version 6.0: Technical Report. *Glob. Land Ice Meas. Space* **2017**. [[CrossRef](#)]
25. Driedger, C.L.; Kennard, P.M. Glacier volume estimation on Cascade volcanoes: An analysis and comparison with other methods. *Ann. Glaciol.* **1986**, *8*, 59–64. [[CrossRef](#)]
26. Nye, J.F. A method of calculating the thicknesses of the ice-sheets. *Nature* **1952**, *169*, 529–530. [[CrossRef](#)]
27. Nye, J.F. The mechanics of glacier flow. *J. Glaciol.* **1952**, *2*, 82–93. [[CrossRef](#)]
28. Pellitero, R.; Rea, B.R.; Spagnolo, M.; Bakke, J.; Ivy-Ochs, S.; Frew, C.R.; Hughes, P.; Ribolini, A.; Lukas, S.; Renssen, H. GlaRe, a GIS tool to reconstruct the 3D surface of palaeoglaciers. *Comput. Geosci-UK* **2016**, *94*, 77–85. [[CrossRef](#)]
29. Benn, D.I.; Hulton, N.R.J. An ExcelTM spreadsheet program for reconstructing the surface profile of former mountain glaciers and ice caps. *Comput. Geosci-UK* **2010**, *36*, 605–610. [[CrossRef](#)]

30. Van Der Veen, C.J. *Fundamentals of Glacier Dynamics*, 2nd ed.; Balkema: Rotterdam, The Netherlands, 2013.
31. Porter, S.C. Equilibrium line altitudes of late Quaternary glaciers in the Southern Alps, New Zealand. *Quat. Res.* **1975**, *5*, 27–47. [[CrossRef](#)]
32. Benn, D.I.; Owen, L.A.; Osmaston, H.A.; Seltzer, G.O.; Porter, S.C.; Mark, B. Reconstruction of equilibrium-line altitudes for tropical and sub-tropical glaciers. *Quatern. Int.* **2005**, *138–139*, 8–21. [[CrossRef](#)]
33. Osmaston, H. Estimates of glacier equilibrium line altitudes by the Area×Altitude, the Area×Altitude Balance Ratio and the Area×Altitude Balance Index methods and their validation. *Quatern. Int.* **2005**, *138–139*, 22–31. [[CrossRef](#)]
34. Dyurgerov, M.; Meier, M.F.; Bahr, D.B. A new index of glacier area change: A tool for glacier monitoring. *J. Glaciol.* **2009**, *55*, 710–716. [[CrossRef](#)]
35. Rea, B.R. Defining modern day Area-Altitude Balance Ratios (AABRs) and their use in glacier-climate reconstructions. *Quat. Sci. Rev.* **2009**, *28*, 237–248. [[CrossRef](#)]
36. Pellitero, R.; Rea, B.R.; Spagnolo, M.; Bakke, J.; Hughes, P.; Ivy-Ochs, S.; Lukas, S.; Ribolini, A. A GIS tool for automatic calculation of glacier equilibrium-line altitudes. *Comput. Geosci-UK* **2015**, *82*, 55–62. [[CrossRef](#)]
37. Ohmura, A.; Kasser, P.; Funk, M. Climate at the Equilibrium Line of Glaciers. *J. Glaciol.* **1992**, *38*, 397–411. [[CrossRef](#)]
38. Yao, T.; Thompson, L.; Yang, W.; Yu, W.; Gao, Y.; Guo, X.; Yang, X.; Duan, K.; Zhao, H.; Xu, B.; et al. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nat. Clim. Chang.* **2012**, *2*, 663–667. [[CrossRef](#)]
39. Yao, T. Dataset of typical glacier changes on Tibetan Plateau and Its surrounding areas (2005–2016). *Natl. Tibetan Plateau Data Cent.* **2018**. [[CrossRef](#)]
40. Chen, F.; Zhang, J.; Liu, J.; Cao, X.; Hou, J.; Zhu, L.; Xu, X.; Liu, X.; Wang, M.; Wu, D.; et al. Climate change, vegetation history, and landscape responses on the Tibetan Plateau during the Holocene: A comprehensive review. *Quat. Sci. Rev.* **2020**, *243*, 1–21. [[CrossRef](#)]
41. Balco, G.; Stone, J.O.; Lifton, N.A.; Dunai, T.J. A complete and easily accessible means of calculating surface exposure ages or erosion rates from ^{10}Be and ^{26}Al measurements. *Quat. Geochronol.* **2008**, *3*, 174–195. [[CrossRef](#)]
42. Balco, G. Glacier change and paleoclimate applications of Cosmogenic-nuclide exposure dating. *Annu. Rev. Earth Planet Sci.* **2020**, *48*, 21–48. [[CrossRef](#)]
43. Birks, H.J.B. Numerical tools in palaeolimnology—Progress, potentialities, and problems. *J. Paleolimnol.* **1998**, *20*, 307–332. [[CrossRef](#)]

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