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Marked acceleration in glacier mass loss across High Mountain Asia since 2000

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Abstract

High Mountain Asia (HMA) contains the largest concentration of glaciers outside the polar regions and is vital in sustaining downstream water resources. However, glacier responses to climate change across HMA exhibit pronounced spatial and temporal heterogeneity, the drivers of which remain insufficiently understood. Using the Open Global Glacier Model (OGGM), we reconstructed glacier mass balance, volume changes, and runoff variations from 1980 to 2019, and further assessed regional glacier sensitivity to temperature and precipitation through perturbation experiments. The results reveal that glacier mass loss accelerated notably after 2000, indicating a clear phase shift. Glacier volume changes display a clear west-to-east zonation, with volume gains in the western regions, initial increases followed by decreases in the central regions, and continuous loss in the eastern regions. Annual glacier runoff increased across most basins, accompanied by declining contributions in July and August, and a corresponding rise in June and September, reflecting a shift in meltwater production timing. Sensitivity analysis revealed that the strongest temperature sensitivity occurs in the southeastern HMA, while the highest precipitation sensitivity is observed in the southern areas. The combination of intensified post-2000 warming and regionally divergent climate sensitivities explains the acceleration and heterogeneity of glacier loss. These findings provide insights into the temporally phased and spatially heterogeneous glacier-climate interactions in HMA, with important implications for future regional climate adaptation.

Keywords:

Glacier mass balance, glacier volume changes, post-2000 acceleration, climate sensitivity, High Mountain Asia, OGGM

1. Introduction

High Mountain Asia (HMA) hosts the largest concentration of glaciers outside the polar regions, with over 95,000 glaciers covering approximately 97,000 km² (RGI Consortium, 2017), mainly distributed across the Pamir, Karakoram and Himalaya, (Nie et al., 2021). These glaciers act as critical freshwater reservoirs, regulating runoff and sustaining major Asian rivers, such as the Indus, Ganges, Brahmaputra, Yellow River, and Yangtze River (Farinotti et al., 2019; Immerzeel et al., 2020; Pritchard, 2019). However, under intensified global warming, glaciers across HMA are undergoing widespread and rapid changes, affecting both mountain ecosystems and downstream socio-economic systems through altered seasonal water availability (Miles et al., 2021; Pritchard, 2019).

Globally, glacier mass loss has accelerated since the early 21st century, primarily driven by climate warming (Hugonnet et al., 2021). This global acceleration is also reflected in many mountain regions worldwide. For instance, glaciers in the European Alps and Alaska have experienced substantial mass loss and volume decline in recent decades (Wouters et al., 2019; Zemp et al., 2019). In the southern Andes, glacier mass loss has been substantial over the past two decades, with an accelerated shift to strongly negative balances in recent years that coincided with prolonged and severe drought conditions (Dussaillant et al., 2019). A notable exception occurs in New Zealand, where several glaciers advanced during recent decades in response to short-term cooling events rather than increased precipitation (Mackintosh et al., 2018). These studies highlight the strong sensitivity of glacier systems to climatic forcing, underscoring the importance of assessing regional variations in glacier climate interactions (Nie et al., 2021). Within this global context, HMA stands out as one of the regions experiencing the most rapid glacier changes, making it essential to understand how its glaciers

respond to ongoing climatic forcing.

In HMA, recent annual warming rate over recent decades has significantly exceeded the global average, accompanied by notable changes in precipitation regimes (Yang et al., 2014; Yao et al., 2022; You et al., 2020). These rapid adjustments in the climate system directly influence glacier mass balance, leading to widespread glacier retreat and mass loss across this region (Hugonnet et al., 2021; Shean et al., 2020). Both remote sensing and in-situ observations indicate that the most glaciers in the HMA region exhibit negative mass balances (Brun et al., 2017; Hugonnet et al., 2021). Glaciers in HMA are particularly sensitive to temperature changes, with rising summer temperatures significantly enhancing melt processes (Bhattacharya et al., 2021). Although increased precipitation under certain temperature conditions can partially offset glacier mass loss, this compensatory effect remains spatially heterogeneous (Marzeion et al., 2014; Sakai and Fujita, 2017).

Despite the overall retreat, the response of HMA glaciers to climate change exhibits marked regional heterogeneity. In western regions, such as the Karakoram, glaciers have shown stable or even slightly positive mass balances in recent decades, a phenomenon referred to as the ‘Karakoram Anomaly’ (Arndt & Schneider, 2023; Farinotti et al., 2020; Lhakpa et al., 2022). In contrast, glaciers in the eastern and southern HMA, such as the Hengduan Shan and the eastern Himalayas, have experienced rapid mass loss and volume decline, making them among the most severely affected regions (Bolch et al., 2019; Shean et al., 2020). While these spatial contrasts are primarily attributed to the interplay of regional climate systems (westerlies, Indian monsoon, and east Asian monsoon), and glacier characteristics (Bolch et al., 2012; Sakai and Fujita, 2017), a systematic quantification of how glaciers in these distinct regimes differentially respond to climate drivers is still lacking. Specifically, it remains

unclear to what extent the observed heterogeneity is driven by varying sensitivities to temperature versus precipitation anomalies across the vast HMA region. Clarifying the relative roles of these competing drivers through systematic identification and quantification of spatiotemporal variability is crucial for improving our understanding of glacier responses to future climate change.

Traditional approaches to studying glacier changes include in-situ glaciological measurements, geodetic assessments using multi-temporal DEMs, and numerical model simulations. While glaciological records offer high accuracy, their sparse spatial coverage, especially in HMA, limits their representativeness (Zemp et al., 2015). Geodetic methods enable large-scale assessments but are constrained by resolution and temporal gaps (Paul et al., 2013). Numerical models, such as the Global Glacier Evolution Model (GloGEM) (Huss and Hock, 2015), Open Global Glacier Model (OGGM) (Maussion et al., 2019), and Open-Source Python Glacier Evolution Model (PyGEM) (Rounce et al., 2020), provide dynamic reconstructions across spatial and temporal scales and have become increasingly important tools for investigating glacier-climate interactions. However, while these models are increasingly used for mass balance reconstruction and projection, few studies have leveraged them to conduct systematic perturbation experiments to isolate the specific sensitivities of glaciers to temperature and precipitation anomalies across HMA.

Building upon recent modeling advances and addressing this need for mechanistic understanding, this study applies OGGM to reconstruct glacier mass balance, volume changes, and runoff dynamics across HMA from 1980 to 2019. Crucially, we conduct temperature and precipitation perturbation experiments to evaluate regional differences in climate sensitivity. Through this approach, the study aims to: (1) provide a long-term assessment of glacier mass balance and volume change across HMA; (2) quantify the

spatiotemporal evolution of glacier runoff; (3) elucidate regional differences in glacier sensitivity to temperature and precipitation.

2. Materials and methods

2.1 Study region and dataset

2.1.1 Study region

This study focuses on the HMA region, encompassing three regions: Central Asia, Western South Asia, and Eastern South Asia. Geographically, the study domain extends from 65°E to 105°E and from 26°N to 46°N ([Figure 1](#)), covering key mountain ranges including the Pamirs, Tien Shan, Kunlun Shan, Karakoram, Himalayas, and Hengduan Shan. The region is characterized by complex terrain, substantial elevation gradients, and highly diverse climate systems. Glaciers in HMA contribute significantly to regional hydrology and are subject to markedly different climatic regimes ([Yao et al., 2012](#)). This region plays a critical role in sustaining water resources for downstream populations, particularly in arid and semi-arid basins that depend heavily on glacier meltwater ([Immerzeel et al., 2010](#)). In addition, its pronounced spatial contrasts in the interactions between glaciers and climate provide an ideal setting for examining how glaciers respond differently to temperature and precipitation variability ([Kääb et al., 2012](#)).

In the western part, glacier accumulation is predominantly influenced by the westerlies. For example, in the western Himalayas and the Karakoram, 60~70% of annual snowfall originates from mid-latitude westerly disturbances ([Bolch et al., 2012](#); [Cannon, 2025](#); [Kapnick et al., 2014](#); [Maussion et al., 2014](#)). In contrast, the eastern Himalayas are strongly affected by the Indian monsoon ([Bookhagen and Burbank, 2006](#)), while the Hengduan Shan is mainly influenced by the East Asia monsoon ([Shean](#)

et al., 2020). These diverse climatic regimes directly influence regional differences in glacier accumulation and ablation. Assessing the full HMA domain therefore enables a consistent comparison across these contrasting climate zones, which is essential for understanding the spatial heterogeneity of glacier change.

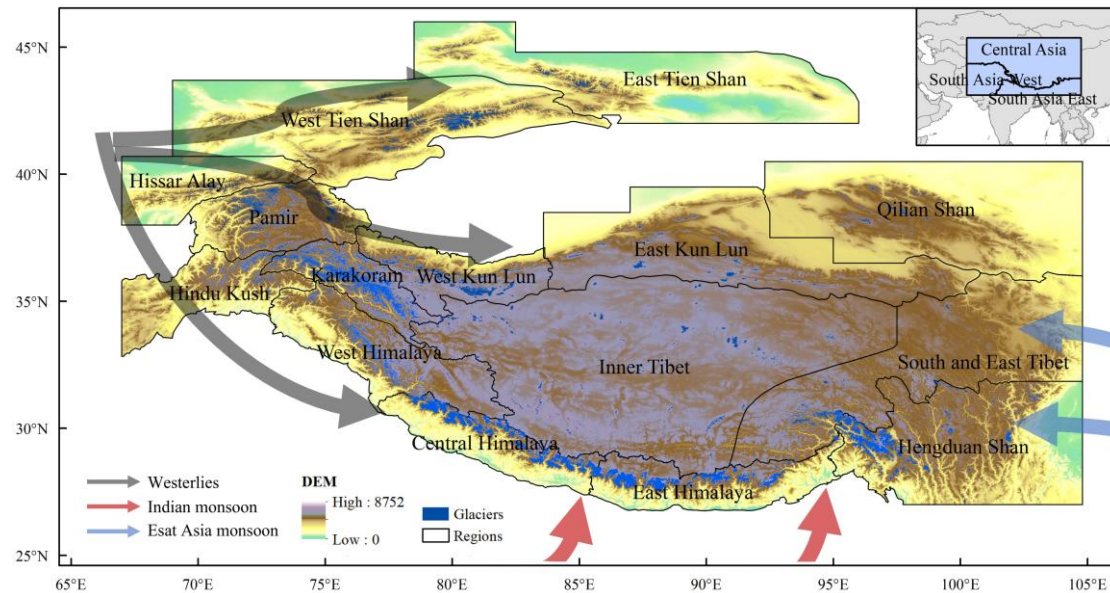


Figure 1. Study region and major climatic influences in the HMA.

2.1.2 Dataset

This study employs the GSWP3 W5E5 climate dataset as the climate forcing to drive the OGGM model. This dataset is provided by the ISIMIP 3b (Inter-Sectoral Impact Model Intercomparison Project Phase 3b) project (Lange, 2019), with a spatial resolution of 0.5°. The W5E5 dataset combines ERA5 reanalysis with WFDE5 bias-adjusted data, providing consistent and high-quality near-surface climate variables (Cucchi et al., 2020). It offers continuous long-term records of temperature and precipitation and has been widely used in glacier modeling, hydrology, and climate impact assessments due to its broad spatial coverage and reliability. For each glacier, the nearest meteorological grid point is selected based on geographic coordinates. Temperature adjustments were made using a vertical lapse rate of 0.65°C per 100 meters,

while precipitation was calibrated using a precipitation correction factor P_f , ultimately obtaining temperature and precipitation for each glacier (Huss and Hock, 2015; Maussion et al., 2019). Although temperature lapse rates vary across space and seasons in mountain regions (Oulkar et al., 2024), the use of a constant lapse rate remains common practice in global and regional glacier modeling because long-term and large-scale observations are limited (Huss and Hock 2018; Rounce et al., 2020). In addition, the mass balance module in OGGM incorporates a calibrated temperature bias, which helps compensate for this limitation to some extent. Detailed explanations of these adjustments can be found on the OGGM website (<https://oggm.org>). For the analysis of climate trends, this study incorporates the CRU V4 (Harris et al., 2020) and MERRA-2 (Gelaro et al., 2017) datasets in addition to W5E5, in order to reduce biases associated with any single climate product. Both datasets have a monthly temporal resolution, with spatial resolutions of $0.5^\circ \times 0.5^\circ$ and $0.5^\circ \times 0.625^\circ$, respectively. CRU V4 is a gridded climate dataset derived from station observations, providing long-term records and widely applied in studies of mountain climate and glacier mass balance (Wang et al., 2019). MERRA-2 is a physically consistent reanalysis product that assimilates a broad range of observations and has been extensively evaluated for land-surface hydrology and precipitation, showing reasonable performance for hydro-climatic applications (Chen et al., 2019; Gelaro et al., 2017). The inclusion of these complementary datasets enhances the robustness of regional climate estimates and reduces uncertainties linked to any single climate product. A bilinear interpolation method is applied to resample all datasets to a uniform spatial resolution of 0.5° . Subsequently, an ensemble means of the GSWP3 W5E5, CRU V4, and MERRA-2 datasets is computed and used for analyzing regional climate trends.

Glacier boundary data are obtained from the RGI 6.0 (RGI Consortium, 2017),

compiled by the Global Land Ice Measurements from Space (GLIMS) project. The RGI dataset is used to initialize glaciers in the OGGM model provide the regional divisions used in this study. The HMA region is divided into three first-order regions and fifteen second-order subregions, as shown in Figure 1. Elevation data required for the simulation are derived from the Shuttle Radar Topography Mission (SRTM), with a spatial resolution of 90 m, and are used to calculate glacier surface slopes and flow paths. The GTOPO30 dataset (<https://www.usgs.gov/>), with a spatial resolution of approximately 1 km, is used only to generate mountain shadows as background for map visualization.

2.2 Open global glacier model

The OGGM model is a modular, and open-source numerical model capable of dynamically simulating historical and future glacier changes worldwide. It incorporates glacier dynamics processes and has strong adaptability to various climate datasets. It has been extensively applied and validated in regional and global studies in glacier mass balance, volume, and runoff estimation (Afzal et al., 2023; Zekollari et al., 2024; Zhao et al., 2023). This study uses the updated version, OGGM v1.6.2. The model comprises two core modules, namely the mass balance module and the glacier geometry evolution module. In OGGM, glacier geometries are represented using a flowline approach, in which glacier centerlines are identified based on RGI glacier outlines and topography following the algorithm of Kienholz et al. (2014). For glaciers with multiple tributaries, the geometry is simplified into a set of connected flowlines, where tributary flowlines route ice mass to a downstream main flowline at predefined junction points (Maussion et al., 2019). The key equation for the mass balance module is as follows:

$$M_i(z) = p_f P_i^{Solid}(z) - \mu \max(T_i(z) - T_{melt}, 0) + \varepsilon \quad (1)$$

where $M_i(z)$ is monthly mass balance at elevation z (mm w. e.); z is the elevation (m);

216 p_f represents precipitation correction factor; $P_i^{Solid}(z)$ represents monthly solid
 217 precipitation at elevation z ; μ represents temperature sensitivity factor (Hock, 2003);
 218 $T_i(z)$ represents monthly mean temperature ($^{\circ}\text{C}$); T_{melt} represents melt threshold
 219 temperature ($^{\circ}\text{C}$), ε represents a residual term.

220 The core equation of the glacier geometry evolution module is as follows:

$$221 \quad \frac{\partial S}{\partial t} = \omega M - \nabla \cdot q \quad (2)$$

222 where S is the cross-sectional area at a point perpendicular to the glacier flowline; ω is
 223 the width along the glacier flowline; M represents the glacier mass balance, which is
 224 evaluated at each flowline grid point and is related to local elevation; $q = v \cdot S$ is the
 225 ice flux; and v is the ice flow velocity. The velocity v is calculated based on Glen's
 226 flow law, expressed as:

$$227 \quad v = v_d + v_s = f_d h \tau^n + f_s \frac{\tau^n}{h} \quad (3)$$

228 Where v_d and v_s are the deformation and sliding components of glacier velocity,
 229 respectively ($n = 3$); f_s is a dimensionless scaling parameter; f_d is the deformation
 230 factor; τ is the shear stress; and h is the ice thickness (m); The factor f_d is related
 231 to Glen's flow parameter A by:

$$232 \quad f_d = \frac{2A}{n+2} \quad (4)$$

233 The shear stress τ depends on the basal geometry of the glacier. Here, it is assumed to
 234 equal the driving stress τ_d which is computed as:

$$235 \quad \tau_d = \alpha \cdot \rho \cdot g \cdot h \quad (5)$$

236 Where α is the slope of the glacier flowline; ρ is the density of ice ($0.9 \text{ g}\cdot\text{cm}^{-3}$);
 237 g is the gravitational acceleration ($980 \text{ cm}\cdot\text{s}^{-2}$).

238 Glacier runoff in OGGM is defined as the amount of water leaving the glacier
 239 initialization area, including both meltwater from glaciers and rainfall contributions

within the glacier area (Huss and Hock, 2018; Maussion et al., 2019). As glaciers retreat, ice-free zones may expand, but are still included in glacier runoff calculations. Specifically, it comprises four components: on-glacier melt, off-glacier melt, on-glacier rainfall, and off-glacier rainfall. The total glacier runoff R can be expressed as:

$$Runoff = M_{on} + M_{off} + P_{on}^{liquid} + P_{off}^{liquid} \quad (6)$$

where M_{on} and M_{off} are the meltwater contributions from on-glacier and off-glacier surfaces; P_{on}^{liquid} and P_{off}^{liquid} are the respective rainfall inputs.

To improve simulation accuracy, the OGGM model calibrates both the mass balance module and the glacier geometry evolution module. The mass balance module involves parameters including melt factor, precipitation correction factor, temperature bias, and temperature threshold (distinguishing rainfall and snowfall). The calibration follows the three-step calibration method proposed by Huss and Hock (2015), using long-term glacier mass balance data provided by Hugonnet et al. (2021) as a reference to establish a globally applicable set of mass balance parameters. Building upon this framework, the temperature bias for RGI regions 13, 14, and 15 is further adjusted to align the regional mass balance with the consensus estimates from Zemp et al. (2019). In the glacier geometry evolution module, glacier volume estimates from Farinotti et al. (2019) are used as independent reference values to calibrate the Glen's creep parameter (4) within the ice thickness inversion, thereby constraining the inferred ice thickness distribution.

2.3 Glacier sensitivity experiments

To assess regional differences in glacier responses to temperature and precipitation changes across the HMA, a series of controlled perturbation experiments were conducted using the OGGM model. In these experiments, temperature and precipitation were perturbed independently while holding the other variable constant, enabling

systematic evaluation of their isolated impacts on glacier mass balance. Temperature perturbations ranged from -1.5°C to $+1.5^{\circ}\text{C}$ in 0.25°C increments, and precipitation perturbations ranged from -30% to $+30\%$ in 5% increments. All perturbations were applied relative to the original climate forcing over the period 1980-2019. In each perturbation experiment, the model was driven by the corresponding perturbed temperature or precipitation time series over the full simulation period, while the other climate variable remained unchanged. Subsequently, the resulting glacier mass balance outputs were aggregated to compute the multi-year mean area-weighted mass balance for each subregion. Based on these results, glacier sensitivity was quantified as the slope of a linear least-squares regression between the imposed climate perturbation levels and the corresponding glacier mass balance. To facilitate comparison among the 15 subregions, the sensitivity slopes were normalized using a scaling approach based on the minimum and maximum values across subregions and rescaled to a range from 0 to 1. This normalization was applied separately for temperature and precipitation sensitivities and is intended to highlight relative differences in glacier sensitivity among subregions rather than absolute physical magnitudes.

2.4 Statistical methods

To comprehensively analyze trends in glacier mass balance and climatic variables across HMA, a suite of robust statistical methods was employed. The use of multiple analytical approaches enhances the reliability of the results and mitigates the potential bias introduced by relying on a single method. To characterize long-term trends and temporal variability in glacier mass balance and climatic variables, four analytical methods were employed. Specifically, the Mann-Kendall (MK) trend test was employed to determine the presence and statistical significance of monotonic trends ([Zhang et al., 2009](#)), while linear regression analysis was used to estimate the rate and direction of

change via trend slopes. In addition, a 5-year moving average was applied to smooth the original time series and highlight medium- to long-term variability. Anomaly analysis was further conducted by standardizing deviations from the long-term mean, enabling clearer identification of interannual variability and abnormal years or events.

3. Results

3.1 Model validation and performance evaluation

To evaluate the performance of the OGGM model in the HMA region, this study uses glacier mass balance observations provided by the World Glacier Monitoring Service ([WGMS, 2025](#)) as a reference, representing direct measurements for individual glaciers. A total of 68 glaciers in the HMA region have observational records, primarily spanning the period from 1980 to 2019. Considering that some glaciers exhibit anomalous deviations, possibly caused by data gaps, observation errors, or model inapplicability, only glaciers with at least five consecutive years of observation were selected. As a result, 59 glaciers with valid and reliable records were retained to avoid misleading assessment outcomes. These glaciers are unevenly distributed across the study area, with Central Asia containing 30 glaciers, South Asia West containing 15 glaciers, and South Asia East containing 14 glaciers. A comparison between the multi-year average observed mass balance and the model simulations shows a moderate agreement, with a correlation coefficient of 0.66 ([Figure 2b](#)), indicating that the model reasonably captures glacier mass balance variations.

To further validate the model's performance at the subregional level, annual glacier mass balance simulations for Central Asia, South Asia West, and South Asia East were compared with the results from [Zemp et al. \(2019\)](#) and [Dussailant et al. \(2025\)](#). ([Figure 2a](#)). [Zemp et al. \(2019\)](#) estimated glacier mass balance across HMA based on regional

extrapolation, while [Dussaillant et al. \(2024\)](#) reconstructed glacier-specific mass balance prior to 2000 by incorporating WGMS observational data. The results indicate that the simulated mass balance in Central Asia and South Asia East correlates well with [Zemp et al. \(2019\)](#), with correlation coefficients exceeding 0.5 ([Table S1](#)). In contrast, the correlation for South Asia West is lower ($R = 0.34$), likely reflecting the combined effects of limited observational data for validation, complex climatic variability at the transition between westerlies and monsoons ([Madhura et al., 2014](#); [Palazzi et al., 2013](#)), and the high prevalence of debris-covered glaciers ([Kraaijenbrink et al., 2017](#); [Scherler et al., 2011](#)), whose effects are not explicitly represented in OGGM. Overall, despite regional differences in correlation strength, the consistent agreement between our simulations and multiple independent datasets confirms the robustness and reliability of the OGGM model in reproducing glacier mass balance dynamics across diverse subregions of HMA.

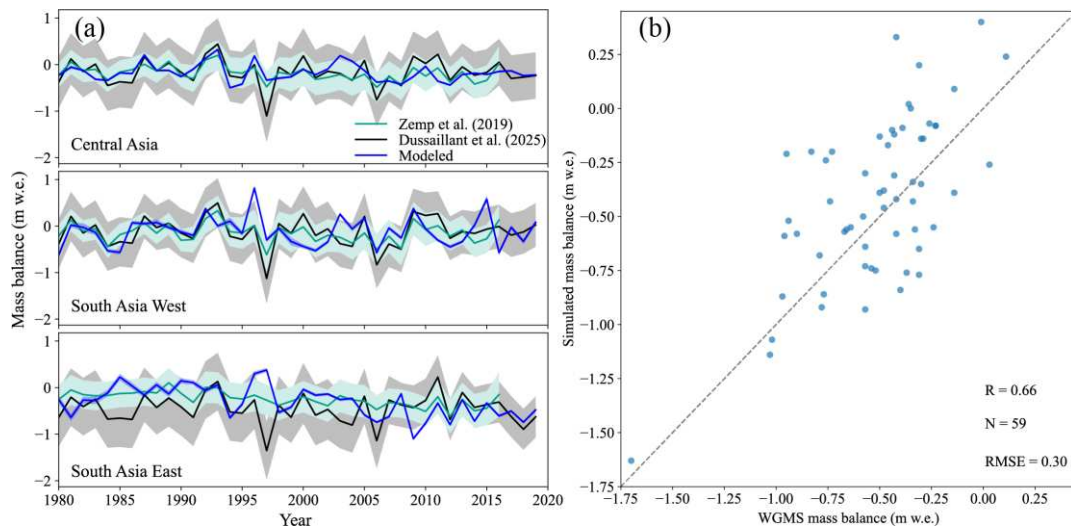


Figure 2. (a) Annual glacier mass change (m w. e. yr⁻¹) from this study compared with results from [Zemp et al. \(2019\)](#) and [Dussaillant et al. \(2024\)](#). (b) Annual glacier mass change (m w. e. yr⁻¹) from this study compared with [WGMS, 2025](#).

3.2 Post-2000 acceleration and spatiotemporal variations of glacier mass balance

To ensure consistency with previous studies and to provide two equal 20-year intervals for robust trend estimation, the study period was divided into two phases: 1980-1999 (Period 1) and 2000-2019 (Period 2). This division facilitates a clearer comparison of temporal trends and helps identify shifts in glacier behavior between the two periods. The overall mass balance across HMA shows a statistically significant decline over the study period ($P < 0.1$), indicating sustained mass loss (Figure 3). More importantly, the post-2000 phase (P2) marks a notable intensification in glacier mass decline. During 1980–1999, glaciers showed slightly negative conditions with a weak and statistically insignificant positive trend. However, after 2000, the region entered a new phase characterized by a consistently negative trajectory, highlighting a transition toward accelerated mass loss (Table S2). This pattern is also captured in the 5-year moving average, which reveals a shift from mild recovery in the late 1980s to pronounced and persistent decline post-2000.

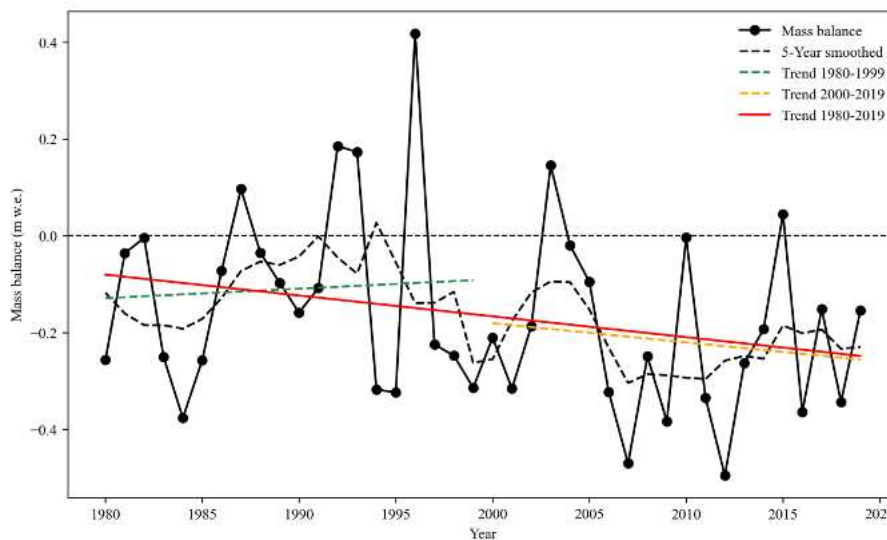


Figure 3. Annual glacier mass balance and 5-year moving average from 1980 to 2019. Linear trends are shown for different periods: 1980–1999 (green dashed line), 2000–2019 (orange dashed line), and the overall 1980–2019 period (red solid line).

The spatial patterns of glacier mass balance further reflect this temporal transition (Figure 4). Here, the glacier mass balance for each grid cell or subregion was obtained as an area-weighted mean of the mass balance of individual glaciers within that unit. During the entire period (1980-2019), the average glacier mass balance was -0.16 ± 0.02 m w. e. yr^{-1} . However, a comparison of the two phases reveals a marked shift, with the mean mass balance declining from -0.10 ± 0.02 m w.e. yr^{-1} in P1 to -0.30 ± 0.01 m w.e. yr^{-1} in P2. This phase shift is particularly evident in several subregions. For example, Hissar Alay transitioned from a slight mass gain in 1980-1999 to a mass loss in 2000-2019. In contrast, the Hengduan Shan experienced severe and persistent loss, declining from -0.45 to -0.61 m w. e. yr^{-1} over the two periods. East Tien Shan, similarly, saw mass balance drop from -0.27 to -0.52 m w. e. yr^{-1} . These examples highlight the pronounced intensification of melt, especially in eastern regions. Conversely, some western areas like the Pamir and Karakoram remained relatively stable. Subregional comparisons further illustrate a west-to-east zonation pattern, in which western regions like Hissar Alay shifted from slight accumulation to net loss, whereas southeastern regions exhibited sustained ablation throughout, reflecting intensified glacier melt under a warming climate. In addition, Figure 4a-c shows spatial averages at the 0.5° grid scale, where variations among individual grid cells reflect pronounced spatial heterogeneity in glacier mass balance. For example, while some grid cells in the Central Himalaya display slightly positive values during 1980-1999, many areas in the southeastern HMA show substantial mass loss, highlighting the pronounced spatial contrasts across the region. Although some glaciers exhibit positive mass balance during certain periods, the overall HMA region maintains a clear long-term trend of negative mass balance.

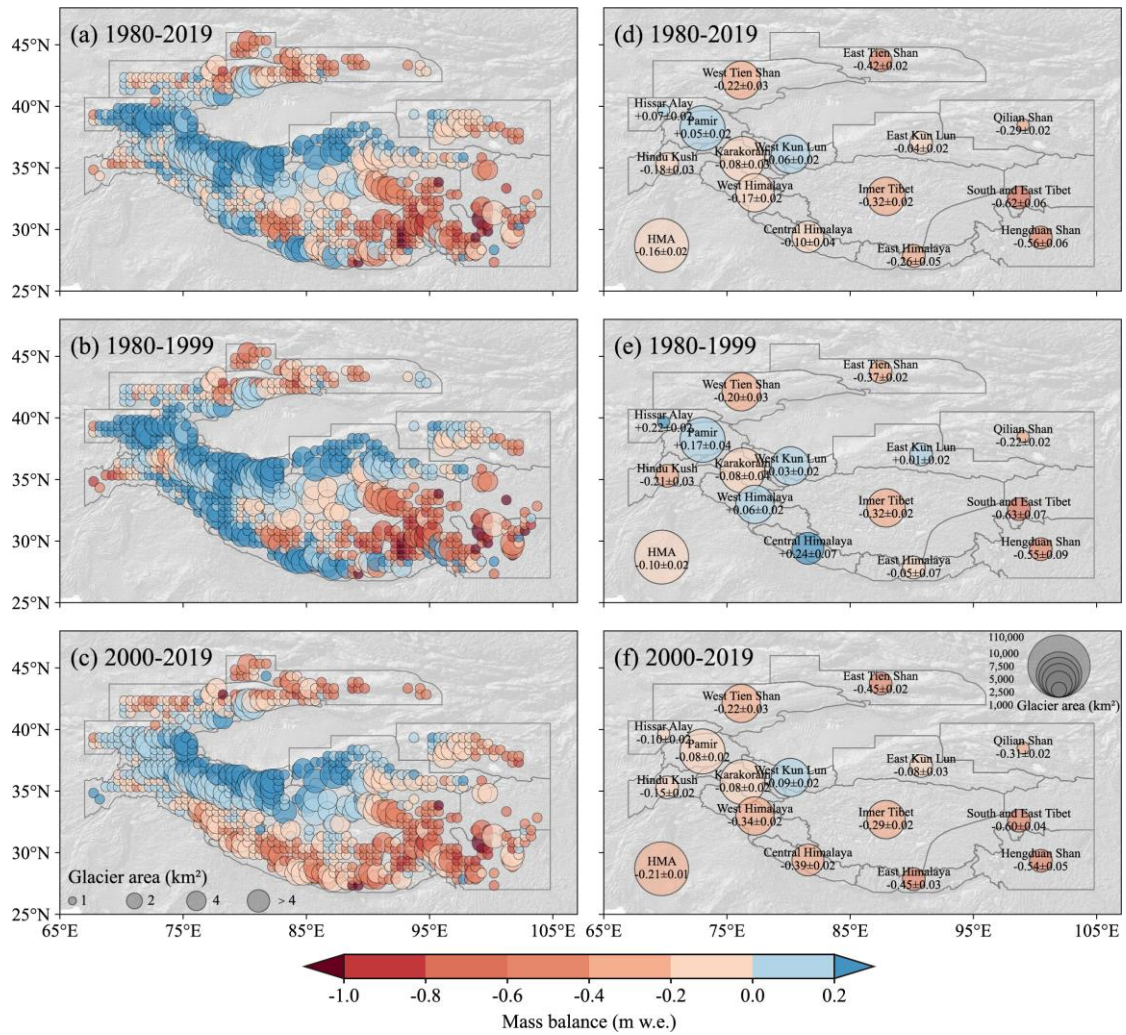


Figure 4. Spatial and temporal variations in annual glacier mass balance at 0.5° grid and subregional scales. Panels (a)-(c) show the area-weighted average annual mass balance within 0.5° grid cells for the periods 1980-1999, 2000-2019, and 1980-2019, respectively. The size of each grid point reflects the average glacier area within the cell. Panels (d)-(f) present the area-weighted average annual mass balance for the entire HMA and its subregions during 1980-2019, 1980-1999, and 2000-2019, respectively. The size of each circle represents the total glacier area within the corresponding subregion.

3.3 West-to-east zonation of glacier volume change

Figure 5 shows the temporal variations in glacier volume across fifteen subregions of the HMA, expressed as a percentage relative to the volume in 1980. Glacier volume

changes across the HMA exhibit pronounced regional heterogeneity, forming a clear west-to-east zonation. Specifically, glaciers in the western regions (e.g., Hissar Alay, Pamir, and West Kunlun) gained small amounts of volume. Glaciers in the central regions (e.g., West Himalaya and Central Himalaya) followed a transitional pattern, with volumes increasing until the late 1990s or early 2000s and then declining. In contrast, glaciers in the eastern regions (e.g., East Himalaya, Qilian Shan, and Hengduan Shan) lost large amounts of volume continuously throughout the study period. Additionally, the two subregions of East Tien Shan and West Tien Shan also continued to lose glacier volume.

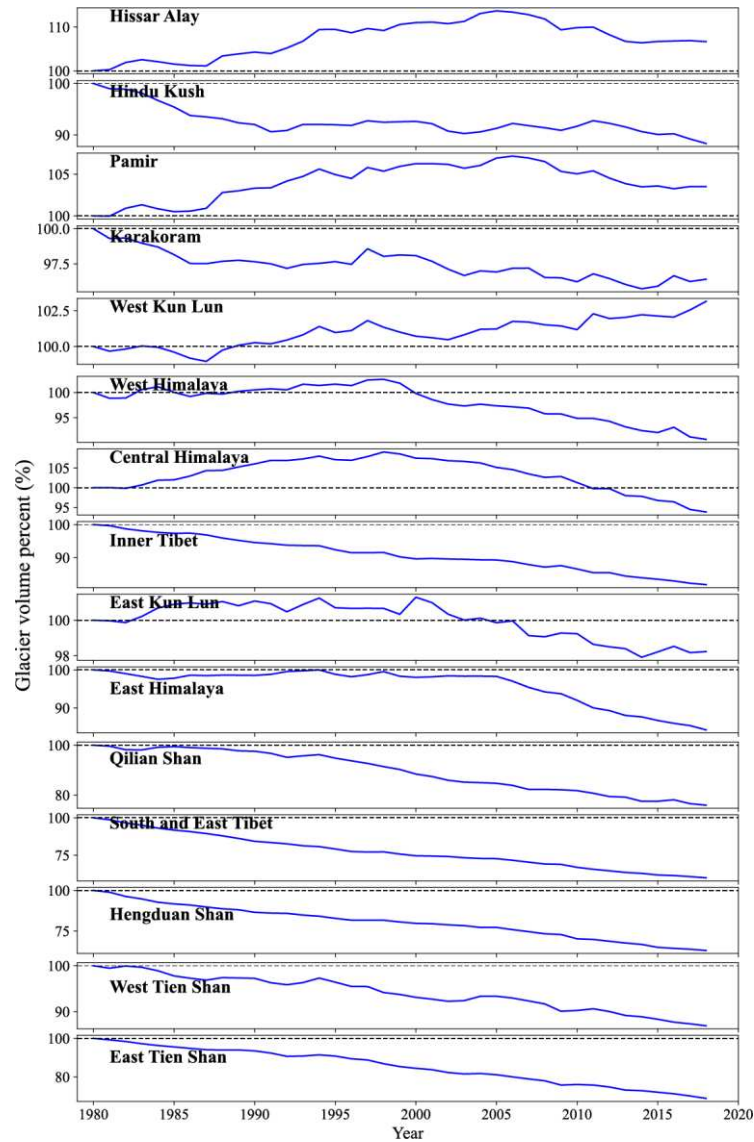


Figure 5. Glacier volume changes in the 15 RGI subregions of High Mountain Asia.

The subregions are arranged from west to east based on their centroid longitude, while East Tien Shan and West Tien Shan, due to their high latitudes, are displayed separately.

Figure 6 further quantifies glacier volume changes during two periods, 1980-1999 (P1) and 2000-2019 (P2). The total glacier volume in HMA decreased from 7205.50 km³ to 6875.33 km³, indicating a declining trend over the past four decades. These values fall within the consensus range of 7000 ± 1800 km³ reported by Farinotti et al. (2019), which represents the most robust multi-model estimate currently available. Nevertheless, the magnitude of volume change varies considerably across regions.

Spatially, western subregions such as Hissar Alay, Pamir, and West Kunlun remained nearly stable or gained small amounts of volume during the second period. In contrast, glaciers in the eastern regions lost substantial amounts of volume. South and East Tibet, Hengduan Shan, and East Tien Shan lost approximately 23%, 20%, and 18% of their volume, respectively, making them the most strongly depleted areas.

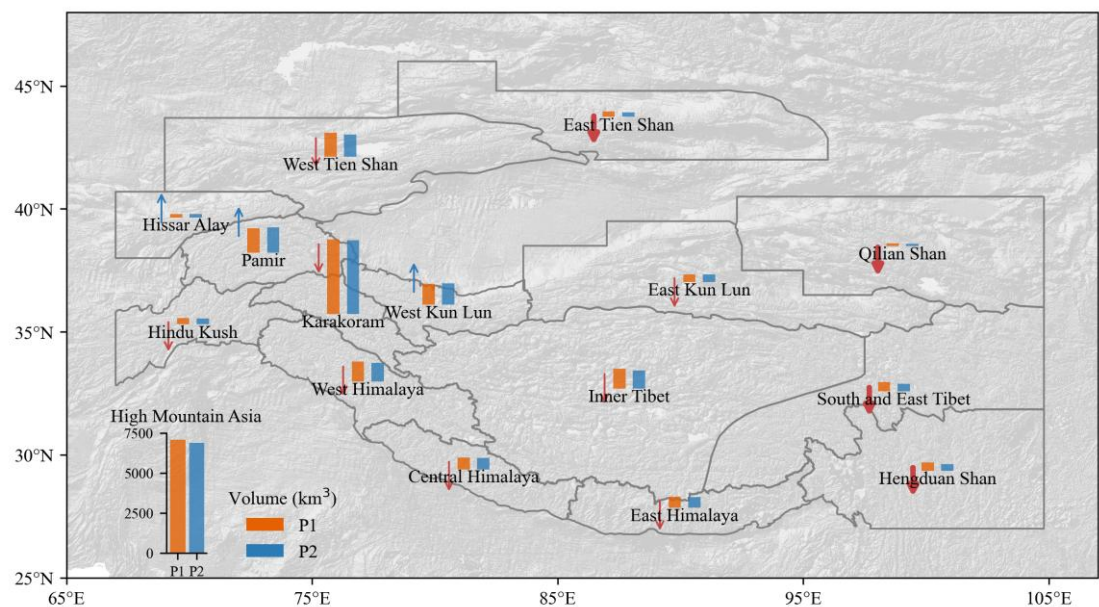


Figure 6. Glacier volume changes in the HMA and its 15 subregions during two periods. P1 represents the period 1980–1999, and P2 represents the period 2000–2019. Blue upward arrows represent an increase, while red downward arrows indicate a decrease. Thicker arrows denote a volume change exceeding 10% between the two periods.

3.4 Changes in glacier runoff and monthly contribution trends

Based on OGGM model simulations, this study estimated annual and monthly glacier runoff across 14 major basins in the HMA region (Figure 7). Results indicate that the Indus, Ganges, and Brahmaputra basins exhibit the highest glacier runoff, consistent with previous studies that identify these monsoon-influenced basins as the dominant meltwater contributors within HMA (Rounce et al., 2020).. These basins support extensive downstream irrigated agriculture and large populations, underscoring

the critical role of glacier meltwater in regional water security. Annual glacier runoff in the Indus and Ganges basins has significantly increased over the past four decades ($P < 0.05$), while the Brahmaputra shows a non-significant increasing trend. Moreover, most basins across HMA display increasing trends in annual glacier runoff, suggesting an intensifying role of glacier melt in regional hydrological processes. The intra-annual distribution of glacier runoff varies between basins. In exorheic basins such as the Salween, Brahmaputra, Indus, Ganges, Mekong, Irrawaddy, Yangtze, and Yellow River, glacier runoff is primarily concentrated between June and September, with the largest monthly contributions typically occurring in July and August (Figure S1). In contrast, for endorheic basins such as the Amu Darya, Syr Darya, and Tarim Interior, peak glacier runoff occurs mainly from June to August, indicating a more temporally concentrated runoff regime.

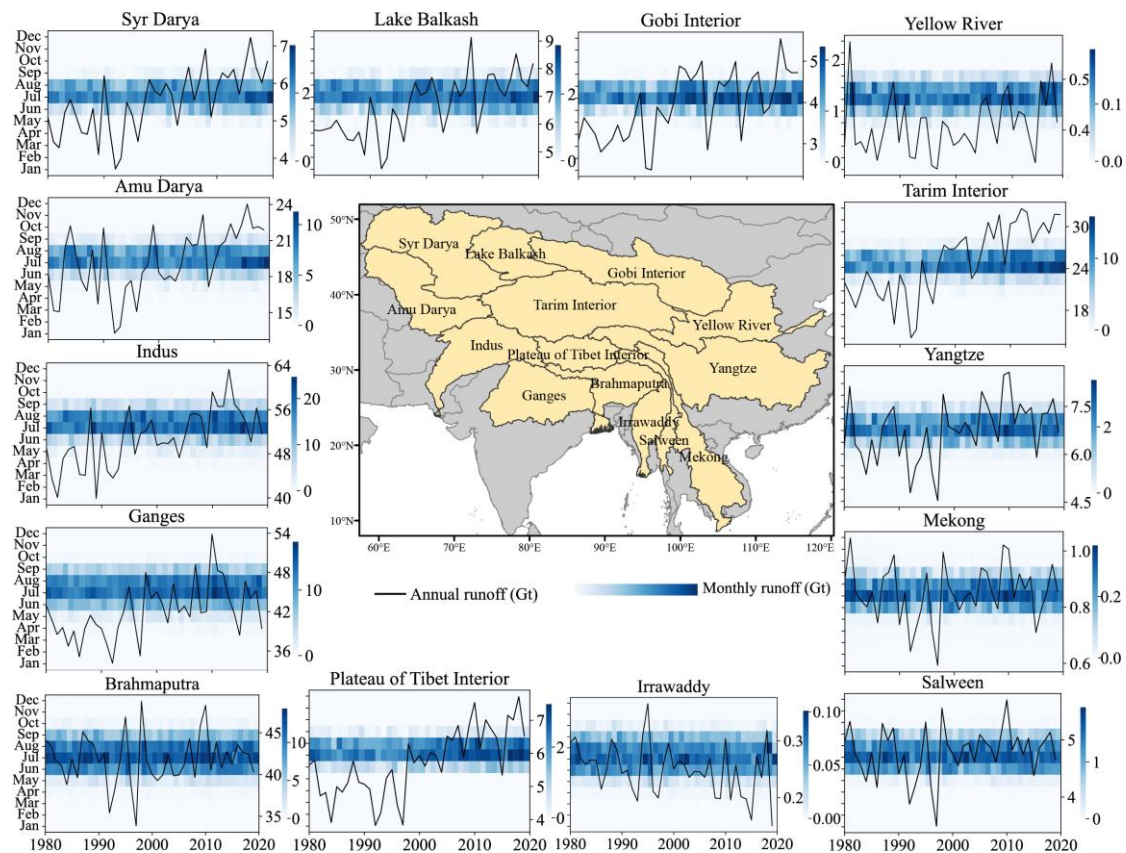


Figure 7. Annual and monthly runoff in 14 basins. The heatmap represents the temporal

variation of monthly runoff, while the black line indicates the temporal trend of annual runoff.

To further investigate temporal changes in the intra-annual distribution of glacier runoff, this study compared the proportions of runoff in June, July, August, and September relative to annual totals across two periods (Figure 8). The results reveal a consistent decrease in the proportion of July and August runoff, with the most significant declines observed in arid endorheic basins such as Lake Balkash, Gobi Interior, and Amu Darya. Conversely, the proportion of June and September runoff has generally increased, with the largest increases also occurring in arid interior regions. These shifts indicate an ongoing adjustment in the intra-annual glacier meltwater distribution, characterized by an extended melt season. This transformation is likely associated with reduced glacier area and storage capacity, as well as enhanced and prolonged melting under rising summer temperatures.

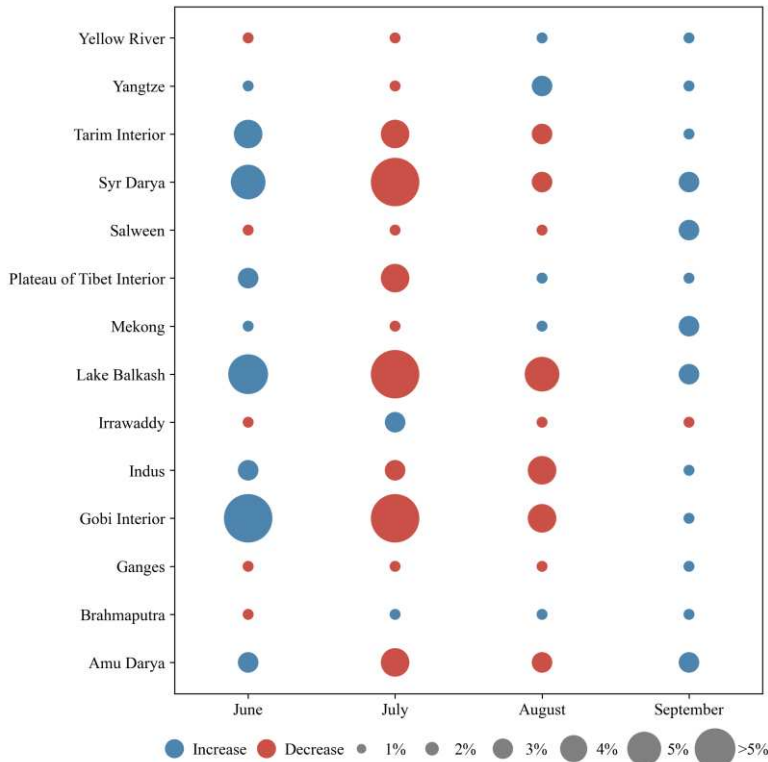


Figure 8. Changes in the proportion of monthly runoff relative to annual runoff between

the periods 1980-1999 and 2000-2019.

4. Discussion

4.1 Divergent climate sensitivities across High Mountain Asia

Glacier mass balance is governed by the competing processes of ablation and accumulation, primarily driven by variations in temperature and precipitation. Additionally, topographic factors and glacier properties, including area, slope, and elevation, further modulate glacier responses to climatic forcing (Brun et al., 2019; Shutkin et al., 2025). Recent studies indicate that the impacts of temperature and precipitation on glacier changes are highly interactive and regionally variable, making it insufficient to attribute glacier evolution to a single climatic factor (Bhattacharya et al., 2021; Parkes and Goosse, 2020). Nevertheless, numerous studies and observations suggest strong correlations between glacier mass changes and both temperature rise and precipitation variability (Ding et al., 2019; Oerlemans, 2005; Wouters et al., 2019). Therefore, understanding the spatiotemporal characteristics of climate change is essential to revealing the mechanisms driving regional glacier dynamics. To reduce uncertainties associated with individual climate products, this study employs an ensemble mean of multiple widely used gridded climate datasets, and the spatial grid outlines of these datasets are provided in the Figure S3.

The HMA region experienced significant average temperature increases during 1980-2019 (Figure 9). Although warming persisted throughout the entire period, temperatures after approximately 2000 remained higher than those before 2000, indicating an intensified warming regime in the later period. Further analysis indicates that temperature and precipitation trends exhibit substantial spatial and seasonal heterogeneity across HMA (Figure S2). The most pronounced warming has occurred in the southwestern and northern parts of HMA, with the East Tien Shan region being one

of the areas with the most severe glacier mass loss. Although winter warming is evident in many regions, its effect on glacier mass balance is largely indirect. Winter warming primarily affects the accumulation season by increasing the likelihood that precipitation falls as rain rather than snow, thereby reducing winter snow accumulation. In contrast, summer warming directly intensifies melting during the ablation season, exerting a much stronger effect on glacier mass loss. Consequently, the combined effect of reduced winter accumulation and intensified summer ablation drives the accelerated mass loss observed in these regions. Simultaneously, annual precipitation also increased significantly ($P < 0.05$), becoming more pronounced after 2005 ([Table S3](#)). However, an increase in total precipitation does not necessarily translate into enhanced glacier accumulation, because only snowfall can add mass to the glacier. Previous studies indicate that recent precipitation increases in several regions of HMA are primarily driven by increases in rainfall rather than snowfall, which does not contribute to glacier mass gain ([Li et al., 2025](#); [Jouberton et al., 2022](#)). Crucially, liquid precipitation not only fails to add mass but can enhance melting by transferring heat to the glacier surface ([Hock, 2005](#)). Particularly, the continued reduction in winter precipitation in certain regions has further suppressed glacier accumulation, challenging the long-term stability of glacier mass. In summary, the contrasting roles of reduced winter accumulation and intensified summer ablation, driven by ongoing climate change, help explain both the spatial divergence and the recent acceleration of glacier mass loss across HMA.

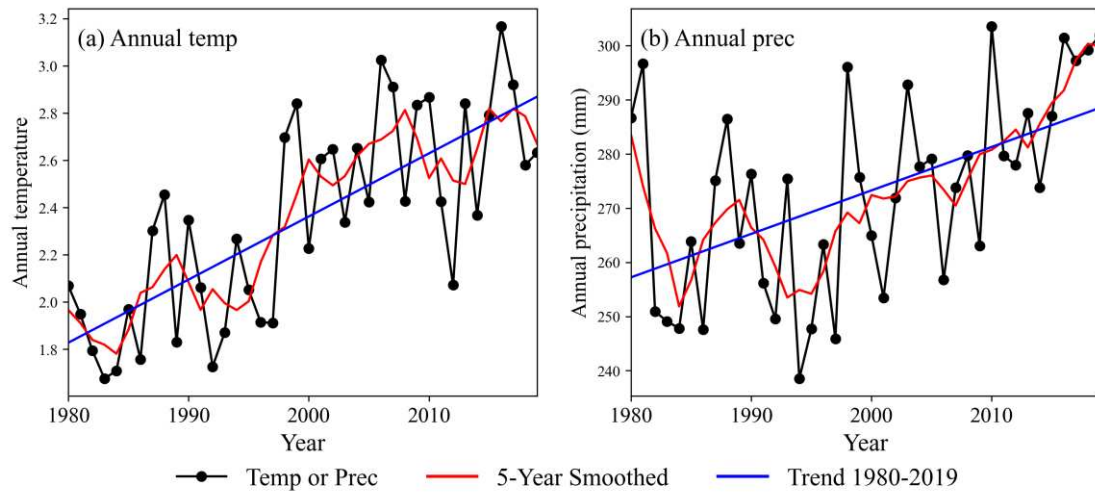


Figure 9. Time series of annual mean temperature and annual precipitation.

Figure 10 presents the climate sensitivities of glaciers across subregions, shown as normalized metrics and organized longitudinally from west to east, consistent with the volume change classification in Figure 5. Because the temperature and precipitation sensitivities are normalized independently, each metric should be interpreted only in terms of regional differences. The spatial zonation of glacier mass balance and volume changes across HMA shows a clear correspondence with temperature and precipitation sensitivity, indicating that regional glacier changes are more strongly influenced by climatic sensitivity than by climate trends alone. Glaciers in the eastern HMA, which exhibit higher temperature sensitivity, have undergone continuous volume loss under intensified warming. In contrast, glaciers in the western HMA, characterized by weaker temperature sensitivity and moderate precipitation sensitivity, have maintained relative stability or slight gains. Specifically, the sensitivity to temperature is weakest in western HMA and gradually increases from west to east. This weak climatic sensitivity in interior subregions such as West Kun Lun, reflects the combined influence of cold, arid climate and high glacier elevations, which restrict the ablation zone and weaken glacier responses to climate variability. Glaciers in southeastern regions such as the East Himalaya and South and East Tibet are particularly sensitive to temperature changes.

In contrast, the spatial pattern of precipitation sensitivity is more complex. Within the precipitation sensitivity experiments, the Himalayan subregions show relatively high sensitivity, indicating a stronger response to precipitation variability compared to other regions.

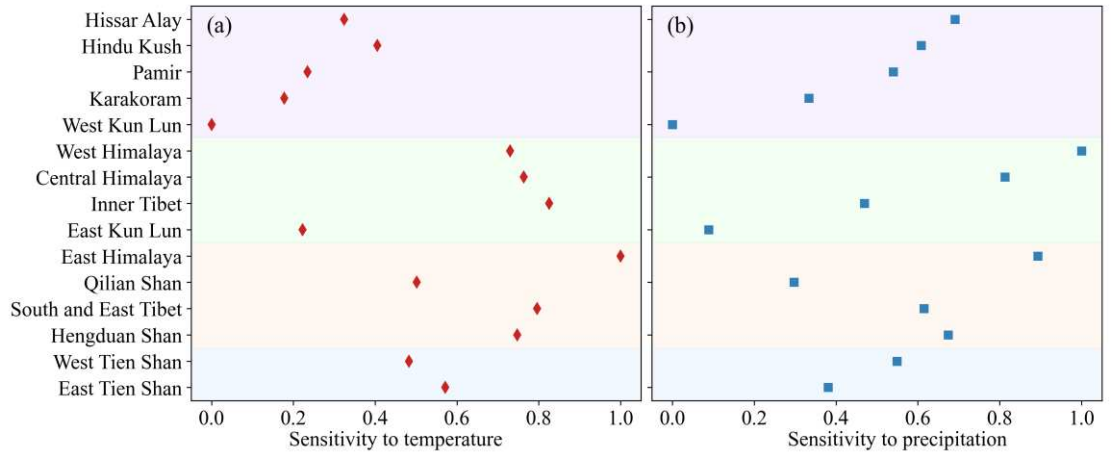


Figure 10. Sensitivity of glacier mass balance to climate perturbations for 15 subregions in the HMA. (a) Relative sensitivity to temperature changes; (b) Relative sensitivity to precipitation changes. Sub-regions are ordered longitudinally from west (top) to east (bottom), background colors denote three main longitudinal zones: western (purple), central (green), and southeastern (orange), with East Tien Shan and West Tien Shan (blue) shown separately due to their distinct higher latitudes.

The sensitivity analyses further emphasize the spatial heterogeneity of glacier-climate responses. Even under the same magnitude of warming or precipitation change, glaciers in different subregions exhibit significant differences in the magnitude of response. In addition, the markedly accelerated melt in the eastern and southeastern HMA can be explained by a combination of climatic and glaciological factors. These regions have experienced some of the strongest warming across HMA (Yao et al., 2012) and reductions in solid precipitation (Salerno et al., 2015), which have led to rising snowline altitudes (Guo et al., 2021; Yao et al., 2012), thereby reducing accumulation

and intensifying melt. Moreover, glaciers in these regions tend to be smaller, steeper, and located at relatively low elevations (Wang et al., 2023), making them more responsive to climatic forcing. In addition, our temperature sensitivity analysis shows that glaciers in the eastern and southeastern HMA respond much more strongly to temperature changes than those in other subregions. This pronounced climatic sensitivity helps link regional climate forcing to the nearly doubled melt intensity observed in this region. Therefore, regions with high climatic sensitivity, particularly in the southeastern HMA, warrant special attention in future glacier change projections and water resource management planning.

4.2 Comparison with previous studies

To validate the reliability of our glacier mass balance simulations for the HMA region, we compared them with several recent studies (Table 1). For the period after 2000, numerous remote sensing and model-based studies consistently indicate that glaciers in the HMA region are experiencing significant negative mass balances. Due to differences in periods and methods, the values of glacier mass change vary somewhat across studies, but generally range from -0.18 to -0.23 m w. e. yr^{-1} , corresponding to glacier mass losses of -15 to -21 Gt yr^{-1} (Brun et al., 2017; Hugonnet et al., 2021; Shean et al., 2020; Zhao et al., 2023). Our simulations for 2000-2019 indicate a mass balance of -0.21 ± 0.02 m w. e. yr^{-1} , equivalent to a total mass loss of -20.65 ± 0.15 Gt yr^{-1} , with uncertainties expressed as 95% confidence intervals of the regional mean estimates. These results fall within the range reported by previous studies, demonstrating the reliability of our model for this period.

For glacier mass balance estimation before 2000, there are fewer related studies due to limited availability of high-quality remote sensing data. Zemp et al. (2019), using extrapolation from limited field measurements, reported a glacier mass balance for the

HMA region of -0.19 ± 0.31 m w. e. yr^{-1} for 1980–2016. [Dussaillant et al. \(2024\)](#) integrated field observations with multi-temporal geodetic data through data fusion and spatial interpolation techniques to estimate glacier mass changes from 1980 to 2019. Our model results for the period 1980–2019 show a mass balance rate of -0.16 ± 0.03 m w. e. yr^{-1} , slightly higher than the aforementioned studies but still within their uncertainty ranges. Furthermore, comparison with [WGMS \(2025\)](#) observational data shows that our simulated results are consistent with the measured trends ([Figure 2](#)). Overall, the consistency with previous studies obtained by various methods provides evidence supporting the reliability of our modeling results.

Table 1. Comparison of glacier mass balance in the HMA region with previous studies. These published estimates are shown for contextual comparison only and were not used for model validation. Glacier density is taken as $\rho = 900 \text{ kg m}^{-3}$ in this study.

Reference	Period	Previous study		This study		Methods
		m w. e. yr^{-1}	Gt yr^{-1}	m w. e. yr^{-1}	Gt yr^{-1}	
Shean et al. (2020)	2000–2018	-0.19 ± 0.03	-19.0 ± 2.5	-0.21 ± 0.02	-19.99 ± 0.15	Geodetic method using multi-temporal DEMs
Brun et al. (2017)	2000–2016	-0.18 ± 0.04	-16.3 ± 3.5	-0.21 ± 0.02	-19.39 ± 0.15	
Hugonnet et al. (2021)	2000–2019	-0.22 ± 0.05	-21.0 ± 2.3	-0.21 ± 0.02	-20.65 ± 0.15	
Zemp et al. (2019)	1980–2016	-0.19 ± 0.31	-19.0 ± 10.2	-0.17 ± 0.03	-15.37 ± 0.15	
Liu et al. (2022)	2000–2018	—	-29.3 ± 2.6	-0.21 ± 0.02	-19.99 ± 0.15	
Dussaillant et al. (2024)	1980–2019	-0.25 ± 0.54	-20.38 ± 16.47	-0.16 ± 0.03	-16.68 ± 0.15	Data fusion of glaciological and geodetic methods
Rounce et al. (2020)	2000–2015	—	-20.3 ± 2.0	-0.2 ± 0.02	-20.91 ± 0.15	PyGEM
Zhao et al. (2023)	2000–2019	-0.23 ± 0.03	-20.8 ± 2.9	-0.21 ± 0.02	-20.65 ± 0.15	OGGM

4.3 Uncertainty and limitations

This study simulated glacier mass balance and volume changes across the HMA from 1980 to 2019 using the OGGM model and evaluated the results against multiple

independent datasets. Despite efforts to reduce uncertainties in model inputs and outputs, uncertainties remain, primarily related to [climate forcing, parameter calibration, and simplified process representations](#). First, when calculating glacier mass balance, a uniform ice density value ($\rho = 900 \text{ kg}\cdot\text{m}^{-3}$) was applied for unit conversion. While this assumption is commonly used in global-scale studies ([Huss, 2013](#)), it neglects the differences in glacier density across different glacier types (e.g., temperate glaciers and polar glaciers) and regions, which may introduce systematic errors. Second, although OGGM accounts for glacier geometric evolution and is one of the most advanced glacier dynamic models currently available ([Maussion et al., 2019](#)), its mass balance module primarily relies on a temperature index model. This method has high efficiency in large-scale simulations but does not explicitly consider radiation energy balance processes ([Pellicciotti et al., 2012](#)), which may lead to an amplification of the response to temperature changes. Moreover, although parameter calibration was conducted to ensure that simulated results are generally consistent with other studies ([Figure 2 and Table 1](#)), uncertainties associated with model parameterization remain. Recent OGGM analyses over HMA show that model outcomes are more sensitive to the precipitation correction factor than to temperature parameters, making precipitation parameterization a dominant source of uncertainty in regional glacier volume and runoff estimates ([Zhao et al., 2023](#)). In addition, the model does not explicitly distinguish between debris-covered and debris-free glaciers, which prevents a detailed analysis of how debris cover affects glacier melt rates. Additional uncertainty arises from the use of a constant temperature lapse rate, as the spatial and seasonal variability in lapse rates cannot be fully captured due to limited long-term and large-scale observational constraints ([Oulkar et al., 2024](#)). While OGGM incorporates a calibrated temperature bias that partly compensates for this limitation, some uncertainty inevitably remains. It should

also be noted that glacier changes before 2000 were simulated by backward extrapolation based on glacier outlines around 2000s. Given the challenges in reconstructing historical glacier states and the lack of early glacier observations, the simulation results for the earlier period inevitably carry a certain degree of uncertainty (Eis et al., 2021). Although regional parameter recalibration led to a generally high degree of agreement between our simulations and previous studies, there may still be some quantitative differences.

Our simulated regional glacier volume over HMA is approximately $7.0 \times 10^3 \text{ km}^3$, consistent with the multi-model consensus estimate of $7.0 \pm 1.8 \times 10^3 \text{ km}^3$ for the region (Farinotti et al., 2019). Glacier runoff estimates inherently carry uncertainties arising from mass balance reconstruction, climate forcing data and model parameterization (Huss and Hock, 2018). Previous studies have demonstrated that basin scale glacier meltwater estimates can differ considerably across modeling frameworks and climate datasets (Rounce et al., 2020; Zhao et al., 2023). Although glacier runoff estimates in this study inevitably contain uncertainties, the simulated spatial distribution and long-term trends remain robust and are consistent with those reported in previous assessments.

Beyond the model related uncertainties, the findings of this study also have broader implications for understanding glacier climate interactions and for anticipating future water availability in HMA region. Our analysis shows that glaciers across the region differ markedly in their climatic sensitivity, with some subregions responding much more strongly to the temperature and precipitation changes. This insight is valuable for identifying glacier systems that are likely to undergo accelerated retreat under future warming, and it also provides a useful reference for research in other mountain regions. Moreover, the identification of highly sensitive subregions in the eastern and

southeastern HMA highlights the need for strengthened monitoring efforts and prioritization in these areas. The results also carry important implications for downstream hydrology and water resource planning. The HMA region is a critical water tower supporting major river systems and densely populated downstream areas. Spatially uneven glacier retreat suggests that future meltwater availability may become increasingly imbalanced across basins, with potential consequences for water supply reliability and seasonal flow regulation. These findings emphasize the need for region specific water management strategies and for integrating glacier information into future climate and hydrological projections. In summary, this work contributes to a deeper understanding of glacier climate linkages and offers actionable insights for long-term water resource resilience in the HMA region.

Looking ahead, further improvements in glacier modelling remain essential for reducing uncertainties in long-term projections. Future developments could focus on more realistic representation of debris-covered glacier processes, improved parameterization of key energy balance components, and integration of higher resolution meteorological and glaciological observations. Such advances will improve the reliability of future estimates of glacier change and basin hydrology under continued climate change.

5. Conclusions

This study presents a comprehensive assessment of glacier mass balance, volume changes, runoff variations, and glacier sensitivity to climate forcing across HMA from 1980 to 2019, based on OGGM simulations. The main conclusions are as follows:

(1) Glacier mass loss in HMA accelerated notably after 2000, marking a significant phase shift in regional glacier–climate responses. This acceleration was accompanied by pronounced spatial heterogeneity, with losses intensifying from west to east.

(2) Glacier volume changes exhibited a clear west-to-east zonation pattern, characterized by a general increase in the western region, and initial increase followed by a decrease in the central region, and a continuous loss in the eastern region. Notably, subregions such as South and East Tibet, and Hengduan Shan, located in the easternmost part of HMA, experienced volume reductions exceeding 10%.

(3) Annual glacier runoff increased across most basins, accompanied by a declining proportion in July and August and increased contributions in September, reflecting enhanced melt intensity under warming conditions.

(4) Sensitivity analysis revealed that the strongest temperature sensitivity occurs in the southeastern HMA, while the highest precipitation sensitivity is observed in the southern areas. The intensified post-2000 warming, together with regionally divergent climate sensitivity, likely contributed to both the acceleration and heterogeneity of glacier changes.

Overall, this study elucidates the spatiotemporal patterns and driving mechanisms of glacier changes across HMA over the past four decades, providing a scientific basis for understanding the future glacier dynamics.

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