



Research Article

Variabilities in climate sensitivities and mass balance of four High Mountain Asian glaciers

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ABSTRACT

We analyse the mass balance evolution and climate sensitivities of four glaciers of High Mountain Asia (HMA) over the last five decades: Tuyuksu and Sary Tor glaciers (Northern and Central Tien Shan, Central Asia), Chhota Shigri Glacier (Western Himalaya), and an unnamed glacier (Glacier No. 4) (Eastern Himalaya). Using declassified Corona and Hexagon imageries (1960–1980) and recent high-resolution optical satellite data, we estimate mass loss rates of -0.3 ± 0.1 m w.e. a^{-1} (Tuyuksu and Chhota Shigri, 1971–2020), -0.6 ± 0.1 m w.e. a^{-1} (Sary Tor, 1973–2023) and -0.4 ± 0.1 m w.e. a^{-1} (Glacier No. 4, 1969–2022). A calibrated mass balance model (SnowModel) coupled with an ice dynamics model was used to simulate long-term annual and seasonal mass balance. Sensitivity analysis indicates temperature has a much stronger influence than precipitation, with Glacier No. 4 being most climate sensitive. Even in the most optimistic future climate scenario (SSP126) temperatures are projected to rise by ~ 2 °C with a $\sim 10\%$ increase in precipitation leading to continuous mass loss. Sensitivity based projections suggest losses within a range of 0.8 m w.e. a^{-1} (Chhota Shigri) and 1.8 m w.e. a^{-1} (Glacier No. 4), with higher losses under more extreme scenarios. Glacier No. 4 faces the greatest threat due to insufficient precipitation to counterbalance warming. These findings highlight the vulnerability of HMA glaciers and the challenge of maintaining equilibrium under future climate scenarios.

1. Introduction

Glaciers are valuable indicators of climate change, and glacier mass balance is highly sensitive to changes in temperature and precipitation (Haeberli et al., 2007; Nesje and Dahl, 2003; Hock and Huss, 2021). Long-term annual and seasonal glacier mass balance records provide important insights about the glacier's response to ongoing climate changes (Liu and Liu, 2016; Carturan et al., 2020). Over the past decades, most of Earth's glaciers lost mass with an accelerating trend (Zemp et al., 2019; Hock et al., 2019; Hugonnet et al., 2021; Bhattacharya et al., 2021; GLAMBIIE, 2025), and the magnitude and spatial pattern of mass change depends on regional climate variability

(Hugonnet et al., 2021; Bhattacharya et al., 2021).

Mass balance sensitivities of glaciers can be interpreted from their long-term annual and seasonal mass balance records. A glacier is considered more sensitive to climate when the magnitudes of average annual and seasonal mass balance over a long period are high (Braithwaite and Hughes, 2020). In general, glaciers receiving high precipitation have large mass turnovers and are more sensitive to climate compared to glaciers in more arid regions (Meier, 1984; Anderson et al., 2010). Mass balance sensitivities of glaciers help us predict the responses of glaciers from different climate zones (Engelhardt et al., 2015).

Long-term mass balance records can be obtained from glaciological

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observations but are available for less than 1% of the glaciers across the world (WGMS, 2024). Glaciological observations are particularly sparse on South Asian glaciers, although there is a high concentration of glaciers in this region, feeding some of the Asia's largest rivers (Bolch et al., 2012; Byers et al., 2014; Bolch et al., 2019; Davis et al., 2021; Yao et al., 2022). Several factors impede the collection of in-situ glaciological observations, ranging from logistical to geopolitical challenges (Bajracharya et al., 2014; Vemsani, 2015; Davis et al., 2021). The Himalayan range, characterized by towering peaks and diverse relief, experiences pronounced variability in precipitation patterns, with increasing annual precipitation from west (Hindu Kush) to east (Hengduan Shan) along its southern flank (Andermann et al., 2011; Maussion et al., 2014). These climatic differences exert significant influence on the short- and long-term responses of glaciers across High Mountain Asia (HMA), necessitating continuous monitoring to detect anomalous trends in mass balance effectively.

Changes in glacier mass using remotely sensed data can supplement existing in-situ records of glacier mass balance or reduce data sparsity in remote settings (Bhattacharya et al., 2021, 2023; King et al., 2020). In some cases geodetic data can be used to tune mass balance models and subsequently generate long-term (~50 years) mass balance time series (Mukherjee et al., 2023). Validation of the modelled mass balance results using the multi-temporal geodetic mass balance improves our confidence in the modelled mass balance outside the calibration periods. The calibrated mass balance models can then be used to simulate long-term mass balance and study the sensitivities of the glaciers to climate changes (Oerlemans and Fortuin, 1992; Yang et al., 2013; Azam et al., 2014).

We focus on four glaciers from different regions of HMA to investigate the variability in their long-term mass balance and sensitivity to climate. These include: one extensively investigated glacier from Central Asia (Tuyuksu), two well-studied glaciers, one in Central Asia (Sary Tor) and the other one in Western Himalaya (Chhota Shigri), and an unstudied glacier in Sikkim (Eastern Himalaya, Glacier No. 4). These selected study sites cover several climatic zones and provide a scope to improve our knowledge of glacier behaviour in less studied regions such as the Eastern Himalaya, a zone experiencing more intense warming and precipitation than the Western Himalaya (Tse-Ring et al., 2010; Kar and Quamar, 2020). Most studies on Himalayan glaciers focus on the western and central regions. Recent climate change has nevertheless greatly affected Eastern Himalayan glaciers (Basnett et al., 2013; Neckel et al., 2017; Brun et al., 2017; Garg et al., 2019; King et al., 2019; Zhu et al., 2025). There is no reference glacier from the Eastern Himalayan region for which long term glaciological mass balance records are available (WGMS, 2024). Our work contributes to bridging this knowledge gap in glacier change for this understudied region. The specific objectives are to: (i) Develop long-term multi-temporal geodetic mass balance records; (ii) Generate modelled (annual and seasonal) mass balance time series of each glacier and compare the seasonal accumulation and ablation patterns; (iii) Calculate mass balance sensitivity of each glacier to variations in temperature and precipitation; and (iv) Use the sensitivity results to assess future response of the glaciers under different climate projection scenarios.

2. Study glaciers

Central Tuyuksu (hereafter Tuyuksu) Glacier (RGI60–13.08624) and Sary Tor Glacier (RGI60–13.08055) lie in Central Asia. Tuyuksu Glacier is a polythermal glacier (Nosenko et al., 2016; Jacquemart et al., 2025), located on the northern slopes of the Ile Alatau in northern Tien Shan, Kazakhstan, Central Asia (43.04°N, 77.08°E). This glacier has one of the longest and most continuous mass balance records, with annual surface mass balance records available from 1957 (WGMS, 2024), making it one of the best studied glaciers in Central Asia (Grosval'd and Kotlyakov, 1969; Kononov, 1977; Dyurgerov et al., 1994; Hagg et al., 2004; Bolch, 2007; Kapitsa et al., 2020). This northern slope of Tien Shan has a more

humid climate because of cold air from north and northwest hitting these mountain ranges (Bolch, 2007). Sary Tor Glacier, also a polythermal glacier (Van Tricht and Huybrechts, 2022) is in the Inner Tien Shan, on the north-western slopes of the Ak-Shiirak massif, Kyrgyzstan, Central Asia (41.82°N, 78.17°E). Compared to Tuyuksu Glacier, this glacier is in the more continental parts of Tien Shan with a relatively small amount of precipitation (Dyurgerov et al., 1994; Petrakov et al., 2016; Van Tricht and Huybrechts, 2022). Continuous surface mass balance records of this glacier are available from 1985 to 1989 and again from 2014 (WGMS, 2024; Van Tricht et al., 2021).

Chhota Shigri (RGI60–14.15990) Glacier, likely a temperate glacier (Azam et al., 2014), is located in the Lahaul Spiti region of Himachal Pradesh (32.23°N, 77.51°E), Western Himalaya. Early research on this glacier primarily examined the chemical properties of its meltwater discharge and its utility for generating hydrological power (Hasnain, 1989; Hasnain et al., 1989). Subsequent studies explored glacier dynamics and morphology and their roles on glacier mass balance (Dobhal et al., 1995; Kumar and Dobhal, 1997). The first geodetic mass balance measurement studies on this glacier were published after 2000 (Berthier et al., 2007; Wagnon et al., 2007; Vincent et al., 2012; Azam et al., 2014). This is the only glacier in Indian Himalaya with an annual surface mass balance record exceeding 15 years (WGMS, 2024). The region receives precipitation during both winter (mid latitude westerlies) and summer (Indian Monsoon) seasons (Azam et al., 2014; Mukherjee et al., 2018), though winter typically receives more rainfall compared to summer (Fig. 1).

In Eastern Himalaya, we focus on Glacier No. 4 in Sikkim Himalaya, India (27.73°N, 88.36°E). Unlike the above three glaciers, this glacier is not a reference glacier and has not been studied explicitly. The nearest glacier from Eastern Himalaya, for which glaciological measurements for more than 15 years exist is Parlung No. 94 (2006–2021), located at 29.38°N, 96.97°E, almost 850 km away (WGMS, 2024). Glacier No. 4 is within 3 km of the South Lhonak Glacier where we observed a devastating glacier lake outburst in 2023 (Zhang et al., 2025; Sattar et al., 2025). This is a much warmer and wetter region compared to the other three (Fig. 1). The significantly higher precipitation and relatively warmer climate in this region encourage us to evaluate how the response of this glacier differs from the others to ongoing climate change. The glacier also has considerable debris cover, which is appropriately representative of many larger Central Himalayan glaciers (Herreid and Pellicciotti, 2020).

3. Data

Declassified American spy satellite images from the 1960s–1980s can establish changes in glacier mass balance going back several decades (Bolch et al., 2008, 2011; Pieczonka and Bolch, 2015; Maurer et al., 2019; Bhattacharya et al., 2021). The accessibility of low-cost medium to high resolution stereo images, such as, Satellite Pour l'Observation de la Terre 5 (SPOT-5), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Cartosat-1, Pléiades-1 A/B etc. increased significantly after 2000, facilitating more frequent glacier mass balance measurements from space.

We utilised stereo satellite images to generate elevation models, gridded climate data to drive the mass balance model and simulate mass balance time series, and climate projection data to assess the glacier responses to future climate scenarios. For validation, we used temperature and precipitation records from nearby climate stations to assess the gridded climate data and glaciological mass balance data to evaluate the mass balance results.

3.1. Satellite data

We used declassified Corona KH-4B and Hexagon KH-9 Metric and Panoramic Camera data and medium-to-high resolution ASTER-L1A, SPOT-5, Cartosat-1 and Pléiades-1 B stereo satellite images.

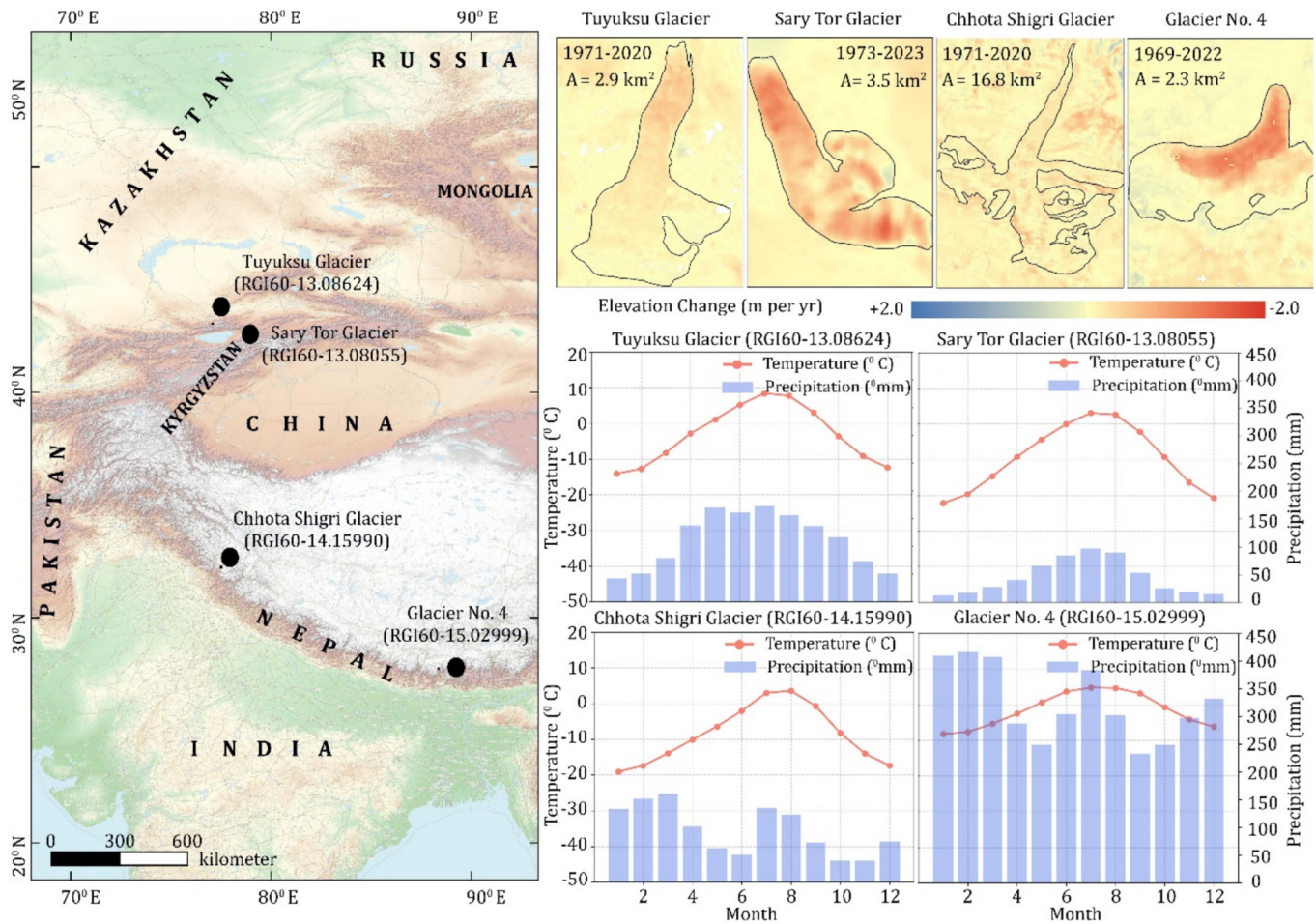


Fig. 1. Location of study glaciers, elevation change rates over the period of observation and climatic conditions (based on ERA5 Land records over 1970–2020) at each glacier location.

“Additionally, freely available Pléiades DEMs (2 m spatial resolution) from the Pléiades Glacier Observatory (PGO) initiative by the French Space Agency (CNES) and LEGOS, France, were also used for the Chhota Shigri Glacier (Berthier et al., 2024).”

A list of all the satellite data with other details is provided in supplement section S1.

3.2. Climate data

We used ERA5 Land climate data (Muñoz-Sabater et al., 2021) at hourly temporal resolution to force our mass balance model. The data are available at ~9 km spatial resolution.

For three of the four glaciers studied, we acquired some of the nearby weather station data to validate the ERA5 Land climate data. For instance, the Tuyuksu Observatory (43.07°N, 77.08°E) at 3434 m above sea level (asl) and Tien Shan weather station (41.88°N, 78.17°E) at 3600 m asl are situated approximately 1.5 km and 5 km from the respective glaciers and thus provide a highly representative record of the glaciers' climate. For Chhota Shigri Glacier, available observations are from the Bhuntar Observatory (31.50°N, 77.10°E), located approximately 80 km from the glacier at an elevation of 1084 m asl. This is significantly lower than the glacier's minimum elevation of around 4150 m asl.

3.3. Climate projection data

We used the CMIP6 (Eyring et al., 2016) mean climate data (mean of

ensemble means) and used near surface monthly air temperature and precipitation for four different shared socioeconomic pathways (SSPs) which integrate socioeconomic pathways with representative concentration pathways (RCPs). SSPs provide a framework for understanding how climate change might evolve under varying socio-economic and policy conditions. SSP126 represents sustainability focused scenario with low emissions and radiative forcing levels. SSP245 represents a balanced pathway with intermediate emissions and radiative forcing levels, whereas SSP370 represents regional rivalry, posing significant challenges to both mitigation and adaptation. Finally, the SSP585 corresponds to a fossil-fuel driven development trajectory, characterized by extremely high emissions and substantial mitigation challenges.

3.4. Ancillary data

Glaciological annual and seasonal mass balance data for few benchmark glaciers are publicly available through the World Glacier Monitoring Service (WGMS, 2024). We used these data to validate the simulated mass balance results of Tuyuksu, Sary Tor, and Chhota Shigri glaciers. We used glacier thickness data provided by Farinotti et al. (2019 and 2021) to construct glacier beds.

4. Methods

We generated DEMs from several sets of stereo satellite images to derive multi-temporal geodetic mass balance estimates. We also used a physically based mass balance model (SnowModel) coupled with an ice

dynamics model to simulate the annual and seasonal mass balance of the glaciers (Mukherjee et al., 2023).

4.1. DEM generation

4.1.1. DEM and ortho image generation from declassified images

We generated declassified Corona KH-4 DEMs using the Remote Sensing Software Package Graz (RSG), developed by Joanneum Research Graz. This software utilizes a Corona-specific image distortion model based on a modified collinearity equation (Sohn et al., 2004). First, we enhanced the raw image contrast by applying a local adaptive filter and histogram equalization. After calculating the panoramic camera orientation parameters by using external GCPs, we coregistered the stereo pairs using automated tie points by using the Forstner operator (Förstner and Gülch, 1987). We applied polynomial rectification (Goerlich et al., 2017) to reduce parallax error (< 1 pixel) for epipolar registration. We used three levels of disparity matching across five pyramid-based levels, using various search windows in both directions, with the window dimensions being iteratively adjusted (Goerlich et al., 2017). Initially, we used a broad search window to identify corresponding matching pixels, which were progressively refined to remove inaccurately assigned pixels (Goerlich et al., 2017). Finally, we generated the DEMs with a 10-m spatial resolution through area resampling.

We stitched individual scans of Hexagon KH9 Panoramic Camera images using tie points from overlapping regions to create a complete image of each scan (Ghuffar et al., 2023). For further processing, we applied the Corona Stereo Pipeline (CoSP) workflow (Ghuffar et al., 2022). The deep-learning model SuperGlue (Sarlin et al., 2020) matched image points between KH9 imagery and reference Landsat 7 ETM+ panchromatic images. Using these matched points and elevation values from ALOS Global Digital Surface Model (AW3D30), we estimated and optimized camera parameters through bundle adjustment (Ghuffar et al., 2023). We applied epipolar resampling to align stereo image points (Deseilligny and Rupnik, 2021) and performed dense matching using the semi-global matching algorithm (Hirschmüller, 2007). Triangulation then generated a 3D point cloud. To align the 3D point cloud with a reference DEM, we performed tile-based coregistration using a least-squares surface matching algorithm (Pfeifer et al., 2014). Finally, we interpolated the coregistered point cloud into a raster DEM with a 10-m spatial resolution.

We further generated a DEM and corresponding orthoimage from a trio of Hexagon KH9 Mapping Camera images acquired in 1980 over the Tuyuksu region using MicMac (Rupnik et al., 2017; Dehecq et al., 2020) following several preprocessing steps to prepare raw imagery for DEM generation. We removed the reseau grid found in KH9 mapping camera imagery and joined image halves to produce an overlapping image set (Pieczonek et al., 2013). We applied contrast limit adaptive histogram equalization (CLAHE) on each image to balance brightness and contrast. Using MicMac, we then found tie points across each image and computed a relative DEM, using relative camera orientations. We then registered the relative DEM and orthoimage to a reference Sentinel-2 image and the Copernicus 30 m DEM over the Tuyuksu study site.

4.1.2. DEM and ortho image generation from recent stereo pairs

We used AMES Stereo Pipeline (ASP, v3.1.0), developed by the National Aeronautics and Space Administration (NASA) and later adapted and modified by Shean et al. (2016), to generate DEMs from the other stereo pairs acquired after 2000 (ASTER Level-1 A, SPOT-5, Cartosat-1 & Pleiades-1 B). A semi-global matching (SGM) correlation algorithm (Hirschmüller, 2007) with 7×7 -pixel window size (Shean et al., 2020) generates the DEMs. To remove the artifacts in the disparity images, we used ASP's default Semi Global Matching (SGM) disparity map filters. All valid pixels in the disparity image were adjusted based on the Bayes EM weighted affine adaptive window correlator (Nefian et al., 2009). We used a rational polynomial coefficient (RPC) model (Grodechi & Dial 2003) in stereo triangulation for all stereo datasets. We generated the

output DEMs at different resolutions (ASTER 1 A: 30 m; SPOT5: 10 m; Cartosat-1: 5 m; Pleiades 1B: 4 m) and the ortho images at the original image resolution.

4.2. Glacier mapping

We estimated the changes in glacier length and area by adjusting the RGI (Arendt et al., 2017) glacier extents by visual interpretation from the various ortho images and DEM difference images. The uncertainties in glacier length and area changes (Hall et al., 2003; Bolch et al., 2010) were estimated by considering the mapping inaccuracy during the adjustment of glacier polygons (Bolch et al., 2010). We considered the following mapping inaccuracies in glacier area estimation. For glacier area delineation, we considered $\pm 2\%$ uncertainty of debris-free glaciers (Paul et al., 2003) and an additional $\pm 0.5\%$ uncertainty for debris-covered glaciers due to difficult visual interpretation to identify the debris-covered tongue (Bolch et al., 2010). We also added uncertainty due to coregistration of the images based on the buffer method described by Granshaw and Fountain (2006), considering a buffer around each glacier having a width equal to twice the root-mean-square error of the mapping and digitizing errors. We estimated approximately 8 m (4 pixels), 7.6 m (1 pixels), 10 m (2 pixels), 7.5 m (0.5 pixels), 7.5 m (3 pixels), and 7.5 m (15 pixels) root-mean-square error for outlines derived from Corona KH-4B, Hexagon-KH9, SPOT-5, ASTER-L1A, Cartosat-1, and Pléiades images, respectively. The overall uncertainty for area change was finally estimated by using the law of error propagation (Bolch et al., 2010; Paul et al., 2017).

4.3. Geodetic mass balance measurements

We considered the most contemporary DEM as the reference DEM and co-registered (aligned) the other DEMs using the analytical approach developed by Nuth and Kääb (2011) and Dehecq et al. (2021). During co-registration, the DEMs to be aligned were resampled to the resolution of the reference DEM. We evaluated elevation-dependent biases resulting from tilt between the DEMs for each dataset by using two-dimensional first-order polynomial trend surfaces as described by Hugonnet et al. (2021). We calculated the glacier mass balance by clipping the elevation difference images (dH) by the larger glacier extent of the two periods. We applied a two-step filtering process to remove outliers from the dH data. In the first step, we considered the pixels having absolute height differences above ± 150 m as outliers and removed. For the remaining pixels we estimated the mean (μ) and standard deviation (σ) of dH for each 50 m altitude bin (Gardelle et al., 2013) and pixels with absolute elevation difference values outside $\mu \pm 3\sigma$ were removed. We then fitted a third order polynomial through the values of average dH calculated for each elevation band (McNabb et al., 2019). The volume change (dV) was estimated by integrating the fitted curve over the glacier hypsometry. We estimated the geodetic mass balance (B_G) by dividing dV by the maximum area of the two periods (A) and considering an ice density conversion factor (ρ_i) of 850 kg m^{-3} and density of water (ρ_w) of 1000 kg m^{-3} (Huss, 2013).

$$B_G = \frac{dV}{A} \frac{\rho_i}{\rho_w} \quad (1)$$

Geodetic mass balance uncertainty (σ_B) was estimated after extracting the pixels over only stable terrain (Rolstad et al., 2009). We used the normalized difference snow, water, and vegetation indices from recent multispectral images to extract the water, vegetation and snow-covered areas. We excluded these pixels while calculating the uncertainties.

Finally, we calculated mass balance uncertainty (σ_B) following Brun et al. (2017) considering that uncertainty arises due to (1) uncertainty in elevation change ($\sigma_{\Delta H}$) (Rolstad et al., 2009), (2) uncertainty in glacier area (σ_A), and (3) the uncertainty from volume to mass conversion using

Eqs. (2) to (4).

$$\sigma_{\Delta H} = \sigma_{dH} \sqrt{\frac{A_{corr}}{5A}} \quad (2)$$

Where, A is the glacier area and $A_{corr} = \pi L^2$, and L is the decorrelation length (500 m, Brun et al., 2017).

The uncertainty on volume change ($\sigma_{\Delta V}$) was calculated using Eq. (3)

$$\sigma_{\Delta V} = \sqrt{[\sigma_{\Delta H}(p_a + 5(1 - p_a)A)]^2 + [\sigma_A dH]^2} \quad (3)$$

Where, p_a is the fraction of glacier area having valid dH values, and $\sigma_A = 0.1A$, i.e., considering 10% error in glacier area (Kääb et al., 2012).

Finally, the mass balance uncertainty (σ_B) was obtained by using Eq. (4).

$$\sigma_{B_G} = \sqrt{(\sigma_{\Delta V} \times \rho_i)^2 + (\sigma_{\rho_i} \times dV)^2} \quad (4)$$

Where, $\sigma_{\rho_i} = 60 \text{ kg m}^{-3}$ is the uncertainty of ρ_i (Huss, 2013).

4.4. Generation of weighted geodetic mass balance time series

We calculated geodetic mass balance using all combinations of the available DEMs. This leads to m_{C_2} pairs of difference DEMs, where m is the number of DEMs for each glacier, and c represents combination. As the different periods of multi-temporal geodetic mass balance often overlap with each other, we calculated an estimate of weighted geodetic annual mass balance time series using an inverse square distance weighting approach (Lepot et al., 2017; Antal et al., 2021), where distance is represented by uncertainty values. To do this, we represented each period of geodetic mass balance observation by a point at the middle year of that period and weighted the mass balance estimates by their uncertainties using Eq. (5) and (6).

$$MB_{weighted} = \frac{\sum_{i=1}^n \frac{MB_i}{\sigma_i^2}}{\sum_{i=1}^n \frac{1}{\sigma_i^2}} \quad (5)$$

$$\sigma_{weighted} = \sqrt{\frac{1}{\sum_{i=1}^n \sigma_i^2}} \quad (6)$$

Where, n is the number of geodetic mass balance observations within ± 10 years of a certain point, MB_i is the mass balance of the i'th year, and σ_i is the corresponding uncertainty. $MB_{weighted}$ is the weighted mass balance and $\sigma_{weighted}$ is the weighted uncertainty of mass balance for any year.

4.5. Mass balance model

We used SnowModel, a physically based distributed snow evolution model (Liston and Elder, 2006) to simulate annual and seasonal mass balance. Additionally, we coupled the SnowModel with an ice dynamics model to consider the influence of ice dynamics (Mukherjee et al., 2023).

4.5.1. SnowModel

SnowModel considers the interaction of meteorological parameters with topography and vegetation and requires two types of data inputs: 1) time dependent values for precipitation, temperature, wind speed and direction, and relative humidity; and 2) spatially distributed fields for topography and land cover class. SnowModel assumes a constant glacier wide albedo ignoring the spatial variation of albedo for snow, firn and ice.

We initiated the model using the topography of the first DEM available from the KH4B Corona images for each glacier after resampling it to 30 m. The extent of the glacier for that year was available from the corresponding ortho image. The climate fields used from ERA5 Land data to simulate the mass balance time series were 2 m dewpoint

temperature, 2 m temperature, precipitation, and wind speed.

SnowModel was employed to calculate glacier mass balance using the sub-models MicroMet, EnBal, and SnowPack. Factors like precipitation, snowmelt, metamorphism, wind redistribution, and sublimation influence mass and energy balances. In SnowModel, these processes are mathematically described at each point in space and time and combined into a spatially distributed snow evolution modelling system based on first-order physics (Liston and Elder, 2006).

MicroMet is a data assimilation and interpolation model and utilises default or user defined monthly lapse rates to adjust the temperature, relative humidity, and precipitation to a common level. Here we used the default rates available with SnowModel. Using Barnes objective analysis (Barnes, 1964), MicroMet then interpolates the meteorological parameters over the model domain and generates spatially distributed fields of each of the input parameters and calculates incoming solar and longwave radiation at each time step (Liston and Elder, 2006). EnBal calculates the surface energy exchanges based on the meteorological conditions, and SnowPack simulates the snow depth and snow water equivalent evolution (Liston and Elder, 2006). SnowModel outputs 16 variables, of which three variables, viz. solid precipitation (P), sublimation (L), and total runoff (R) are used to calculate the modelled mass balance using the equation $B_M = P - L - R$. The glacier wide mass balance was computed by calculating the mean over all the glacier pixels.

We considered October 1st of any year to September 30th of the next year as one hydrological year, with June 1st to September 30th for summer mass balance and rest for winter mass balance.

4.5.2. Ice dynamics model

The inputs to the ice dynamics model are a mass balance grid, the glacier surface topography and a constant bed topography. Glacier bed topography is constructed by subtracting the glacier thickness (Farinotti et al., 2019) grid from the SRTM DEM. The ice dynamics model uses a glacier surface and an ice mask to simulate glacier flow based on the shallow-ice approximation and assumes isothermal ice (Clarke et al., 2015). These simplifications provide a computationally efficient framework for estimating glacier flow, especially in data-scarce regions, while omitting spatial variations in ice temperature and basal boundary conditions. Clarke et al. (2015) emphasize that the dominant source of uncertainty in modelling glacier response to climate lies in the surface mass balance, which is climate-driven, rather than in the simplifications inherent to the ice dynamics formulation. The resulting equations are solved using a finite-difference method, which updates the glacier surface over time, ensuring mass conservation (Clarke et al., 2015). We iterated the glacier surface elevations after each month and grid cells were classified as ice when the ice thickness, obtained by subtracting the bed from the surface is more than a specified threshold (Mukherjee et al., 2023). However, for the debris-covered glacier, we kept the glacier extent unaltered based on the observed extent, while changing the modelled surface after each year. More details on ice dynamics model and preparation of climate data for SnowModel can be found in supplement sections S2 to S3.

4.5.3. Model calibration and uncertainty assessment

For Tuyuksu, Sary Tor and Chhota Shigri glaciers, we used geodetic mass balance estimates over a period slightly above forty years to calibrate the mass balance model with ice dynamics. The long period reduces the uncertainties in the mass balance estimates and helps to constrain our model better. The first DEM used for calibration was generated from the declassified images and the other one from recent high resolution stereo images, such as from Pleiades and SPOT (supplement section S1) data. We calibrated the model using only one period of geodetic mass balance and ran the model for the whole period keeping the parameters unchanged.

For Glacier No. 4, we tuned the model using two sets of parameters for two periods (1969–1983, 1983–2015), as we have not explicitly accounted for the effects of debris on glacier melting. We tuned the

model using a combination of station elevation and glacier albedo values, while keeping the glacier extent unchanged (based on observation from the geodetic data), to match closely with the mean geodetic mass balance estimates for the two periods.

We calculated the modelled mass balance uncertainties using the root mean square error of model and geodetic mean mass balance for different periods.

4.5.4. Validation of modelled mass balance

We used the glaciological mass balance records of Tuyuksu, Sary Tor and Chhota Shigri glaciers available from [WGMS \(2024\)](#) to validate the modelled results. We were unable to validate the annual and seasonal modelled mass balance for Glacier No. 4 due to the lack of available records. However, we validated the cumulative modelled mass balance for all other periods (13 of 15) except the calibration periods (2) against the corresponding geodetic mass balance results.

4.6. Climate sensitivities of individual glaciers

The dynamic mass balance sensitivities to temperature (β_T) and precipitation (β_p) were determined by calculating the mean annual changes in mass balance due to 1 °C change in temperature and 30% change in precipitation as described in [Oerlemans et al. \(1998\)](#) and [Engelhardt et al. \(2015\)](#) as follows.

$$\beta_T(1^\circ\text{C}) = \frac{|B_a(+1^\circ\text{C}) - B_a(-1^\circ\text{C})|}{2} \quad (7)$$

$$\beta_p(30\%) = \frac{|B_a(+30\%) - B_a(-30\%)|}{2} \quad (8)$$

Where, B_a is annual mass balance. We calculated the seasonal mass balance sensitivities by replacing B_a with B_s (summer mass balance) and B_w (winter mass balance).

Additionally, for capturing the combined effects of both temperature and precipitation on glacier mass balance, we followed [Engelhardt et al. \(2015\)](#). Temperature values were systematically varied from −3 °C to +3 °C in 0.5 °C increments, while all other model parameters were held constant as determined during calibration. Similarly, precipitation was varied from −30% to +30% in 5% increments, with other parameters remaining unchanged. A second-order polynomial was fitted to the resulting mass balance data points, and the fitted equations were used to estimate and visualize mass balance changes across a temperature-precipitation grid.

4.7. Climatic trends and future mass balance response

We used monthly ERA5 Land climate data during the study period to investigate the annual and seasonal trends in temperature and precipitation for grid cells nearest to each of the four glaciers. We used Mann-Kendall trend test to investigate if there is a statistically significant trend in the time series of the climate variables. The climate station data were used to validate the ERA5 Land data.

We used CMIP6 climate data (mean temperature and precipitation) to comment about the future mass balance responses of the glaciers based on their sensitivity indicators. We considered the period 1970–2020 as the baseline climate and calculated the average annual temperature and precipitation of this period. To analyse long-term trends, we calculated yearly anomalies by calculating a ten-year moving average starting from 1950. We estimated the anomalies in °C and in percentage (%) for temperature and precipitation data, respectively.

5. Results

5.1. Changes in glacier area and length

Among the four glaciers, Chhota Shigri Glacier retreated least, while

Glacier No. 4 lost the least amount of area over the past five decades.

Chhota Shigri Glacier retreated by 247.8 ± 14.9 m (5.1 ± 0.3 m a^{−1}) from 1971 to 2020. A comparable retreat rate (7.6 ± 0.5 m a^{−1}) was observed for Glacier No. 4 between 1969 and 2023. In contrast, Tuyuksu Glacier retreated most (937 ± 14.1 m, 19.1 ± 0.3 m a^{−1}) from 1971 to 2020. Sary-Tor Glacier experienced a comparable retreat rate of 17.0 ± 0.4 m a^{−1} between 1973 and 2023.

Glacier No. 4 lost $1.6 \pm 1.4\%$ area over the observation period 1969–2022 and Chhota Shigri Glacier lost $4.0 \pm 0.6\%$ area between 1971 and 2020. Like length change, Tuyuksu Glacier lost maximum glacierized area of $25.4 \pm 4.5\%$ between 1971 and 2020. The area of the Sary Tor Glacier decreased by $21.6 \pm 1.7\%$ between 1973 and 2023.

5.2. Multitemporal geodetic and modelled mass balance

Our geodetic mass balance estimates capture substantial changes in the regimes of ice accumulation and ice loss for each glacier over recent decades. The highest positive mass budget (0.7 ± 0.1 m w.e. a^{−1}) was estimated for Glacier No. 4 during 1969–1983, while the most negative mass budget (-1.0 ± 0.5 m w.e. a^{−1}) was observed for Sary Tor Glacier in Central Asia from 2015 to 2023 ([Fig. 2](#)). The mass budgets of both South Asian glaciers were positive in the first decade (1970–1980) of observation and then the rate of mass loss from both the glaciers gradually increased throughout the observation period, while the Central Asian glaciers exhibited negative mass budget over the whole period of observation. The cumulative mass loss over a period of approximately fifty years was greatest for Sary Tor Glacier from Ak-Shiirak (-29.1 ± 4.6 m w.e) and least for Chhota Shigri Glacier from Western Himalaya (-13.8 ± 2.5 m w.e.). The average mass budgets over the whole period of observation were -0.3 ± 0.05 m w.e a^{−1} for both Chhota Shigri and Tuyuksu glaciers, followed by Glacier No. 4 (-0.4 ± 0.1 m w.e a^{−1}) and Sary Tor Glacier (-0.6 ± 0.1 m w.e a^{−1}).

We utilised six DEMs for Tuyuksu, Chhota Shigri, and Glacier No. 4 and seven DEMs for Sary Tor Glacier to generate multi-temporal mass balance estimates. This resulted in 15 mass balance combinations for the first three glaciers and 21 combinations for Sary Tor Glacier (supplement section S4). We interpolated the geodetic mass balance observations using [Eq. \(5\) and \(6\)](#) and overlaid them with the annual modelled mass balance ([Fig. 3](#)). This comparison indicates a gradual increase in mass loss for Chhota Shigri Glacier, a nearly stable mass budget for Tuyuksu and Sary Tor glaciers between 1980 and 2005 and an accelerated mass loss for Glacier No. 4. The modelled series provide a more detailed representation, capturing variabilities in mass budgets by accounting for glacier-climate interactions and glacier dynamics. Overall, the model vs. geodetic mass balance trends accord.

5.3. Modelled annual and seasonal mass balance

The modelled annual and seasonal mass balance demonstrates significant variability in the regimes of accumulation and ablation across the studied glaciers ([Figs. 3, 4](#)). The mass balance range was similar for Tuyuksu and Chhota Shigri glaciers. Sary Tor Glacier had a narrower range and Glacier No. 4 experienced the most extreme variations ([Fig. 4](#)). Cumulatively, Chhota Shigri and Tuyuksu Glaciers accumulated 41.8 m w.e. and 45.2 m w.e. respectively, with corresponding ablation of −52.2 m w.e. and −61.7 m w.e., respectively. Sary Tor Glacier had the smallest accumulation (12.7 m w.e) and ablation (−38.1 m w.e), while Glacier No. 4 experienced the highest accumulation (130.2 m w.e) and ablation (−150.8 m w.e.).

No statistically significant trends were observed in annual or seasonal mass balance for Chhota Shigri and Sary Tor Glaciers. However, Tuyuksu Glacier exhibited negative trends in both summer and annual mass balance. Glacier No. 4 showed a significant decreasing trend in both annual and seasonal mass balances, particularly during the period (1983–2015) when adjustments in model parameters, such as albedo and station elevation, captured the glacier's dynamic response to

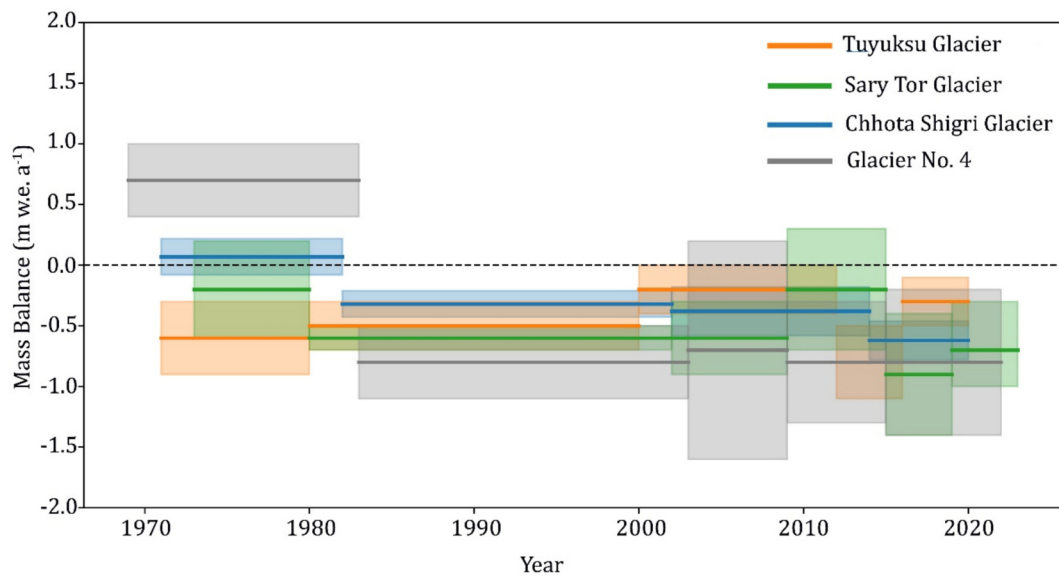


Fig. 2. Multi-temporal non-overlapping geodetic mass balance of the four glaciers under study. The lighter shades represent the uncertainty ranges.

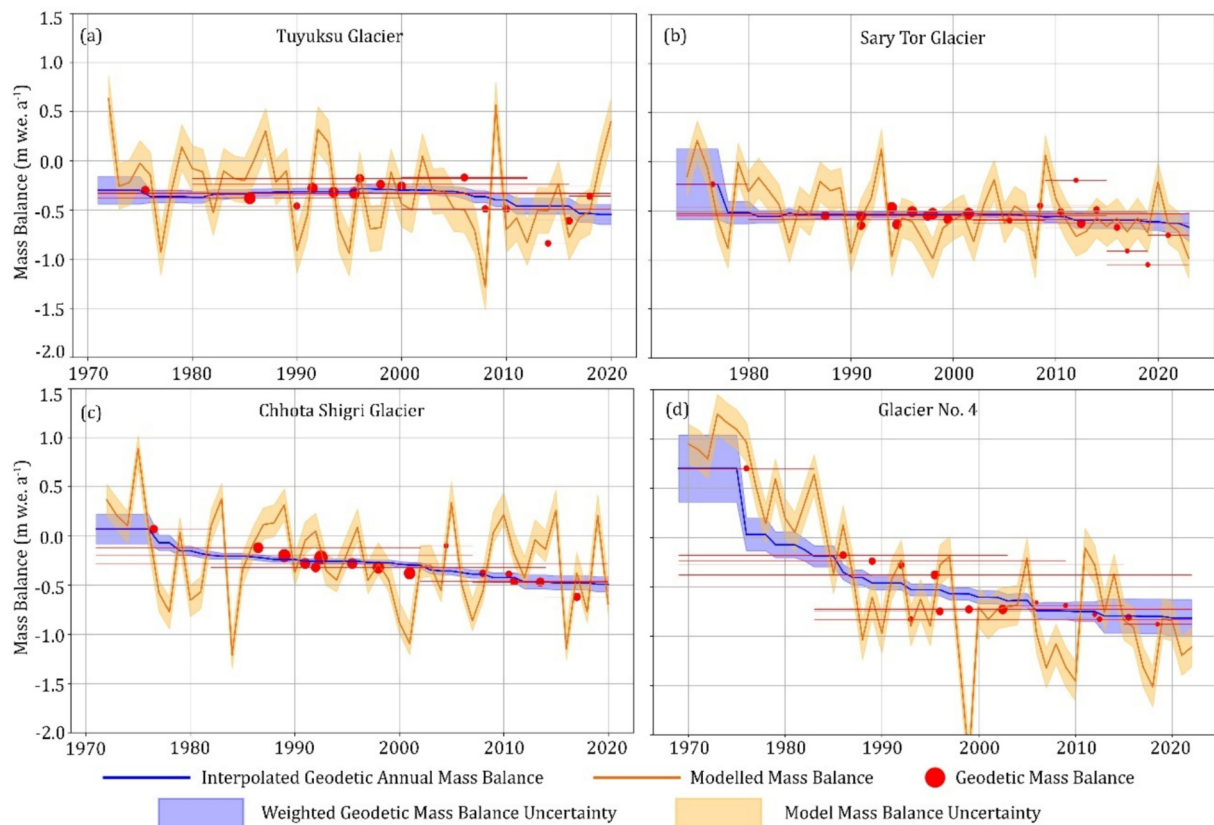


Fig. 3. Annual modelled mass balance and interpolated geodetic mass balance. The red dots represent the geodetic mass balance for different periods represented by the red horizontal lines. The size of the dot is inversely proportional to the uncertainty values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

changing climatic conditions.

5.4. Validation of modelled mass balances using geodetic and glaciological mass balance

We compared the simulated cumulative modelled mass balance of different periods with corresponding geodetic mass balance

observations (Fig. 5). We observe a general agreement between the geodetic and modelled mass balance, though the geodetic mass balance estimates are often more negative compared to the modelled estimates over the same period. This could be due to geodetic mass balance including both internal and basal mass balance while modelled mass balance considers only the surface mass balance (Zemp et al., 2013). Considering the uncertainties of the geodetic estimates, the differences

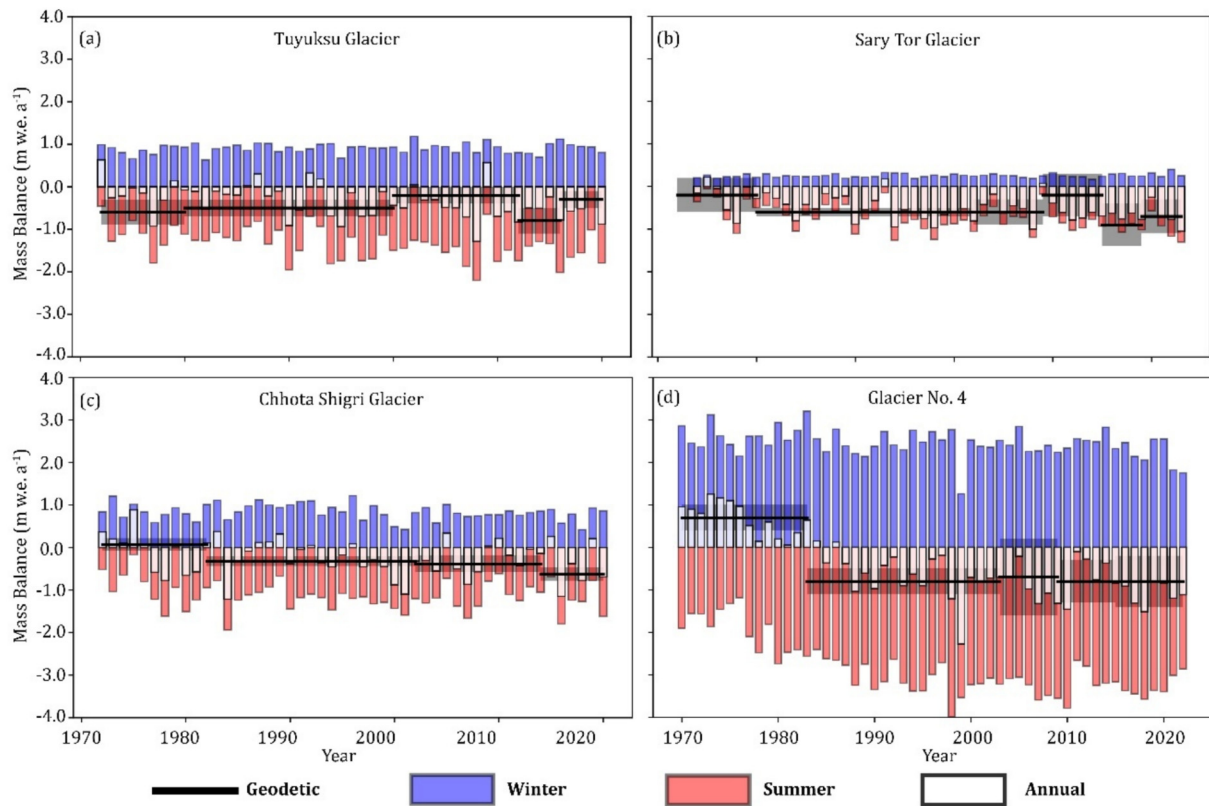


Fig. 4. Simulated annual and seasonal mass balance series of the study glaciers. Geodetic mass balance uncertainties are represented by light grey shades.

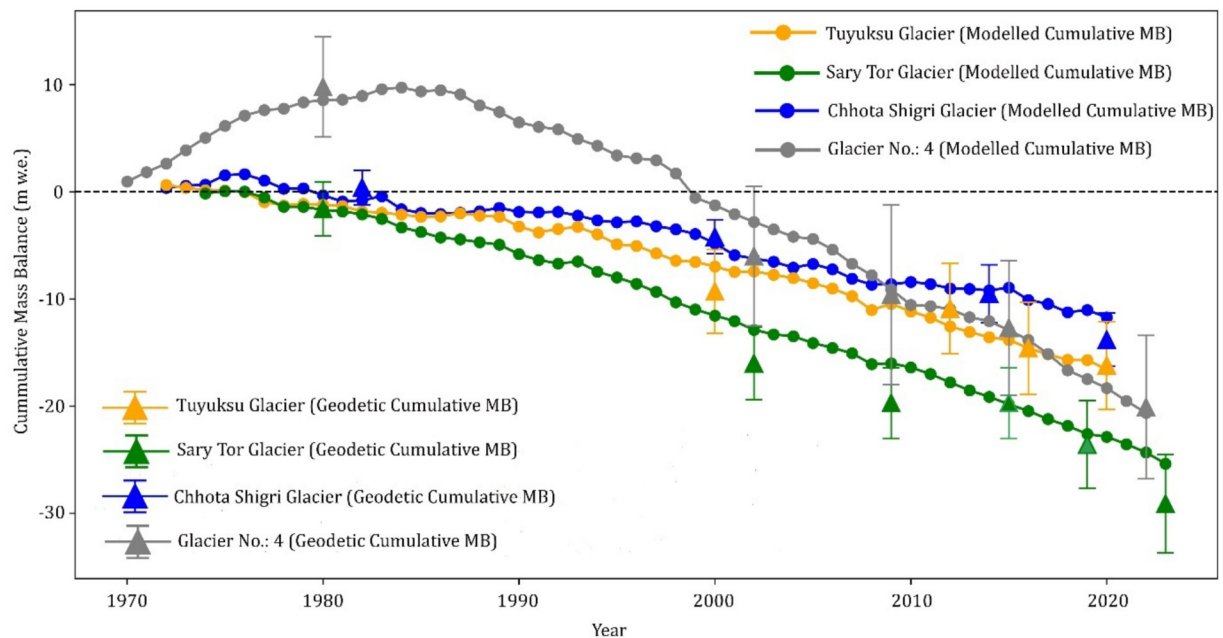


Fig. 5. Cumulative modelled vs. geodetic mass balance (MB: Mass Balance). The geodetic cumulative mass balance is calculated with respect to the first available DEM for each glacier region.

are acceptable. However, the uncertainties in geodetic mass balance computations are often high, particularly when the reference DEM is derived from spy satellite images (as in Fig. 5). The older images have a limited dynamic range compared to recent high-resolution images, leading to less image contrast and possibility of finding matching points from the stereo pairs. This leads to unrealistic elevations which are then

removed from the elevation difference image leading to voids, resulting in high uncertainties as explained by Eq. (3). Additionally, successful removal of unstable terrain before co-registration was particularly challenging for pre-2000 DEMs due to snow cover and panchromatic data, thus limiting our abilities of automated removal, leading to uncertainties in the stable terrain (Eq. 2). More explanations are provided

in the discussion section.

5.4.1. Annual and seasonal mass balance comparison

Glaciological mass balance observations are available for three of the four glaciers from WGMS (2024) (Table 1). For Tuyuksu, Sary Tor and Chhota Shigri glaciers, geodetic and modelled mass balance data are available from 1971–2020, 1973–2023, and 1971–2020, respectively. We observed a statistically significant correlation between the modelled and glaciological annual and seasonal mass balance series, with a moderate positive correlation for annual mass balance and strong positive correlation for seasonal mass balance (Fig. 6). This suggests that overall, despite some differences in the absolute values of mass budgets, the trends are similar.

5.4.2. Elevation-band-wise mass balance comparison

For Tuyuksu Glacier, elevation band wise glaciological, geodetic and modelled mass balance exhibit close agreement in annual mass balance, with some deviations at higher elevation (above 3900 m) (Fig. 7, top a). Seasonal mass balance results indicate that the model tends to overestimate both summer mass loss and winter gain (Fig. 7, top b, c). For Sary Tor Glacier, modelled, glaciological, and geodetic annual mass balances show strong agreement throughout the elevation range (Fig. 7, middle a). Seasonal mass balance estimations are generally consistent, though the model slightly underestimates summer loss at lower elevations and winter gain at higher elevations (Fig. 7, middle b, c). For Chhota Shigri Glacier, the glaciological mass balance is slightly more negative at lower elevations compared to modelled or geodetic estimates (Fig. 7, bottom).

5.5. Mass balance sensitivities to climate

The annual and seasonal mass balance sensitivities (Table 2) indicate that Glacier No. 4 exhibits the highest sensitivity to changes in both annual temperature and precipitation, while Sary Tor Glacier shows the lowest sensitivity. Summer temperatures exert greatest influence on the mass balance changes for all glaciers. Winter temperatures contribute substantially to the mass balance changes of Glacier No. 4 but have minimal effect on other glaciers.

Regarding precipitation, summer and winter precipitation have nearly equal influence on the mass balance of Chhota Shigri and Tuyuksu glaciers. In contrast, summer precipitation dominates the mass balance of Sary Tor Glacier, whereas winter precipitation has a significantly greater impact than summer precipitation on Glacier No. 4.

These findings suggest that Chhota Shigri and Tuyuksu glaciers accumulate mass relatively evenly during both summer and winter seasons. However, Sary Tor Glacier primarily accumulates during summer and Glacier No. 4 accumulates predominantly during winter.

The dynamic mass balance sensitivity, considering the combined influence of temperature and precipitation, is lowest for Sary Tor Glacier, followed by Chhota Shigri Glacier and Tuyuksu Glacier, and highest for Glacier No. 4, as reflected in its more densely spaced contours (contour interval: 0.25 m w.e., Fig. 8). The nearly vertical orientation of the contours for all glaciers suggests a strong sensitivity to temperature changes than to precipitation. Glacier No. 4 exhibits steepest contours,

emphasizing its heightened sensitivity to climate.

For the other glaciers, the mass balance response is non-linear with respect to both temperature and precipitation changes (Fig. 8), especially at the lower temperature and precipitation levels. It implies that to maintain a constant mass balance, precipitation must increase substantially more compared to temperature in a warmer climate.

Additionally, we found that the effect of a 1 °C increase in annual temperature can be offset by a 30% increase in annual precipitation for Chhota Shigri and Tuyuksu glaciers. However, for Sary Tor Glacier and Glacier No. 4, even a 30% increase in precipitation is inadequate to fully compensate the mass loss caused by a 1 °C temperature rise. These results indicate the differential sensitivities of the glaciers and underscore the dominant influence of temperature changes on glacier mass balance in warmer climates.

5.6. Climatic trends

To understand the climatic trends, we performed Mann-Kendall trend test along with statistical significance (p), which represents the probability (p) that the observed trend is due to random chance (Table 3).

Climatic trend test results reveal that Tuyuksu and Sary Tor glaciers experienced significant rise in summer and winter temperatures, whereas precipitation has not changed significantly. However, no significant change in either temperature or precipitation was observed for Chhota Shigri Glacier. For Glacier No. 4, both temperature and precipitation have significantly increased, except for winter precipitation, which has no significant trend.

5.6.1. Validation of ERA5 Land climate data using station data

To validate the climate data from ERA5 Land using climate station data, we calculated the correlation (r) along with statistical significance (p) (supplement section S5).

For Tuyuksu Station, both temperature ($r = 0.99$, $p < 0.001$) and precipitation ($r = 0.79$, $p < 0.001$) show strong correlations with ERA5 Land, although there is a slight positive bias. At Tien Shan Station, the temperature measurements from ERA5 Land closely align with the station values ($r = 0.99$, $p < 0.001$), indicating a strong correlation. However, ERA5 Land tends to overestimate precipitation compared to the station data, although the overall correlation remains statistically significant ($r = 0.80$, $p < 0.001$).

Monthly temperature and precipitation data for Bhuntar Station reveal that ERA5 Land tends to underestimate temperature values by approximately 5–10 °C, with a mean bias of around 6.5 °C. Despite this discrepancy, the correlation between ERA5 Land and station temperature is very strong, with $r = 0.98$ and $p < 0.001$. For precipitation, while there is a notable correlation ($r = 0.53$, $p < 0.001$), ERA5 Land tends to overestimate some values significantly. Specifically, the maximum recorded monthly precipitation at the station is around 300 mm, whereas ERA5 Land estimates can reach up to 1000 mm. Notably, values exceeding 400 mm account for only about 3% of all recorded precipitation values.

Table 1
Study glaciers.

#	Name (RGI60_ID)	Area in 1970s (km ²)	Altitude range in 1970s (m)	Latitude	Longitude	Elevation band wise glaciological mass balance (mm w.e)	
						Annual	Seasonal
1	Chhota Shigri (14.15990)	16.8	4150–5780	32.23°N	77.51°E	1987–1988, 2003–2019, 2022-present	None
2	Tuyuksu (13.08624)	2.9	3358–4174	43.04°N	77.08°E	1957–present	1957–present
3	Sary Tor (13.08055)	3.5	3858–4730	41.82°N	78.17°E	1985–1989, 2015–present	1985–1989, 2015–present
4	Glacier No.4 (15.02999)	2.3	4787–5520	27.73°N	88.36°E	None	None

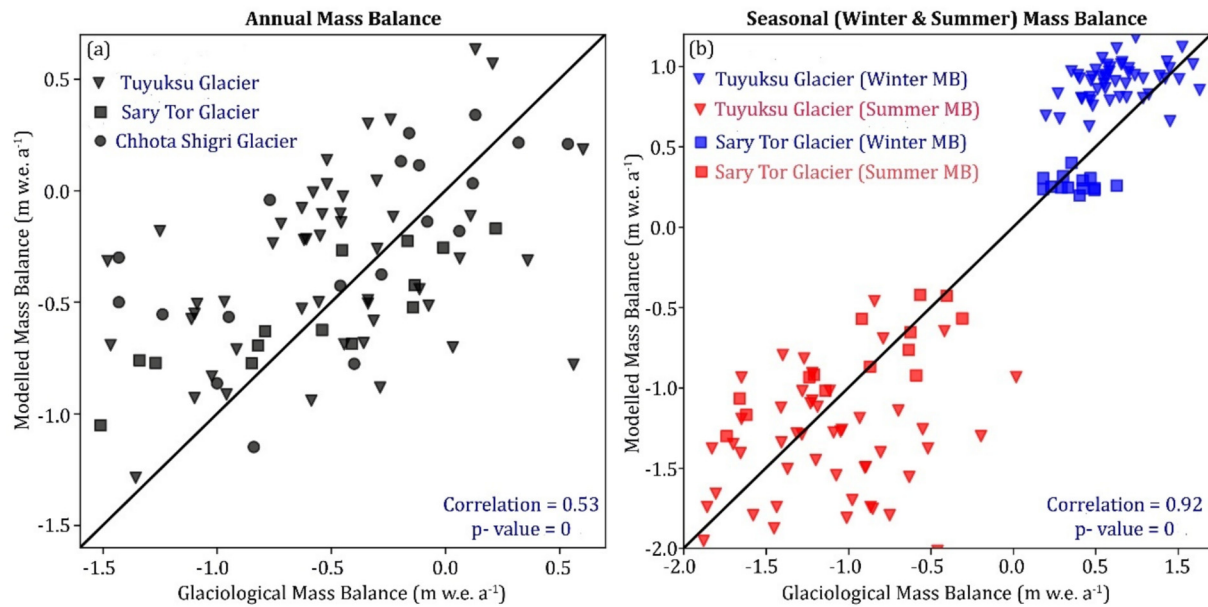


Fig. 6. Glaciological vs. modelled annual and seasonal mass balance.

5.6.2. Projected climate trends

Projected temperature and precipitation anomalies indicate heterogeneous changes for all investigated glaciers (Figs. 9, 10). Differences between the various scenarios are more pronounced, particularly after 2040.

Temperature anomalies (Fig. 9) indicate a similar temperature increase (2 °C) across all regions for SSP126. However, for the three higher emission SSP scenarios, temperature increases are more pronounced for Central Asian glaciers than the South Asian glaciers.

Precipitation anomalies (Fig. 10) indicate a more varied pattern across different glacier regions and SSP scenarios. For South Asian Glaciers, SSP126 and SSP245 project a moderate precipitation increase (<10%), while higher emission scenarios suggest a more significant rise, especially after 2060. In contrast, for Central Asian glaciers, precipitation increases are less pronounced under higher emission scenarios.

Overall, SSP126 represents a limited temperature rise restricted to 2 °C and a maximum precipitation increase of 10% across the glacier regions.

6. Discussions

6.1. Comparison of changes in glacier extents with previous studies

The length and area change rates of the South Asian glaciers were much less compared to those of the Central Asian glaciers. There are slight variations of the length and area change rate of Chhota Shigri Glacier with other studies (supplement section S6). One reason could be due to previous studies focusing primarily on area changes near the glacier's snout. The variations may also result from differences in methodology, datasets and observation periods. However, the length and area fluctuations of the Tuyuksu and Sary Tor glaciers were comparable to other published studies. Please see supplement section S6 for more details.

6.2. Comparison of geodetic mass balance with previous studies

Various studies have derived geodetic mass balance estimates for Tuyuksu, Sary Tor, and Chhota Shigri glaciers (Supplement section S7). We compared our results with published estimates focusing on the longest period pre- and post- 2000 (Fig. 11).

The range of geodetic mass budget estimates for Tuyuksu Glacier was

within $-0.32 \text{ m.w.e. a}^{-1}$ (1958–1998, Hagg et al., 2004) and $-0.48 \text{ m.w.e. a}^{-1}$ (2000–2019, data from Hugonnet et al., 2021). Our results of $-0.38 \text{ m.w.e. a}^{-1}$ for 1971–2000 and $-0.49 \text{ m.w.e. a}^{-1}$ for 2000–2020 agree with these results and those reported in other studies (Kapitsa et al., 2020; Bhattacharya et al., 2021; Brun et al., 2017; Shean et al., 2020). Glaciological mass balance is, however, slightly more negative (-0.42 to $-0.55 \text{ m.w.e. a}^{-1}$) for the period before 2000 (Hagg et al., 2004; WGMS, 2024). For the period after 2000, glaciological mass balance ($-0.44 \text{ m.w.e. a}^{-1}$) is comparable with geodetic mass balance.

Sary Tor Glacier's annual geodetic mass balances ranges within $-0.27 \text{ m.w.e. a}^{-1}$ (1964–1980, Bhattacharya et al., 2021) and $-0.53 \text{ m.w.e. a}^{-1}$ (1980–2002, Bhattacharya et al., 2021). The other studies reported mass balance values within this range (Brun et al., 2017; Goerlich et al., 2017; Hugonnet et al., 2021). In this study, however, we estimated a higher mass loss of $-0.63 \text{ m.w.e. a}^{-1}$ for the period after 2000 (2002–2023). This could be a result of the accelerated mass loss in the most recent period (2015–2013, $-1.05 \text{ m.w.e. a}^{-1}$, see supplement section S4). The glaciological mass loss considerably increased for the period after 2000 compared to the period before 2000, with an average mass loss of $-0.14 \text{ m.w.e. a}^{-1}$ in 1985–1989, which increased to $-0.84 \text{ m.w.e. a}^{-1}$ in 2015–2023.

Satellite-based mass budget estimates for Chhota Shigri Glacier since 2000 have ranged from approximately 0.09 ± 2.4 (1988–1999) to $-0.77 \pm 0.25 \text{ m.w.e. a}^{-1}$ (2002–2014) (Vincent et al., 2013; Gardelle et al., 2013; Vijay and Braun, 2016; Brun et al., 2017; Garg et al., 2017; Mukherjee et al., 2018; Shean et al., 2020). Our mass loss estimates for 2002–2020 ($-0.46 \pm 0.14 \text{ m.w.e. a}^{-1}$) is slightly higher than Hugonnet et al. (2021), who reported $-0.26 \pm 0.06 \text{ m.w.e. a}^{-1}$ for 2000–2019 and $-0.27 \pm 0.07 \text{ m.w.e. a}^{-1}$ for 2002–2022. Most probably, this discrepancy arises due to our use of modified RGI 6.0 glacier polygons, whereas Hugonnet et al. (2021) used the original RGI 6.0 polygons, which connected Chhota Shigri Glacier with another adjacent glacier. Moreover, the glacier tongue was also delineated correctly in this study (supplement section S8). The glaciological mass budget estimates of Chhota Shigri Glacier were in general more negative than the geodetic measurements.

For the closest reference glacier to Glacier No. 4, Parlung Glacier, the mass balance ranged within $0.16 \text{ m.w.e. a}^{-1}$ (2011) and $-2.06 \text{ m.w.e. a}^{-1}$ (2021) (WGMS, 2024), with an average of $-1.1 \text{ m.w.e. a}^{-1}$ and cumulative mass balance of -17.8 m.w.e. for the whole period. The cumulative geodetic mass balance for Glacier No. 4 for the period

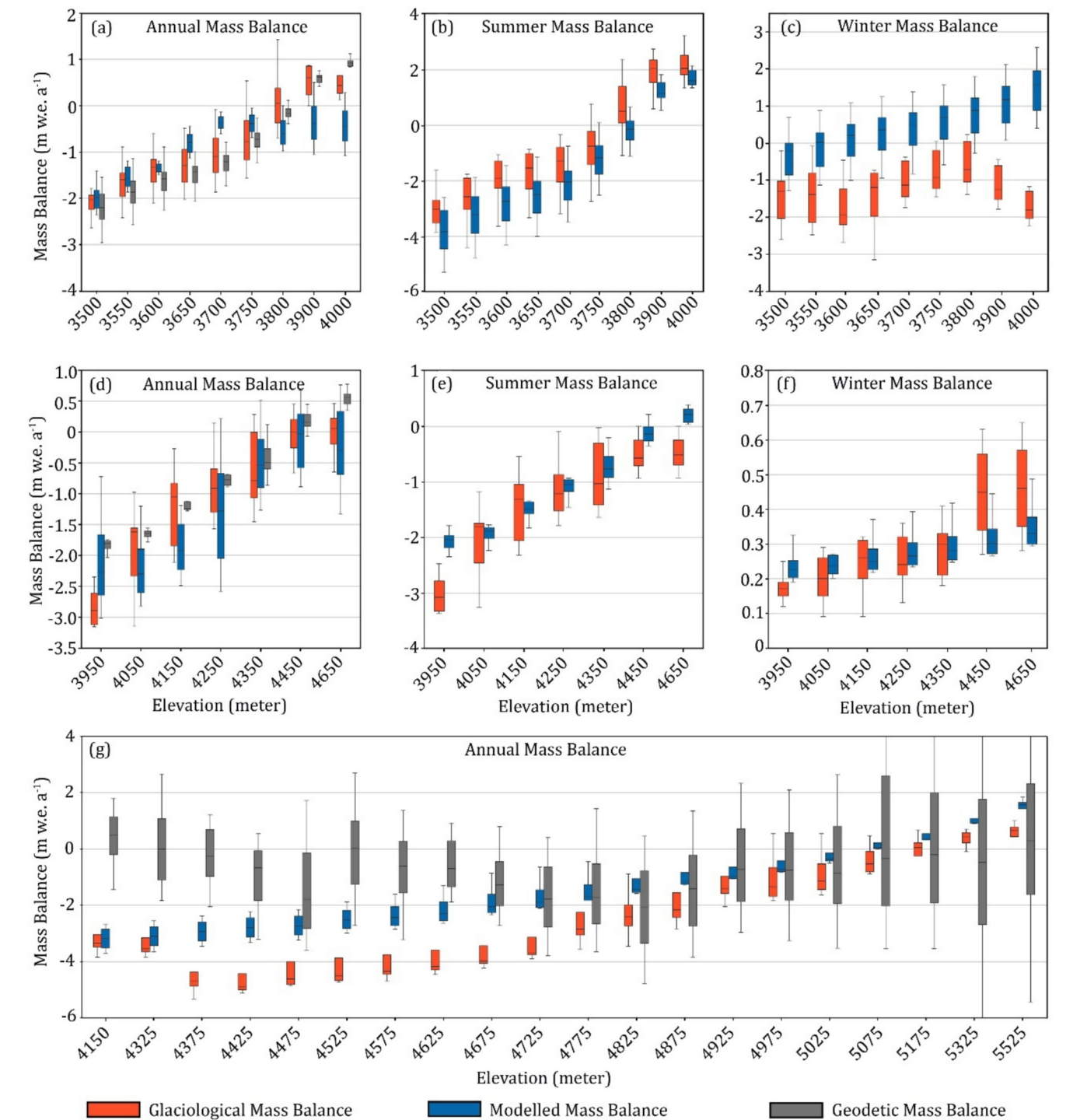


Fig. 7. Elevation band wise (a-c) Annual and seasonal mass balance of Tuyuksu Glacier and (d-f) Sary Tor Glacier; (g) annual mass balance of Chhota Shigri Glacier;

Table 2
Annual (A) and seasonal (summer: S, winter: W) mass balance sensitivity to temperature (β_T) and precipitation (β_P).

	Tuyuksu			Sary Tor			Chhota Shigri			Glacier No. 4		
	S	W	A	S	W	A	S	W	A	S	W	A
β_T	0.50	0.02	0.51	0.43	0	0.43	0.43	0.01	0.45	0.99	0.26	1.26
β_P	0.28	0.29	0.57	0.27	0.09	0.36	0.25	0.27	0.51	0.08	0.89	0.81

Unit of β_T : m w.e. °C⁻¹; Unit of β_P : m w.e. for 30% increase in precipitation.

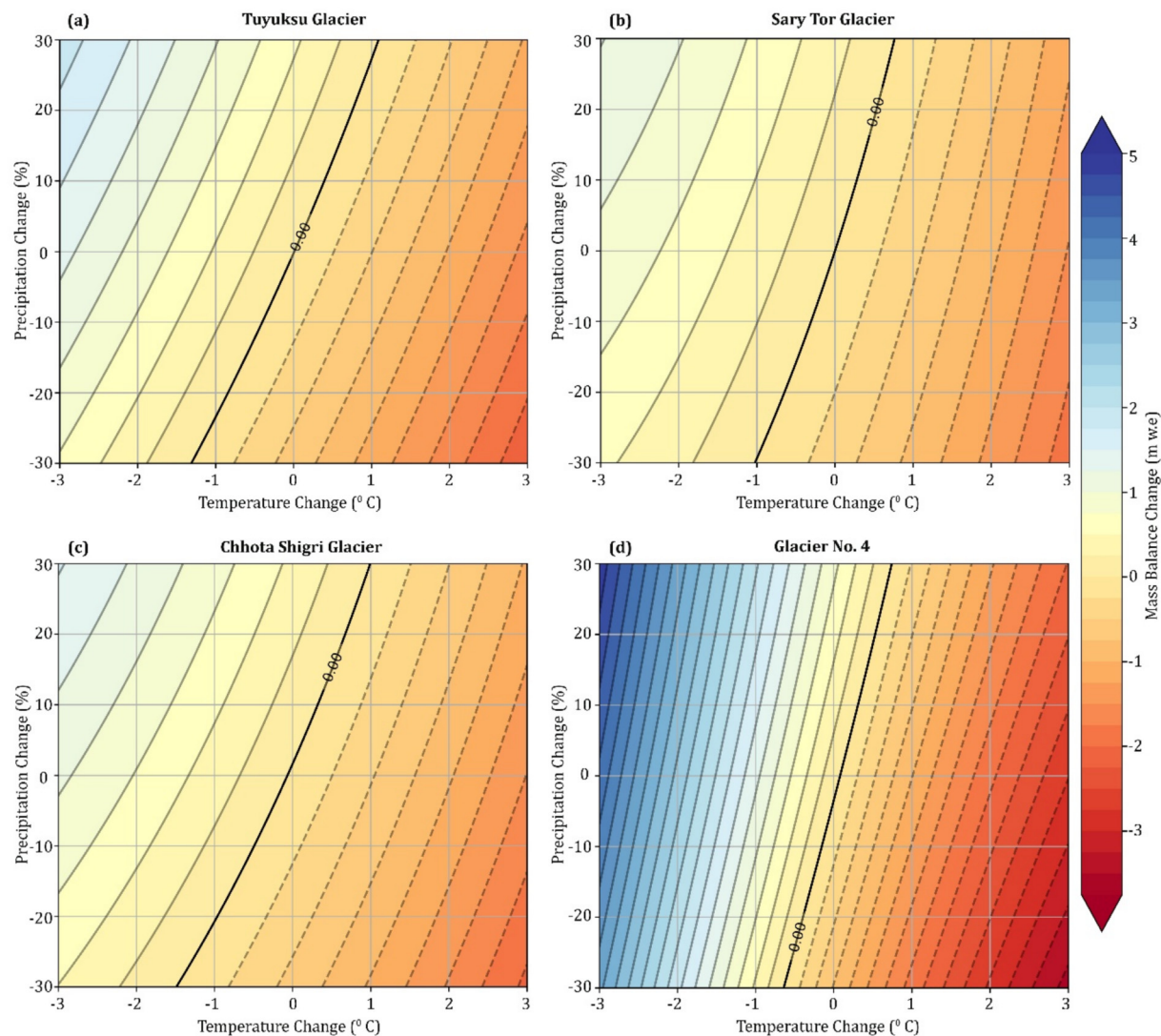


Fig. 8. Dynamic climate sensitivities of the glaciers under the combined impact of temperature and precipitation.

Table 3
Mann-Kendall trend test of the seasonal climate parameters for each glacier using ERA5 Land climate data for the period 1950–2020.

–	Tuyuksu			Sary Tor			Chhota Shigri			Glacier No.4		
	S	W	A	S	W	A	S	W	A	S	W	A
T	Inc	Inc	Inc	Inc	Inc	Inc	None	None	None	Inc	Inc	Inc
P	None	None	None	None	None	None	None	None	None	Inc	None	Inc

S: Summer; W: Winter, A: Annual; T: Temperature; P: Precipitation; Inc: Increasing trend; None: No trend; p < 0.05 for both increasing and decreasing trends.

2003–2022 is -15.8 ± 7.3 m w.e. with an annual mass budget of -0.8 ± 0.4 m w.e. a^{-1} . However, Parlung Glacier is almost 850 km away from Glacier No. 4 and in a different mountain range.

6.3. Uncertainties in mass balance measurements

The discrepancy of glaciological mass balance with geodetic mass balance may be due to glaciological point measurements unable to fully capture spatial variability of the mass budget (Elsberg et al., 2001; Cogley et al., 2010). Here we observed one such example for Tuyuksu Glacier where the glaciological point observations do not cover most of the highest accumulation region, and this might be the reason behind the underestimation of winter mass gain in those elevation bands as observed in Fig. 7 (Hagg et al., 2004; Shahgedanova et al., 2020; WGMS,

2024). Additionally, glaciological mass balance measures the surface mass balance and is directly linked to climate and does not include dynamic adjustments, whereas geodetic mass balance includes the basal and internal mass balances and the effects of dynamic adjustments of the glacier (Elsberg et al., 2001; Zemp et al., 2013; Demuth and Ednie, 2016). Hagg et al. (2004) observed that while glaciological measurements capture seasonal variations in mass budget, there can be significant uncertainties in cumulative mass budget estimates due to incomplete observation network and cumulative systematic errors over a long period (Zemp et al., 2013). These uncertainties can be more effectively addressed through long-term geodetic measurements covering the whole glacier.

Geodetic mass balance estimates may also suffer from significant uncertainties stemming from the quality of the stereo pairs, DEM

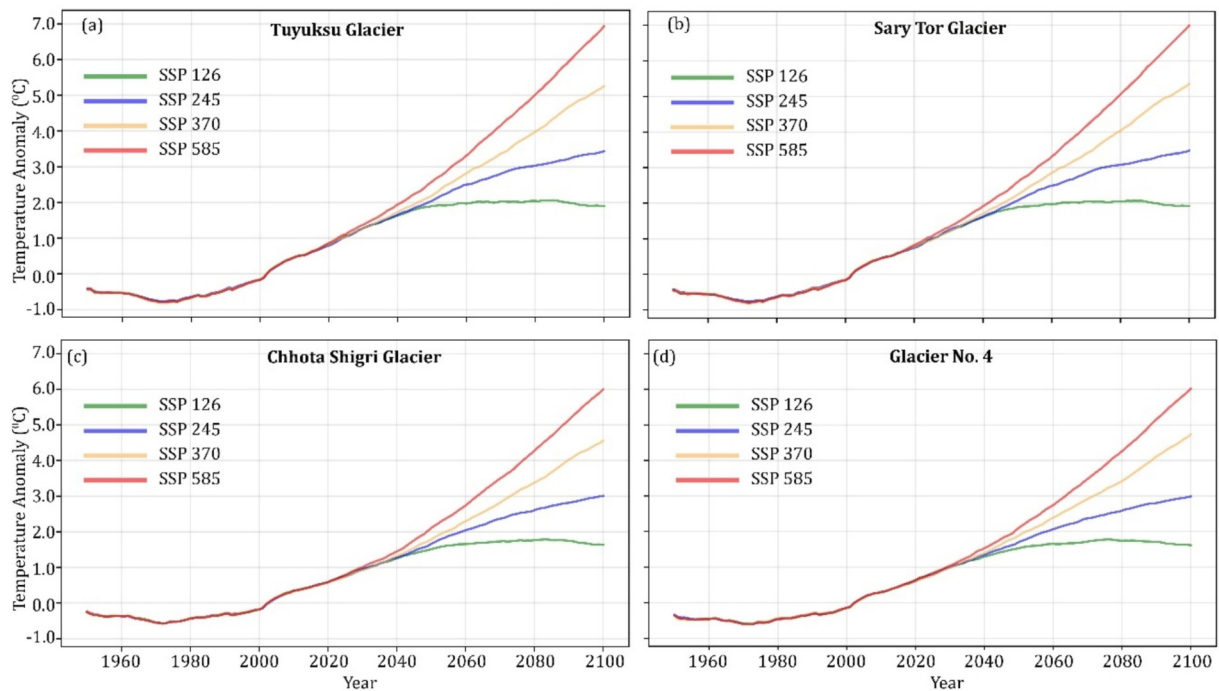


Fig. 9. Temperature anomalies ($^{\circ}\text{C}$, ten years moving average) with the baseline mean annual temperature for the four glacier regions.

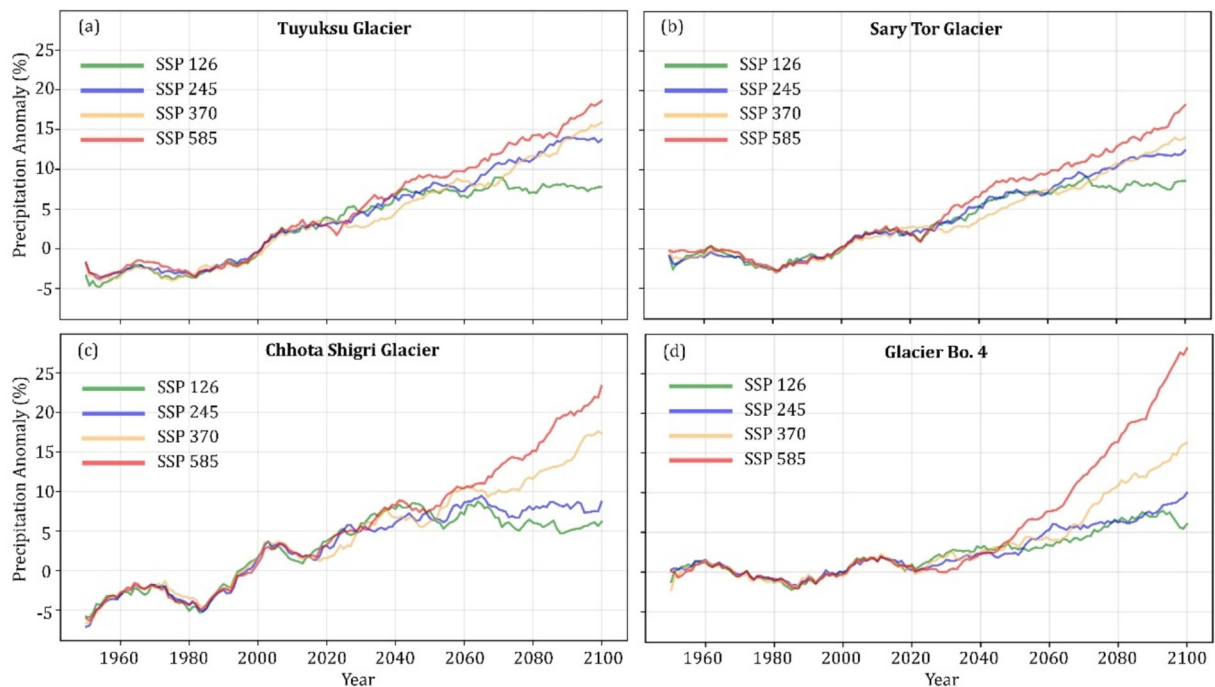


Fig. 10. Precipitation anomalies (% , ten years moving average) with the baseline mean annual precipitation for the four glacier regions.

processing, DEM co-registration, and outlier handling (Zemp et al., 2013; McNabb et al., 2019; Mukherjee et al., 2023; Piermattei et al., 2024). Low dynamic range and poor contrast of the historical spy satellite imagery limit the accuracy of the elevation models generated using these images (Shean et al., 2016). In this study, an important source of mass balance uncertainty originates from imperfect co-registration of DEM pairs due to the challenges associated with the selection of stable terrain during co-registration. This was also identified as a major source of uncertainty in an intercomparison exercise (Piermattei et al., 2024).

Identifying stable terrain (pixels with unchanged elevation over the study period), is often quite challenging, requiring the exclusion of pixels representing snow, water surfaces, vegetation such as new tree cover, or glaciers. Some of the stereo images for Glacier No. 4 we used in this study contained substantial snow cover. To address this, we used a combination of normalized indices to filter out snow, vegetation, and water pixels (Carlson and Ripley, 1997; Hall and Riggs, 2011). To automate this process, we used recent multi-spectral images having visible, near infrared and short-wave infrared bands. However, for older

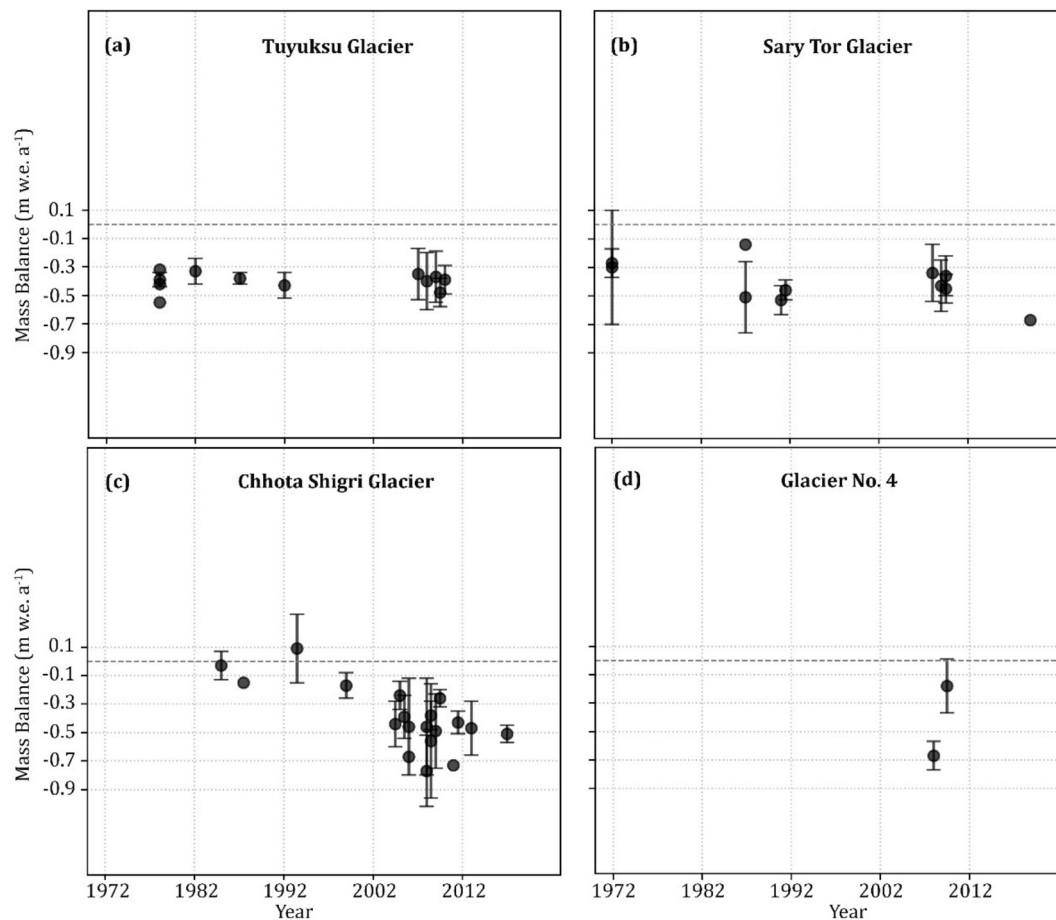


Fig. 11. Mass balance measurement results from other studies by using the midpoint year of each mass balance measurement period (Please see supplementary information S7 for more details).

DEMs derived from the declassified images, the lack of suitable multi-spectral images limited our ability to fully eliminate all the unstable pixels. This has led to higher uncertainty values for some of the geodetic mass balance estimates. Additionally, uncertainties also arise from the methods chosen for outlier removal, and handling data voids after outlier removal (McNabb et al., 2019).

6.4. Utility of multi-temporal geodetic mass balance and modelled mass balance

Multi-temporal geodetic mass balance provides us with an opportunity to generate a mass balance time series (Fig. 3), enabling an overall comparison of how different glaciers react to climate change. However, physically based models offer a more comprehensive analysis by incorporating the physics of glacier-climate interactions. Such detailed assessments provide us with the opportunity to quantify the varying sensitivities of glaciers to climate change. For instance, if we consider only post-2000 geodetic mass balance, as most studies have focused on this era, all four glaciers exhibit mass loss. The fluctuation of geodetic mass balance suggest that Sary Tor Glacier experienced the greatest variation in mass loss, ranging from -0.19 ± 0.47 m w.e. a^{-1} (2009–2015) to -1.05 ± 0.48 m w.e. a^{-1} (2015–2023), meaning most sensitive to climate. However, this interpretation is misleading, as simulation of long-term mass budget and climate sensitivity estimations indicate that Sary Tor glacier is least sensitive to climate (Table 2, Fig. 8).

The elevation band wise annual modelled mass balance (Fig. 7) indicates larger differences with those of geodetic mass balance, particularly at lower elevations of Chhota Shigri Glacier. This difference may be

attributed to ice dynamics and the resulting ice emergence at lower elevations, which are captured by geodetic observations, but not by glaciological observations. Such a difference also exists for Sary Tor Glacier, whereas no such difference is evident for Tuyuksu Glacier.

The modelled winter mass balance of Tuyuksu Glacier (Fig. 7) widely deviates from the glaciological mass balance, particularly at higher elevations. Overall, the model predicts greater summer losses and higher winter gains for this glacier. The overestimated summer loss is compensated by the winter gain, leading to an overall good agreement in the elevation band wise annual mass budget. Summer was defined as June to September, with winter encompassing the remaining months. It is possible that the glaciological observations do not coincide with this time, which leads to the large deviation. Additionally, the discrepancies may also be caused due to the imperfection of the observational network, which, for Tuyuksu Glacier does not cover the accumulation well (Shahgedanova et al., 2020; WGMS, 2024). Without a proper consideration to calculate the mass balance for each elevation band, while considering the lack of proper coverage, we can expect deviations with geodetic results where the whole glacier is covered by the images. In contrast, for Sary Tor Glacier, seasonal modelled and glaciological mass balance values align more closely across elevation bands.

The geodetic mass balance is often more negative than the cumulative modelled mass balance (Fig. 5), although the values remain within the uncertainty bounds. One of the reasons could be that geodetic mass balance includes basal and internal balance in addition to surface mass balance. Another explanation is that the model was calibrated using a single representative albedo value for the entire simulation period. Glacier albedo varies interannually, influenced by factors such as snowfall accumulation and surface melt, both of which are closely

linked to mass balance (Johnson and Rupper, 2020). However, as we do not have reliable estimates of albedos or equilibrium line altitudes for the glaciers over the whole period to calibrate and validate the model, we used a constant representative albedo (Mortezapour et al., 2020; Mukherjee et al., 2023). This approach ensured consistent calibration and enabled application beyond the calibration period without introducing additional, unvalidated parameters. Although spatiotemporal variations in albedo could be prescribed (e.g., decreasing albedo over time to reflect surface darkening, which would lead to greater modelled mass loss), such choices would necessitate further tuning beyond the calibration period and add complexity. Given the already substantial number of parameters in SnowModel, we prioritized model stability and consistency.

Similarly, the assumption of isothermal ice in the ice dynamics component may introduce some error, particularly for polythermal glaciers like Tuyuksu and Sary Tor (Nosenko et al., 2016; Jacquemart et al., 2025; Van Tricht and Huybrechts, 2022), where internal temperature gradients and basal conditions influence ice flow behaviour.

The mass balance observed for Glacier No. 4 during the period 1969–1983 is more positive than has been reported elsewhere in HMA for similar period (Goerlich et al., 2017; Bhattacharya et al., 2021). Bhattacharya et al. (2018) reported an average annual mass budget of -0.2 ± 0.3 m w.e. a^{-1} for ~400 glaciers in this region for the period 1975–2006, similar to our estimate for Glacier No. 4 (-0.2 ± 0.2 m w.e. a^{-1} , 1969–2003). To improve confidence in our mass balance estimates of this glacier for the period before 2000, we compared two independent estimates of multi-temporal mass budgets: (1) summing the mean mass balance of consecutive periods (1969–1983, 1983–2003, 2003–2009, 2009–2015, 2015–2022), which totalled -21.7 m w.e., and (2) estimating the mean mass balance using only the first (1969) and last (2022) DEMs, which yielded -20.1 ± 6.7 m w.e. The close agreement between these estimates suggests that a positive mass balance during 1969–1983 as reported here remains a possibility. Similarly, we validated the mass balance for all other periods and observed consistent results (supplement section S9).

However, this variation of mass balance before and after 1983 for Glacier No. 4 could not be explained by ERA5 Land forcing data. ERA5 Land data is generated through a climate reanalysis process, which combines historical weather observations with advanced numerical model to reconstruct past climate conditions (Munoz Sabater et al., 2021). Observations are available from satellites, weather stations, buoys, and radiosondes, among others, and are used to develop and validate ECMWF's land surface model, which is then used to fill the spatial and temporal data gaps ensuring consistency. As there are no station observations close to Glacier No. 4, ERA5 Land data may not have been able to reconstruct the climate for this region as well as for other regions having better climate observation data. This is also proved by the close agreement of ERA5 Land data with the station observations for Tuyuksu and Sary Tor glaciers, but not so well for Chhota Shigri Glacier (section 5.6.1, supplement section S5).

Another consideration is that the dates of the available KH4 and KH9 stereo images for Glacier No. 4 are 19th December 1969 and 11th November 1983, respectively. Ideally, we need stereo images of the end of summer (July–September, for northern hemisphere) for accurate mass balance calculations, so that the surface surrounding the glacier is free of snow cover and the extents can be clearly visualised and delineated. This was challenging for the above images as the scenes were mostly snow covered, and we believe this has introduced additional uncertainties in mass balance calculations, which we have not explicitly considered and used an area uncertainty of 10% for each mass balance measurement (Section 4.3). As we calibrated our model using the mean mass balance of different periods, the uncertainty of mass balance does not influence the model results.

To assess whether the pre-2000 geodetic mass balance significantly influences the modelled sensitivity, we also calibrated the model using geodetic mass balance data from 2003 to 2022. The resulting sensitivity

contours remained largely consistent, with a slightly narrower range of mass balance variation for the same temperature and precipitation changes (supplement section S10). Thus, while precisely reconstructing past mass balance is challenging, its impact on estimating the glacier's sensitivity to climate change and projected mass balance remains minimal.

6.5. Climatic trends and mass balance sensitivity

Glacier mass balance is primarily influenced by temperature, which controls ablation, and precipitation, which determines accumulation. Rising temperatures can impact its mass balance if they exceed freezing, reducing snowfall.

We observed that Sary Tor Glacier is a summer accumulation glacier, as it receives more precipitation in summer than in winter and is most sensitive to summer precipitation and temperature. Chhota Shigri and Tuyuksu glaciers accumulate in both seasons, more in winter due to lower temperatures. Since winter temperatures remain below freezing, they do not directly influence mass balance for these glaciers.

Glacier No. 4, however, is sensitive to both summer and winter temperature and precipitation, though summer temperature and winter precipitation have the most influence. Being in a comparatively warmer climate, Glacier No. 4 is sensitive to winter temperature increases, which have risen significantly without a corresponding increase in precipitation. In contrast, the other three glaciers, located in colder regions, are minimally affected by winter temperature changes.

CMIP6 projections for Tuyuksu Glacier indicates temperature increases of 2–7 °C and precipitation increase of 8–18% for different SSP scenarios. Due to its higher sensitivity to temperature, it is likely to experience significant mass loss. This glacier's lack of compensatory precipitation changes exacerbates the impacts of warming. For a 2 °C temperature rise accompanied by a 10% increase in precipitation, mass loss is projected to exceed -0.9 m w.e. a^{-1} (Fig. 8b).

Sary Tor Glacier, being the least climate-sensitive, may experience relatively smaller impacts. However, significant summer warming will still drive increased mass loss, as it is a summer-accumulation type glacier. Limited changes in precipitation further constrain its ability to counterbalance temperature-driven melting, resulting in a likely negative mass balance trend. CMIP6 projections indicate temperature increases of 2–7 °C and a 8–18% increase in precipitation, like Tuyuksu Glacier. Although Sary Tor's lower sensitivity may lead to slightly smaller losses (around -0.85 m w.e. a^{-1} or more for a 2 °C temperature rise with a 10% increase in precipitation, Fig. 8c), warming without enough increase of precipitation will still significantly impact its stability.

Projections for Chhota Shigri Glacier suggest temperature increases of 2–6 °C under different SSP scenarios. Precipitation increases by ~10% for lower emission scenarios, and higher for higher emission scenarios. Rising temperatures coupled with insufficient increases in precipitation would lead to mass loss. For instance, a 2 °C temperature rise with a 10% increase in precipitation would result in a mass loss of -0.81 m w.e. a^{-1} (Fig. 8a), with even greater mass losses expected at higher temperatures.

Our modelling experiments indicate that Glacier No. 4 is the most climate-sensitive glacier (Fig. 8d). Although increased precipitation could partially offset mass loss, the glacier's extreme sensitivity to temperature changes ensures that warming will remain the dominant factor. Projections indicate temperature increases of 2–6 °C and precipitation increase of 5–30%. With a 2 °C temperature rise and a 10% increase in precipitation, Glacier No. 4 is expected to lose approximately 1.8 m w.e. a^{-1} , struggling to maintain equilibrium despite being in a moderately wet climate regime.

Our coupled modelling builds on previous studies which have examined the sensitivity of glaciers to changes in climate using more simplistic model structures. The static mass balance sensitivities of Chhota Shigri and Tuyuksu glaciers were determined using simple temperature index mass balance models by Azam et al. (2014) and Liu

and Liu (2016). For Chhota Shigri, the sensitivity values were $-0.52 \text{ m w.e. } ^\circ\text{C}^{-1}$ and 0.16 m w.e. for 10% increase in precipitation. Among the five glaciers analysed by Liu and Liu (2016), Tuyuksu glacier was identified as one of the most climate sensitive in the Tien Shan region.

The mass balance sensitivity to temperature for eight HMA glaciers monitored by WGMS ranged from -0.5 to $-0.2 \text{ m w.e. a}^{-1} ^\circ\text{C}^{-1}$, based on a simple positive degree day mass balance model (Rasmussen, 2013). Tuyuksu Glacier exhibited a sensitivity of $-0.4 \text{ m w.e. a}^{-1} ^\circ\text{C}^{-1}$. Wang et al. (2019) reported a mean mass balance sensitivity $-0.59 \text{ m w.e. } ^\circ\text{C}^{-1}$ and 0.22 m w.e. for 30% increase in precipitation for 45 HMA glaciers with in-situ mass balance records spanning at least two years. Engelhardt et al. (2015) analysed four Norwegian glaciers using simple melt index model and reported annual mass balance sensitivities to temperature ranging from 0.55 to $1.74 \text{ m w.e. K}^{-1}$ and to a 30% change in precipitation ranging from 0.5 to 1.39 m w.e. These glaciers, like Glacier No. 4, exhibited higher sensitivity to summer temperature and winter precipitation.

Notably, the sensitivity values reported in these studies were static, as the empirical models did not account for the dynamic adjustments of glaciers. Moreover, in situ glaciological observations played a crucial role in calibrating mass balance models and determining sensitivity values in these studies. In contrast, our approach utilized geodetic mass balance observations to calibrate the mass balance model, allowing for dynamic adjustments of glacier extents after each hydrological year. By incorporating multi-temporal geodetic mass balance measurements for model calibration and validation, we present an alternative method for mass balance reconstruction and sensitivity analysis, particularly for data scarce regions such as Glacier No. 4 in the Sikkim Himalaya, where no prior studies exist. The high sensitivity of this glacier to climate changes underscores urgent need for enhanced glacier monitoring in this region.

While most monitored HMA glaciers analysed for sensitivity studies are small (Wang et al., 2019), three of the four glaciers in our study also fall into this category, with area smaller than 5 km^2 . In contrast, many Himalayan glaciers are significantly larger and often covered by substantial debris, yet multi-temporal geodetic mass balance studies have been conducted for some of the glaciers (Mukherjee et al., 2018; Bhat-tacharya et al., 2021, 2023). Our study presents a new opportunity to enhance understanding of the climate sensitivity of the larger Himalayan glaciers where similar multi-temporal geodetic mass balance data are available.

6.6. Utility of ERA5 Land climate data

The comparison of ERA5 Land data with climate station data suggests that ERA5 Land tends to represent a wetter climate for most regions. While temperature values show some biases, these can often be corrected due to their strong 1:1 correlation with station data. However, precipitation values, particularly in the Chhota Shigri region, exhibit significant discrepancies, especially at higher ranges. These differences, along with the lack of nearby climate station data for Glacier No. 4 underscore the need for more climate stations and the refinement of gridded reanalysis climate products through the integration of additional station data. Nevertheless, the statistically significant correlation scores increase our confidence in the climatic trends and mass balance sensitivities determined in this study.

In the absence of station observations, gridded reanalysis data is often utilized in modelling studies, such as those in glaciology and hydrology, to assess and predict water resource availability, distribution and management in an increasingly erratic climate. As a result, discrepancies between reanalysis data and observations can directly impact the accuracy of these assessments. Large deviations from true glacier mass balance can be avoided by calibrating and validating the mass balance model using geodetic/glaciological observations. However, when models are extended beyond the observation periods, for example to simulate mass balance changes under future climate scenarios, such

inaccuracies could lead to substantial errors and mislead our understanding of future water resource availability. The establishment of more climate stations and better access to station data would significantly enhance our ability to understand and mitigate the environmental impacts of climate change.

6.7. Comparative insights across climatic regimes of High Mountain Asia

Exploring glaciers across diverse climatic zones of High Mountain Asia, we reveal how local climate fundamentally shapes glacier behaviour and mass balance sensitivity. By combining glaciological, geodetic, and modelled mass balance estimates, we demonstrate how these approaches enrich each other and provide a more complete picture. Crucially, by including a glacier from a data-scarce region in the eastern Himalaya, where sensitivity to climate change is notably high, we underscore the urgent need for closer monitoring of this understudied yet vulnerable region. Our findings are consistent with recent studies across HMA that show glacier mass balance sensitivity (MBS) is strongly governed by summer temperature and its range, as well as the seasonal distribution of precipitation (Sakai and Fujita, 2017; Wang et al., 2019). A strong correlation of glacier surface elevation changes and MBS to temperature was reported by Sakai and Fujita (2017), which clearly explained the spatial heterogeneity of mass balance across the HMA. Consistent with our findings, Halji Glacier in Western Himalaya also shows that warming amplifies glacier mass loss asymmetrically, with stronger impacts from rising temperature (Arndt et al., 2021). MBS is also model dependent. Studies on the modelling work from Storglaciären demonstrate that simpler temperature-index models tend to underestimate glacier response to climate change, leading to underprediction of future mass loss compared to more complex, physically distributed energy balance models (Hock et al., 2007). This highlights that glacier sensitivity is shaped not only by climatic conditions but also by the methodological framework employed in modelling.

With continuous temperature increases projected across HMA, and glaciers in warmer, wetter climate regimes (like Glacier No. 4) showing heightened vulnerability, it is unlikely that these systems will re-establish equilibrium, even under wetter future scenarios. This comparative analysis illustrates how spatial variability in climate across HMA leads to distinct glacier responses and underscores the importance of incorporating both regional climatic regimes and methodological rigor into glacier projections. It further reinforces the need for regionally differentiated glacier adaptation strategies, particularly as warming intensifies across diverse glaciated landscapes.

7. Conclusions

Our analysis of annual and seasonal mass balance trends, along with calculated glacier sensitivities to temperature and precipitation, offer insight into the complex interplay between climate trends and glacial mass balance in High Mountain Asia. Using simulated mass balance of three well-studied glaciers, we extended the approach to a fourth glacier located in a region that, despite its high vulnerability to climate change, has received limited attention. Remote sensing-based modelling approaches complement in-situ observations of glacier change and enhance our ability to observe, monitor, and safeguard invaluable freshwater resources.

Our findings underscore the crucial role that temperature play in driving glacier mass loss in High Mountain Asia. Glaciers such as Tuyuksu and Glacier No. 4, which are most sensitive to temperature have the highest probability of accelerated mass loss in a warming climate. The absence of significant increases in precipitation for all glaciers further limits their ability to buffer against temperature-driven impacts. Notably, the pronounced mass balance sensitivity of Glacier No. 4 to climate change suggests it is particularly vulnerable, with even modest warming trends likely to lead to rapid deglaciation. Other glaciers in this region with similar climatic conditions are likely to share a

comparable vulnerability, further underscoring the urgent need for more frequent observations to better understand and mitigate the impacts of rapid deglaciation.

Although the mass balance regime of Chhota Shigri Glacier has been relatively stable in recent decades, its moderate sensitivity to temperature combined with a lack of proportionate future precipitation increases, heightens its vulnerability to warming. Similarly, while Sary Tor Glacier is the least sensitive overall, substantial temperature increases are still expected to drive considerable mass loss.

The proposed integration of remote sensing-based monitoring and modelling has been instrumental in predicting future hydrological impacts. Such analyses are essential for developing adaptive management strategies to address the challenges associated with climate-induced glacier changes.

CRediT authorship contribution statement

Kriti Mukherjee: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Atanu Bhattacharya:** Writing – review & editing, Software, Resources, Funding acquisition, Data curation, Conceptualization. **Sajid Ghuffar:** Software, Resources, Data curation. **Owen King:** Writing – review & editing, Software, Resources, Data curation. **Ankita Paul:** Data curation. **Tobias Bolch:** Writing – review & editing. **Brian Menounos:** Writing – review & editing, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work KM used chatgpt to refine the language in certain places. After using this tool, KM and all other authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

Kriti Mukherjee reports financial support was provided by Cranfield University. Kriti Mukherjee reports a relationship with Cranfield University that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloplacha.2025.105044>.

Data availability

Please see supplementary material S1 for the sources of satellite imageries. The Pléiades satellite data used in this study were provided by the Pléiades Glacier Observatory (Berthier et al., 2024), funded by DINAMIS, the French national infrastructure for shared access to very high-resolution satellite imagery.

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