# Spatial variability between glacier mass balance and environmental factors in the High Mountain Asia (Postprint)

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## Abstract

Abstract: High Mountain Asia (HMA) region contains the world's highest peaks and the largest concentration of glaciers except for the polar regions, making it sensitive to global climate change. In the context of global warming, most glaciers in the HMA show various degrees of negative mass balance, while some show positive or near-neutral balance. Many studies have reported that spatial heterogeneity in glacier mass balance is strongly related to a combination of climate parameters. However, this spatial heterogeneity may vary according to the dynamic patterns of climate change at regional or continental scale. The reasons for this may be related to non-climatic factors. To understand the mechanisms by which spatial heterogeneity forms, it is necessary to establish the relationships between glacier mass balance and environmental factors related to topography and morphology. In this study, climate, topography, morphology, and other environmental factors are investigated. Geodetector and linear regression analysis were used to explore the driving factors of spatial variability of glacier mass balance in the HMA by using elevation change data during 2000–2016. The results show that the coverage of supraglacial debris is an essential factor affecting the spatial heterogeneity of glacier mass balance, followed by climatic factors and topographic factors, especially the median elevation and slope in the HMA. There are some differences among mountain regions and the explanatory power of climatic factors on the spatial differentiation of glacier mass balance in each mountain region is weak, indicating that climatic background of each mountain region is similar. Therefore, under similar climatic backgrounds, the median elevation and slope are most correlated with glacier mass balance. The interaction of various factors is enhanced, but no unified interaction factor plays a primary role. Topographic and morphological factors also control the spatial heterogeneity of glacier mass balance by influencing its

sensitivity to climate change. In conclusion, geodetector method provides an objective framework for revealing the factors controlling glacier mass balance.

## Full Text

## Preamble

### Spatial Variability between Glacier Mass Balance and Environmental Factors in High Mountain Asia

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## Abstract

The High Mountain Asia (HMA) region contains the world' s highest peaks and the largest concentration of glaciers outside the polar regions, making it highly sensitive to global climate change. In the context of global warming, most glaciers in HMA exhibit various degrees of negative mass balance, while some show positive or near-neutral balance. Many studies have reported that spatial heterogeneity in glacier mass balance is strongly related to a combination of climate parameters. However, this spatial heterogeneity may vary according to the dynamic patterns of climate change at regional or continental scales, with reasons potentially related to non-climatic factors. To understand the mechanisms by which spatial heterogeneity forms, it is necessary to establish relationships between glacier mass balance and environmental factors related to topography and morphology. This study investigates climate, topography, morphology, and other environmental factors using geodetector and linear regression analysis to explore the driving factors of spatial variability in glacier mass balance across HMA based on elevation change data from 2000–2016. The results show that supraglacial debris coverage is an essential factor affecting the spatial heterogeneity of glacier mass balance, followed by climatic factors and topographic factors—particularly median elevation and slope. There are some differences among mountain regions, and the explanatory power of climatic factors on the spatial differentiation of glacier mass balance in each region is weak, indicating that the climatic background of each mountain region is similar. Therefore, under similar climatic backgrounds, median elevation and slope are most correlated with glacier mass balance. The interaction of various factors is enhanced, but no single interaction factor plays a primary role. Topographic and morphological factors also control the spatial heterogeneity of glacier mass balance by influencing its sensitivity to climate change. In conclusion, the geodetector method provides an objective framework for revealing the factors controlling glacier mass balance.

**Keywords:** geodetector; glacier change; mass balance; climate change; High Mountain Asia

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## 1 Introduction

Temporal and spatial variation characteristics of glacier mass balance are closely related to climate and environment. Glacier mass balance affects a series of glacier material properties (such as ice formation, temperature, and movement) and glacier scale (such as area, length, and volume). Therefore, glacier mass balance is the critical link to the climate environment. High Mountain Asia (HMA) is the most glacially developed region in the middle latitudes and the largest glacier concentration outside the polar regions. As a result of interaction with westerlies, monsoons, and global warming, glacier mass changes will significantly impact downstream water resources and water environment. However, the change of glacier mass balance is spatially heterogeneous. Most glaciers show negative mass balance, while a few regions (such as the West Kunlun and Karakoram mountains) maintain stable or positive mass balance.

The reasons for these temporal and spatial variations remain unclear, as topography and other environmental factors complicate the glacier's response to climate change. There are two possible explanations for the differences in glacier mass balance: spatial heterogeneity of climate change and different glacier responses to climate change. Recent studies have shown that glacier mass in the Nyainqêntanglha and Hengduan mountains has decreased dramatically, while glacier mass in the Karakoram and West Kunlun mountains has increased slightly. The latter increase, known as the "Karakoram Anomaly," is thought to be due to cooling temperatures in summer and increased precipitation in winter. However, the effects of climate heterogeneity across HMA have not been fully quantified, leaving the possibility that most anomalies are due to the glaciers' different responses to similar climate changes. A simple index, such as the sensitivity of glacier mass balance to temperature and precipitation, can be numerically estimated to characterize heterogeneity in the response of glacier mass balance to climate change. Sakai and Fujita (2017) suggested that, in explaining recent glacial changes in HMA, spatial heterogeneity in glacier mass balance is more informative than regional differences in climate change. Whether or not the local or regional sensitivity of glacier mass balance to temperature and precipitation is related to the topographic parameters of glaciers is not well understood.

Furthermore, the sensitivity of glaciers to climate change depends on the current environment of the glacier—that is, the environmental control over the heat and mass balance of the glacier. Salerno et al. (2017) conducted a statistical analysis of the relationship between glacier thinning rates and morphological variables in the Himalaya Mountains and found that reduced downstream surface slope was the primary morphological variable controlling thickness changes. Scherler et al. (2011) demonstrated that supraglacial debris caused spatial variations in glacier fluctuations in the Karakoram and Himalaya mountains. Brun et al. (2019) reported that glacier tongue slope, mean elevation, debris cover, and avalanche contribution area together account for mass balance variability in HMA. Few studies have investigated the controlling factors of glacier mass balance in HMA, and most focus on local areas. This kind of research for areas outside HMA also mainly focuses on local studies. In the European Alps, the mass balance of individual glaciers is also related to glacier morphology. Potentially, outcomes from previous studies investigating controlling factors are sometimes contradictory because the factors controlling the spatial distribution of glacier mass balance vary from region to region (i.e., findings from one region cannot be generalized and applied to other regions). Moreover, previous studies used linear regression, making it difficult to detect nonlinear relationships between environmental variables and glacier mass balance. The relationships between glacier mass balance and environmental variables are often not simply linear due to the complex dynamic processes involved. Determining such relationships, especially potentially nonlinear ones, is helpful for understanding the influences of environmental factors on glacier mass balance.

Geodetector can detect both linear and nonlinear relationships between glacier mass balance and environmental variables. The current study uses the geodetector method to quantitatively analyze the explanatory power of climate, topography, and other environmental factors on glacier mass balance. These relationships are considered not only from a whole-HMA perspective but also by investigating individual mountain regions. Overall, the driving mechanism of the spatial heterogeneity of glacier mass balance in HMA is examined from a new perspective.

## 2.1 Study Area

HMA refers to the high-altitude region of Asia composed of the Tibetan Plateau and its surrounding areas. It spans several Central Asian countries within 23°N–47°N, 65°E–105°E, from the Pamir Plateau and Hindu Kush Mountains in the west to the Hengduan Mountains in the east, the Tianshan Mountains in the north, and the Himalaya Mountains in the south. HMA is the highest mountain area on Earth and the largest glacier-gathering area outside the polar regions. It is also the largest glacial region of the mid-to-low latitudes. Known as the "third pole" of the world, the area is sensitive to global climate change and has a vulnerable ecosystem with extensive glaciers, permafrost, snow, lakes, and land. This ecosystem makes HMA a unique geographical unit that not only regulates runoff from glacial meltwater but also influences climate change at Asian and even global scales, thereby serving as an indicator and regulator of global climate change. Therefore, HMA plays very important roles in ecological security, human survival, and sustainable economic development in Asia.

## 2.2 Glacier Mass Balance Data

Mass balance data for individual glaciers come from regional statistics in ArcGIS software based on geodetic mass balance, which was extracted from glacier elevation change rates during 2000-2016 as described by Brun et al. (2017). Only glaciers larger than 2 $km^2$ were included to minimize errors. We used Randolph Glacier Inventory v. 6.0 (RGI 6.0) as glacier mask data.

## 2.3 Glacier Morphological Data

The area (A), minimum elevation (Zmin), maximum elevation (Zmax), median elevation (Zmed), slope (S), aspect (As), and length (Lmax) of glaciers were derived from the attribute data of RGI 6.0. The elevation difference between Zmax and Zmin is called the difference of glaciation (DG; i.e., Zmax-Zmin). The elevation difference between Zmax and the snowline altitude of a glacier (here taken as Zmed) is called the positive difference of glaciation (PDG; i.e., Zmax-Zmed). Correspondingly, the negative difference of glaciation (NDG) is defined as Zmed-Zmin. The hypsometric index (HI) is calculated by Equation 1.

The debris cover dataset (Scherler et al., 2018) provides the global distribution of supraglacial debris cover and is available from GFZ Data Services. The debris coverage rate (DCR) is the proportion of supraglacial debris area to total glacier area.

## 2.4 Meteorological Data

We used monthly ERA5 data to calculate the annual mean temperature (T), mean annual precipitation (P), the changing trend of annual mean temperature (Tc), and mean annual precipitation (Pc) from 2000 to 2016. The changing trend of T and P was derived using linear regression. Since the resolution of ERA5 data is 0.1°, most glaciers are smaller than a grid cell. Meteorological data for glaciers smaller than a grid cell are taken from the grid value, while values for glaciers larger than a grid cell are calculated using the regional statistics method in ArcGIS software.

## 2.5 Geodetector Method

Previous studies utilized spatial regression methods (such as correlation analysis) that linearly correlated dependent variable Y to independent variable X. The heterogeneity of the spatial distributions of dependent variable Y and independent variable X also reflects the correlation between the two variables, which includes both linear and nonlinear portions. Both types of relationships can be included and considered within geodetector. When linear regression is significant, geodetector must be significant. When linear regression is not significant, geodetector may still be significant as long as there is a relationship between the two variables that geodetector can characterize. Detailed information on geodetector can be referenced from Wang et al. (2010). The following is a brief review of the application of this approach to the current study.

Geodetector is a statistical method used to detect spatial heterogeneity and its drivers. The core idea is based on the assumption that if an independent variable has a strong influence on a dependent variable, their spatial distributions should be similar (Wang et al., 2010). In this study, if an environmental factor influences glacier mass balance, the spatial distributions of the factor and the mass balance are expected to be similar.

To probe the spatial stratification heterogeneity of variable Y and the extent to which factor X explains the spatial heterogeneity of variable Y, we described the q value by Equation 2, where Nh and N are the unit numbers of strata h and the whole region, respectively; $\sigma^2$_h and $\sigma^2$ are the variances of Y at strata h and the whole region, respectively; and the value range of q is 0–1.

The q value implies that X explains 100q% of Y. The larger the q value, the more directly correlated X is with Y. In other words, if the q value of the correlation between an environmental factor and glacier mass balance is 1, then the factor' s explanatory power is 100%—the factor completely controls the glacier mass balance.

A simple transformation of the q value description satisfies the non-central F distribution, where L is the maximum count of strata; ~ denotes the distribution; $\lambda$ is the non-central parameter; and Y_h is the mean value of strata h.

The principle of the geodetector method is shown in Figure 1 [Figure 1: see original paper]. The example diagram includes two coverages: dependent variable Y and explanatory variable X. The explanatory variable X is typically expressed as a polygon. If X is grid data, it needs to be converted to categorical data by reclassification. In classification, except when slope is classified by eight directions, the classification scheme with the largest q value is followed. The dependent variable Y for every glacier is mass balance, and the average Y and variance ($\sigma^2$) are calculated.

The two coverages are compared, enabling calculation of the average Y value and variance ($\sigma^2$_h) for each stratum. Substituting these mean values and variances into Equation 2 produces the q value. Subsequent substitution into the distribution equations and checking the non-central F distribution table yields the statistical significance test of the q value.

Interaction between X1 and X2 (q_{X1} X2) is evaluated by comparing it with values of q_{X1} and q_{X2}, where q_{X1} X2 represents the determinative force of the new factor resulting from the superposition of X1 and X2. All processes are undertaken with the geodetector software.

## 3.1 Glacier Mass Balance Variability in HMA

The average glacier mass balance in HMA was −0.18 ($±0.04)*mw.e./aduring*2000–2016, *butglaciermasschange*
*seeoriginalpaper*]).*Forexample*, *glaciermassbalanceintheHengduanandNyainqntanglhamountainswasthem*
0.65(±0.23)*and*−0.56(±0.23)*mw.e./a*, *respectively.GlaciersintheWestKunlunandEastKunlunmountainssho*
m w.e./a, respectively. The heterogeneity of regional mass balance change in HMA is primarily correlated with climate. Glaciers in the southern Tibetan Plateau experienced the most extensive mass loss due to the Indian monsoon. In contrast, the dominance of westerly winds results in minimal glacier mass loss in northwestern HMA, with some glaciers even showing positive mass balance. Glaciers in the central Tibetan Plateau, dominated by transitional modes, had moderate mass loss. The strengthening of westerly winds and weakening of monsoon are the main drivers of current glacial conditions in HMA. Glacier morphology is also an essential factor affecting the heterogeneity of glacier mass balance. In particular, glaciers in the same region with similar climatic backgrounds show different change states, with two adjacent glaciers identified as having positive and negative balances, respectively. Therefore, Section 3.2 discusses the influence of these environmental factors on glacier mass balance.

## 3.2 Environmental Factors Affecting the Variability of Glacier Mass Balance

Table 1 shows the influencing factors of glacier mass balance variability in HMA and other mountains, listing q values from largest to smallest. The q value of DCR was the largest, inferring that debris cover has an influential effect on the spatial differentiation of mass balance across all glaciers in HMA. Moreover, climatic factors (T, Pc, and P) play a secondary role. Since not all glaciers are covered with supraglacial debris, climate should be the primary factor accounting for the spatial heterogeneity of glacier mass balance. However, the q value of temperature change (Tc) is not higher, indicating that the spatial heterogeneity of temperature change has less influence on the spatial heterogeneity of glacier mass balance than other climate factors (T, Pc, and P). There is little difference in temperature change across HMA, and spatial heterogeneity of temperature change has a relatively poor correlation with the spatial heterogeneity of glacier mass balance.

Topography has less explanatory power for all glaciers in HMA than DCR and climate factors, but topography is the dominant effector of mass balance for most glaciers in mountain regions. Slope and median elevation have the highest q values among all topographic factors. Assuming that the climatic background of each mountain region is similar, slope and median elevation are the dominant factors of mass balance heterogeneity for glaciers in most mountain regions. However, there are exceptions. For example, slope has a weak correlation with the heterogeneity of glacier mass balance in the West Kunlun Mountains due to generally gentle slopes. Similarly, median elevation has a weak explanatory effect on the heterogeneity of glacier mass balance in the Hissar Alay Mountains due to generally lower median elevation.

Aspect, glacier area, maximum length, and PDG have little influence on glacier mass balance, and the correlation is not significant (Tables 2 and 3). However, there are exceptions. For example, glacier area and maximum length in the West Kunlun Mountains strongly correlate with glacier mass balance. Glacier mass balance in the West Kunlun Mountains is positive, and the difference in glacier mass balance in this region is closely related to glacier size and precipitation.

Our results show that the effects of any two environmental factors on glacier mass balance are mutually enhanced. Table 1 shows only the two environmental factors with the largest interaction enhancement effect (q value). For the whole HMA, the interaction between supraglacial debris and slope is dominant. In combination with Tables 2 and 3, it is inferred that bare ice with no supraglacial debris coverage and gentle slopes has a more negative mass balance. The pattern of the Tibetan Interior Mountains is the same as that for the whole HMA. The dominant interaction types of glacier mass balance in other mountain regions differ. However, in most cases, slope or median elevation is the most outstanding interaction factor compared with others. It is worth mentioning that the interaction between median elevation and air temperature accounts for 99% of glacier mass balance variation in the eastern Tibetan Plateau.

The geographical analysis results (Table 1) for different mountain regions show that, except for the West Kunlun, Hissar Alay, and Qilian mountains, climate is not the dominant factor. This is presumably because climate differences within each mountain region are slight; therefore, we assume that the climate background in each mountain region is similar. As a result of this assumption, median elevation or slope becomes the dominant factor of glacial mass balance in regions with the same climatic background. Slope is the most crucial factor affecting glacier mass balance in the western Himalayas, eastern Himalayas, Hindu Kush, western Tianshan, Tibetan Interior Mountains, Nyainqêntanglha Mountains, and Pamir Plateau. Median elevation is the most important factor affecting glacier mass balance in the eastern Tianshan, eastern Kunlun, Tanggula, Gangdise Mountains, and eastern Tibetan Plateau. Precipitation plays a dominant role in glacier mass balance in the West Kunlun Mountains, where the correlation between maximum length and precipitation is strongest. Glaciers with longer lengths may receive more precipitation, increasing the influence of precipitation on glacier mass balance. Enhanced westerlies bring more precipitation to the West Kunlun Mountains, resulting in positive glacier mass balance in the region. Precipitation plays a leading role in glacier mass balance in the Hissar Alay Mountains, but the correlation between temperature and temperature change is strongest. Temperature change plays a dominant role in glacier mass balance in the Qilian Mountains, where the correlation between temperature and median altitude is strongest. We also assessed the linear regression method, and the results in Tables 2 and 3 are consistent with the geodetector method results.

### 4.1 Limitations of This Study

The most significant limitation of this study is data accuracy, particularly for glacier mass balance and climate reanalysis data. The individual glacier mass balance dataset is inherently highly uncertain, depending on glacier area, the proportion of glacier surface surveyed, and the number of Digital Elevation Models (DEMs) used to extract reliable elevation change rates. However, after Monte Carlo simulations, Brun et al. (2019) suggested that the spatial heterogeneity of the data was relatively robust and could be used for statistical analysis. Additionally, other data sources are affected by uncertainty in glacier delineation. Since glaciers larger than 2 $km^2$ were selected, glacier boundary uncertainty had little effect on mass balance. The debris cover data, however, were uncertain, with glacier classification accuracy of 91%, which was sufficient for this study.

The spatial resolution (0.1°$×$0.1°) of climate reanalysis data is too coarse to reflect intra-mountain differences, limiting its accuracy. Although values may be inaccurate, geodetector only requires classification of each glacier, not exact values. We classify glaciers according to climate data, dividing them into eight climate condition types. Geodetector does not require accurate quantitative values, only qualitative classification results. The classification results can roughly reflect differences in glacier climate. Our results (Table 1) show that climate in most mountainous regions has little influence on differences in glacier mass balance, which is related to the coarse resolution of climate data. Thus, we can assume that climate conditions in each mountain region are similar. Therefore, climate is the dominant factor affecting glacier mass balance differences in HMA, indicating that the resolution of climate data is sufficient to explain differences in glacier mass balance in every mountain region of HMA. In future studies, ERA5 data could be scaled to the glacial level and then divided into mountain regions to detect climate effects. However, using new climate data will not change results for other factors because the q value of each factor in geodetector is calculated independently. New calculations only affect the q values of climate factors, which in turn affect the ranking of climate factors relative to various environmental factors.

Another limitation is that glacier surface features are not considered, such as supraglacial lakes, proglacial lakes, and ice cliffs. Ice cliffs and supraglacial lakes may exacerbate glacier mass loss, and these factors may complicate the effect of supraglacial debris. These effects are complex and need further exploration. Notwithstanding that if these factors are considered in the future, the impact factor q value of our present conclusions will remain the same.

Finally, the current study fails to consider the temporal heterogeneity of glacier change. Studies have shown that glacier mass in most regions exhibits an accelerated retreat trend, but the degree of retreat is heterogeneous. In terms of temporal heterogeneity, temperature and precipitation or their changes play essential roles, but topography and morphology cannot be ignored.

## 4.2 Effect of Supraglacial Debris

Due to differences in reflectivity, particle size, color, and other physical properties, supraglacial debris has unique thermal characteristics that influence the physical processes of glacier ice ablation. When debris thickness is less than a critical threshold (<20-30 mm), melting of underlying glacier ice is greater than that of bare ice; that is, debris accelerates glacier melting. As debris thickens (beyond the critical threshold), the thermal resistance of the debris inhibits glacier ablation.

Supraglacial debris is the strongest correlating factor explaining all glacier mass balance across HMA. However, many glaciers lack supraglacial debris or are covered with minimal amounts. The reason is that the mean climate of a region is constrained by its geography, topography, and morphology. There may have been insufficient sampling of debris-covered glaciers in various mountain regions, so supraglacial debris has not been reported as the greatest influence on glacier mass balance in most mountain regions. Many glaciers are covered by supraglacial debris in the Karakoram Mountains; therefore, the relationship between supraglacial debris coverage and glacier mass balance has the highest reported q values in this region. Supraglacial debris may be a contributing reason for the development of the "Karakoram Anomaly." However, q values of all influencing factors for Karakoram glaciers are very low, which on one hand is related to large numbers of debris-covered glaciers, and on the other hand may reveal unique characteristics of Karakoram glaciers (Table 1). Furthermore, debris coverage also plays an essential role in explaining glacier mass balance heterogeneity in the Pamir Plateau, with q value ranking behind slope and median elevation factors (Table 1).

Geodetector does not easily differentiate whether supraglacial debris has a positive or negative effect on glacier mass balance. Therefore, linear regression was used to analyze this relationship. Except for the Nyainqêntanglha, Hengduan, and Tianshan mountains, supraglacial debris in other mountain regions is negatively correlated with glacier mass balance (Table 2). However, only the Central Himalayas, Karakoram, East Kunlun, and Tanggula mountains show negative correlation ($P<0.01$). The Hissar Alay, Western Kunlun, and Gangdise mountains show negative correlation ($P<0.05$). The Hengduan Mountains show positive correlation ($P<0.01$). Thick supraglacial debris can inhibit glacier mass balance, while thin debris can promote melting. The positive or negative correlation between supraglacial debris and mass balance may depend on debris thickness. If surface features such as ice cliffs and supraglacial lakes are considered, the influence of debris becomes more complex. Therefore, the effect of surface debris on mass balance is relevant and worth further exploration.

## 4.3 Effect of Climate

Not all glaciers are covered with supraglacial debris, and many have minimal debris coverage. Therefore, climate is the primarily dominant and significant factor for heterogeneity of glacier mass balance throughout HMA. Glacier mass balance is negatively correlated with temperature and precipitation (Table 2), indicating that glaciers in regions with higher temperatures or more precipitation may suffer more severe mass loss under climate warming. It seems counterintuitive that areas with greater precipitation suffer more glacier mass loss. There are two reasons for this phenomenon. First, precipitation is negatively correlated with elevation, meaning areas with more precipitation tend to have lower elevations, and glaciers at lower elevations are more sensitive to rising temperatures. Second, there is more precipitation in monsoon regions, and Indian monsoon-affected glaciers are extremely sensitive to temperature. Slight warming leads to large-scale glacier loss, so Indian monsoon-affected glaciers are considered temperature-controlled. The effect of precipitation on glacier mass balance is complex. For the whole of HMA, precipitation change is positively correlated with glacier mass balance (Table 2). In particular, increased solid precipitation in recent years leads to slightly positive glacier mass balance in the Karakoram Mountains. Additionally, precipitation seasonality varies greatly across HMA, which affects the sensitivity of glacier mass balances.

## 4.4 Effect of Topography

Topography may influence climate heterogeneity or climate sensitivity. Elevation influences temperature heterogeneity because it is warmer at lower elevations and cooler at higher ones. Zmin, Zmax, and Zmed are all related parameters describing glacier elevation. Aspect causes inhomogeneity in solar radiation, which may affect climatic heterogeneity. Slope influences glacier flow and morphology, thus affecting climate sensitivity. PDG, NDG, and HI are related to slope and elevation. Furthermore, elevation range and slope determine temperature and precipitation gradients on glacier surfaces. Topography has less correlation for all glaciers in HMA than DCR and climate factors. However, topography is the dominant factor for glacier mass balance in most mountain regions. Among all topographic factors, median elevation and slope are the most critical factors affecting glacier mass balance in each mountain region. The median elevation correlation with equilibrium line altitude and mass balance is zero at that elevation. Hence, median elevation is an important factor affecting glacier mass balance. The lower the median elevation, the lower the equilibrium line altitude, and the less glacier mass loss.

Slope-controlled glacier change has also been demonstrated by previous studies. Data from the current study show that the gentler the slope, the more negative the glacier mass balance (Tables 2 and 3). Gentle slopes may lead to slower glacier flow, slower transport of glacial mass downstream, slower recharge in the ablation area, and more negative glacier mass balance. Moreover, driving stress is conducive to ice separation and loss.

## 4.5 Comparison of Geodetector and Linear Regression Analysis

Univariate linear analysis was performed by calculating Pearson correlation coefficients and P values for mass balance and other environmental factors. The purpose of linear regression is to linearly and statistically relate dependent variable Y to independent variable X. Glacier mass balance is closely related to climate, environment, and terrain. The physical processes of climate and terrain impacts on mass balance are very complex, and their relationship is not necessarily linear. Geodetector is suitable for detecting both linear and nonlinear relationships, making it more appropriate for exploring glacier mass balance factors than linear regression. When linear regression results are significant, geodetector results are inevitably significant. When linear regression results are not significant, geodetector results may still be significant. Geodetector is more powerful, more confident, and better suggests causality than general statistics. It is much more difficult for two variables to be uniformly distributed in two-dimensional space than in one-dimensional space. Therefore, we recommend that geodetector be used in future studies to explore influencing factors of heterogeneity in glacier mass balance.

## 4.6 Sensitivity of Glacier Mass Balance to Environmental Factors

Sensitivity of glacier mass balance refers to the response degree of mass balance to temperature or precipitation change, generally defined as mass balance change when temperature increases by 1°C or precipitation increases by 10%. Glacier mass balance is more sensitive to temperature at mid-to-high latitudes and more sensitive to precipitation at lower elevations. This is because net shortwave radiation is the most variable energy flux at the glacier-atmosphere interface and is controlled by surface albedo. Most snow and ice mass loss (about 65%) occurs via sublimation, followed by melting. Surface albedo depends on precipitation amount and frequency. Results have found that glacier mass balance has nonlinear sensitivity to temperature and linear sensitivity to precipitation. Thus, temperature is the main driver of mass balance change in maritime glaciers, while in continental glaciers, interactions among temperature, precipitation seasonality, and snow/rain separation are main drivers. Accordingly, topography may be the driver with obvious spatial heterogeneity and nonlinear relationship with temperature. Based on the temperature sensitivity classification of all glaciers in China by Wang et al. (2008), we used geodetector to explore heterogeneity in temperature sensitivity affected by topography. The results show that the sequence of significant topographic factors is DCR (0.07) > Zmin (0.06) > Zmax (0.02) > HI (0.02) > Zmed (0.02) > slope (0.01) > aspect (0.01). Supraglacial debris can increase or decrease the rate of glacial melting, thus affecting temperature sensitivity. Elevation range determines temperature and precipitation gradients on glacier surfaces. In this study, slope has less effect on temperature sensitivity than elevation. Slope sensitivity is not only controlled by temperature gradients but also by glacier flow and morphology. Glacier flow controls mass transport changes, which further lead to responses in glacier mass balance. Glacier morphology affects glacier flow. For example, when a glacier with a large accumulation area flows through a narrow valley bed, flow velocity must increase. Therefore, topography and morphology also control the spatial heterogeneity of mass balance by influencing the sensitivity of mass balance to climate change. In the future, more attention should be paid to relationships among mass balance sensitivity and topographic and morphological parameters.

## 5 Conclusions

The purpose of this study is to examine potential factors controlling the spatial distribution of glacier mass balance in HMA during 2000–2016. The larger the q value of an influencing factor, the more significant its correlation to glacier mass balance in the region. This research utilized various potential factors from available digital data, proposing a new geodetector computing framework to quantify and compare glacier mass balance associated with various factors and interactions between different factors.

The results highlight that supraglacial debris is an important factor affecting the spatial differentiation of glacier mass balance in HMA, but not all glaciers are covered by supraglacial debris. Therefore, climate is the dominant factor for spatial differentiation of glacier mass balance. When we assume the climatic background of each mountain is similar, median elevation or slope becomes the dominant factor of spatial differentiation. The effects of various factors on glacier mass balance are mutually enhanced, but there is no unified dominant and controlling interaction between factors. These outcomes suggest that geodetector provides a quantitative and objective analytical framework that can be used to investigate potentially controlling factors of glacier mass balance more thoroughly.

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*Note: Figure translations are in progress. See original paper for figures.*