Mass Balance Changes of Arctic Mountain Glaciers and Their Response to Climate: Postprint

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Abstract

Glacier mass balance, as a crucial indicator of climate change, is commonly employed to evaluate the contribution of glaciers to runoff and sea level rise. This study utilizes the most recently published mass balance, equilibrium line altitude, and accumulation area ratio data from the World Glacier Monitoring Service (WGMS), analyzing 23 glaciers in the Arctic region with long-term observation records to examine both the status of Arctic mountain glacier mass balance and the relationship between mass balance and equilibrium line altitude and accumulation area ratio. The analysis demonstrates: (1) From 1960 to 2017, the average thickness of Arctic glaciers decreased by 14.8 m, with the least thinning in the Russian Arctic (4.3 m) and the most severe thinning in Alaska (27.7 m); (2) Among the 23 glaciers, only Engabreen glacier exhibited a positive average mass balance, Kongsvegen glacier maintained a slightly negative balance, while the other 21 glaciers were in strongly negative balance states, indicating severe overall mass loss in Arctic glaciers; (3) Over the past 60 years, Arctic glacier mass balance has been predominantly negative; since the late 1990s, glaciers have undergone accelerated melting, with the loss rate increasing from -128.2 mm·a-1 to -594 mm·a-1; (4) Mass balance exhibits a negative correlation with equilibrium line altitude and a positive correlation with accumulation area ratio, with statistically significant correlations; (5) Rising Arctic temperatures are the primary driver of glacier mass loss; the substantial temperature increase after the 1990s resulted in substantial mass loss during the same period, while precipitation has a relatively minor influence on mass balance.

Full Text

Changes in the Mass Balance of Arctic Mountain Glaciers and Their Response to Climate Change

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Abstract

Glacier mass balance serves as a crucial indicator of climate change and is commonly used to assess the contribution of glaciers to runoff and sea-level rise. This study analyzes the mass balance status of Arctic mountain glaciers and its relationship with equilibrium line altitude (ELA) and accumulation area ratio (AAR) using the latest mass balance, ELA, and AAR data published by the World Glacier Monitoring Service (WGMS). Our analysis focuses on 23 glaciers in the Arctic with long-term observation records. The results reveal that between 1960 and 2017, the average thickness of Arctic glaciers decreased by 14.8 m, with the smallest reduction (4.3 m) occurring in the Russian Arctic and the most severe thinning (27.7 m) in Alaska. Among the 23 glaciers studied, only Engabreen maintained a positive average mass balance, while Kongsvegen exhibited a weak negative balance; the remaining 21 glaciers all showed strongly negative mass balances, indicating substantial overall mass loss in the Arctic. Since the late 1990s, glaciers have experienced accelerated melting, with the loss rate increasing from -128.2 $\mathrm{mm \cdot a^{-1}}$ to -594 $\mathrm{mm \cdot a^{-1}}$. Mass balance demonstrates a significant negative correlation with ELA and a significant positive correlation with AAR. Rising Arctic temperatures represent the primary driver of glacier mass loss, with the pronounced warming after the 1990s causing substantial mass loss during that period, while precipitation exerts a relatively minor influence on mass balance.

Keywords: glacier change; mass balance; equilibrium line altitude; mountain glacier; Arctic

1. Study Area Overview

The southern boundary of the Arctic region has been variously defined using criteria such as the Arctic Circle, isotherms, and the Arctic treeline, with no unified standard currently established. This study adopts the definition used by the Arctic Monitoring and Assessment Programme (AMAP) under the Arctic Council. The Arctic region (Figure 1) essentially includes land and ocean areas north of the Arctic Circle (66°32’ N), the Asian region north of 62°N, the North

American region north of the Aleutian Islands, the Hudson Bay, and parts of the North Atlantic including the Labrador Sea, covering a total area of 3.33 $\times 10^7$ km^2. The region hosts 4,212 glaciers covering an area of 257,000 km^2, with diverse glacier types. The Arctic climate features cold, long winters (October-April) with mean monthly temperatures between -40°C and -20°C, and brief summers (July-August). Annual precipitation is relatively low, occurring primarily as snowfall, with most areas receiving less than 250 mm. Under the influence of polar easterlies, precipitation is scarce, though coastal areas experience relatively warm and humid conditions due to maritime climate and ocean currents, while inland regions remain cold and dry.

2. Data and Methods

2.1 Data Sources

This study analyzes mass balance, equilibrium line altitude, and accumulation area ratio data for 23 glaciers in the Arctic (Table 1) to characterize mass balance variations, regional differences, and relationships with ELA and AAR, while also examining the climatic context using Arctic temperature and precipitation data. Mass balance data, including ELA and AAR, were obtained from the World Glacier Monitoring Service (https://wgms.ch/). Temperature and precipitation data for Svalbard and Scandinavia were sourced from the Norwegian Meteorological Institute, while temperature data for other regions and all precipitation data were obtained from the National Oceanic and Atmospheric Administration (http://www.noaa.gov/web.html).

2.2 Mass Balance Calculation Methods

Point mass balance was measured using the traditional glaciological method, whereby a network of stakes was installed on the glacier surface and the distance from the top of each stake to the ice surface was measured at different times. The difference between two readings represents the depth of snow/ice melt. Combined with the density of ice ($850\ \mathrm{kg} \cdot \mathrm{m}^{-3}$), this yields point mass balance values. The mass balance of the entire glacier was calculated using the contour line method: point mass balance values (Bi) were plotted on a large-scale glacier topographic map to create a mass balance contour map. The annual mass balance (Bn) of the entire glacier was then calculated using the formula:

$$Bn = \frac{\sum_{i=1}^{n} s_i B_i}{S}$$

where s_i represents the projected area between adjacent contour lines, n is the total number of s_i areas, B_i is the average net balance for area s_i, and S is the total glacier area. Regional annual mass balance was obtained by arithmetically averaging the mass balances of all glaciers in each region over their respective observation periods. Cumulative mass balance was then calculated by accumulating these regional annual mass balance values.

3. Results

3.1 Characteristics of Individual Glacier Mass Balance

We selected 23 Arctic glaciers with relatively long observation records to analyze mass balance variations and reveal general patterns of change in Arctic mountain glaciers. Figure 2 illustrates the interannual mass balance variations for individual glaciers in the Arctic. Among the 23 glaciers, only Engabreen maintained a positive average mass balance, with annual and cumulative mass balances of 17 mm and 832 mm, respectively. Kongsvegen exhibited a weak negative balance, with annual and cumulative mass balances of -82 mm and -2,545 mm, respectively. The remaining 21 glaciers showed strongly negative mass balances, with annual values ranging from -134 mm to -975 mm. Obruchev glacier had the most negative annual mass balance (-975 mm), indicating severe mass loss, with cumulative mass balance ranging from -2,711 mm to -31,712 mm. The Gulkana glacier showed the greatest cumulative mass loss (-31,712 mm), corresponding to a thickness reduction of approximately 27.7 m, indicating the highest ablation among all studied glaciers. Mass balance change rates ranged from -576 $\mathrm{mm \cdot (10a)^{-1}}$ to 189 $\mathrm{mm \cdot (10a)^{-1}}$, with Obruchev, Storglaciären, and Irenbreen showing increasing trends at rates of 11 $\mathrm{mm \cdot (10a)^{-1}}$, 42 $\mathrm{mm \cdot (10a)^{-1}}$, and 189 $\mathrm{mm \cdot (10a)^{-1}}$, respectively. However, these glaciers remained in negative balance overall, not altering the general negative trend of Arctic glaciers. Glaciers in the Canadian Arctic and Svalbard showed relatively small mass balance fluctuations, while those in Scandinavia and the Russian Arctic exhibited larger amplitude variations.

3.2 Regional Characteristics of Glacier Mass Balance Changes

Glacier mass balance represents the combined product of regional climate, topographic conditions, and geographic location, resulting in similarities within regions and differences between them. As shown in Figure 3, glacier mass balance in all Arctic regions generally exhibits a declining trend (the Russian Arctic temporarily shows a positive trend because its time series ends in 1988). Each region displays distinct trends with characteristic regional features.

The Canadian Arctic region (Figure 3a) has the longest mass balance observation record. Glacier mass balance varied between -236 mm and 251 mm, with an average mass balance of -6.54 $\mathrm{mm \cdot a^{-1}}$. The region shows a slowly increasing negative balance trend. Dominated by polar climate, glaciers in this region are less sensitive to climate change. Strong westerly winds cause significant snow redistribution through wind drift, moving substantial snow from windward slopes and glacier summits to leeward slopes, creating accumulation patterns not directly related to elevation.

The Scandinavian region (Figure 3b) is strongly influenced by the warm, humid maritime climate of the Atlantic Ocean. Winter mass balance is significantly affected by the Pacific Decadal Oscillation (PDO) and Arctic Oscillation (AO). Glacier mass balance ranged from -429 mm to 1,250 mm, with an average of -8.42 mm · a^{-1}. This region shows large mass balance fluctuations and pronounced interannual variability. A notable positive balance period centered around 1990 was followed by strong mass loss after 2000, with the most negative balance (-1,739 mm) occurring in 2010.

The Russian Arctic region (Figure 3c) is dominated by westerly airflow, with low-pressure systems over the Barents Sea providing the main source of precipitation year-round. The Obruchev glacier shows consistent interannual mass balance variation patterns, with an average mass balance of -161 mm and a range from -215 mm to 2,150 mm. Mass balance interannual variability is substantial, with the most significant losses occurring in the mid-1980s.

The Alaska region (Figure 3d) experienced mass balance ranging from -1,575 mm to 332 mm, with an average of -23.89 mm · a^{-1}. This region shows the most significant negative balance trend and the largest annual mass balance amplitude. After 1990, mass balance declined sharply, reaching a minimum of -2,355 mm in 2005, making the cumulative mass loss in Alaska exceed the Arctic average.

The Svalbard region (Figure 3e) contains mostly subpolar or polythermal glaciers. Mass balance ranged from -476 mm to 332 mm, with an average of -3.31 mm · a^{-1} and relatively small interannual variability, indicating weak ablation. Glaciers in this region showed more positive balance years before 1990, displaying a weak increasing trend, but entered a state of strong ablation after 2000.

3.3 Overall Mass Balance Status and Trends of Arctic Mountain Glaciers

Analysis of average mass balance and cumulative mass balance curves since the 1960s reveals that Arctic glacier mass balance has shown an overall negative trend (Figure 5). During the 1960s–1970s, mass balance exhibited an increasing trend. The 1980s represented a stable negative balance period, while the 1990s saw accelerated ablation. After the late 1990s, glaciers experienced further mass loss, with the loss rate increasing from -128.2 mm · a^{-1} to -594 mm · a^{-1}. Table 3 presents the average mass balance, trend slope (K), and cumulative mass balance for glaciers in five Arctic regions. The K value indicates the rate of mass balance change: a positive K suggests increasing mass balance, while a negative K indicates decreasing mass balance. Only the Russian Arctic shows a positive K value (11 mm · a^{-1}), but this reflects the data ending in 1988. All other regions show negative K values, with Svalbard having the slowest mass loss rate and Alaska the fastest.

3.4 Relationships Between Mass Balance and ELA/AAR

The equilibrium line altitude (ELA) represents the elevation where annual accumulation equals ablation. The accumulation area ratio (AAR) is the proportion of the glacier’ s accumulation area to its total area, reflecting the glacier’ s nourishment status. Table 4 shows that for 18 glaciers with available data, mass balance is significantly negatively correlated with ELA and significantly positively correlated with AAR. When mass balance decreases by 100 mm, ELA rises by 65-113 m, with Storglaciären showing the smallest increase and White glacier the largest. When mass balance decreases by 100 mm, AAR declines by 1.1%-11%, with Storglaciären showing the smallest decline and Langfjordjøkelen the most severe. Some glaciers, such as Austre Brøggerbreen and Marmaglaciaeren, have experienced consecutive years of AAR = 0, indicating the entire glacier has become an ablation zone.

4. Influence of Regional Climate Change on Glacier Mass Balance

As a global climate amplifier, the Arctic responds more dramatically to climate change than mid-latitude regions. The vast Arctic territory exhibits substantial regional climate differences that affect glacier mass balance differently. Figure 6 shows that while precipitation changes are relatively minor across Arctic regions, temperature increases are pronounced and correspond well with mass balance variations.

From 1960 to 2017, the Canadian Arctic experienced a clear warming trend, with temperatures rising by 5.7°C at a rate of $0.1°\mathrm{C} \cdot (10\mathrm{a})^{-1}$. All seasons warmed, with winter warming fastest and summer slowest. During the 1960s–1970s, temperatures decreased, coinciding with increased mass balance. After the 1980s, temperatures rose fluctuatingly at $0.07°\mathrm{C} \cdot \mathrm{a}^{-1}$, leading to increased mass loss. Correlation analysis reveals significant negative relationships between mass balance and autumn/winter temperatures (r = -0.55, rw = -0.53, $p < 0.05$), indicating that autumn and winter warming accelerates mass loss. Precipitation shows little change and no significant correlation with mass balance, suggesting minimal influence.

From 1960 to 2017, Scandinavia showed small precipitation changes but significant warming, with temperatures rising 1.7°C at $0.3°\mathrm{C} \cdot (10\mathrm{a})^{-1}$. Winter warming was most pronounced. After 1990, temperatures rose at $0.4°\mathrm{C} \cdot (10\mathrm{a})^{-1}$, intensifying mass loss. Mass balance shows a significant negative correlation with summer temperature (r = -0.76, $p < 0.01$), indicating summer warming drives ablation.

From 1960 to 2017, Alaska’ s average temperature rose 0.53°C at $0.2°\mathrm{C} \cdot (10\mathrm{a})^{-1}$. After 1990, temperatures increased by 0.4°C compared to the previous period, while mass balance loss rates rose from $-27.47\ \mathrm{mm} \cdot \mathrm{a}^{-1}$ to $-69.85\ \mathrm{mm} \cdot \mathrm{a}^{-1}$. The maximum positive mass balance (1,575 mm) occurred in 2000 when temperatures were -4.3°C, below the average. Mass balance shows a negative correlation with winter temperature (rw = -0.55, $p < 0.05$), while precipitation changes are small and weakly correlated.

From 1960 to 2017, Svalbard temperatures rose significantly at 1.1°C $\cdot$ $(10a)^{-1}$, with a mean of -5.5°C. A climate shift occurred around 1990, with mass balance accelerating concurrently. Mass balance shows a significant negative correlation with summer temperature (r = -0.75, $p < 0.01$), confirming summer warming as a major cause of glacier mass loss. Precipitation changes are minor and not significantly correlated with mass balance, consistent with He et al. [26].

5. Conclusions

1) Arctic glaciers have experienced severe mass loss and accelerated melting in recent decades. The average glacier thickness decreased by 14.8 m, with the smallest reduction in the Russian Arctic (4.3 m) and the most severe thinning in Alaska (27.7 m). Due to differences in local climate, ocean currents, glacier type, size, and topography, regional mass balance variations differ. Since the 1960s, Arctic glacier mass balance has shown an overall negative trend. The 1960s–1970s exhibited an increasing trend, the 1980s were stable, the 1990s showed accelerated ablation, and after the late 1990s, mass loss intensified, with rates increasing from -128.2 mm $\cdot$ a^{-1} to -594 mm $\cdot$ a^{-1}.
2) Arctic glacier mass balance is negatively correlated with ELA and positively correlated with AAR. When mass balance decreases by 100 mm, ELA rises by varying degrees across glaciers, with the largest increase at White glacier and the smallest at Storglaciären. When mass balance decreases by 100 mm, AAR declines, with the most severe reduction at Langfjordjøkelen and the smallest at Storglaciären. Some glaciers have experienced consecutive years of AAR = 0, converting the entire glacier into an ablation zone.
3) Rising Arctic temperatures are the primary factor affecting glacier mass changes. The significant temperature increase across Arctic regions after the 1990s caused accelerated mass loss during that period, while precipitation changes have minimal impact on mass balance.

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

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