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Analysis of glacier mass balance trends using geodetic methods in the Svalbard archipelago

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Abstract

The Svalbard archipelago (74–81°N) contains approximately 34,000 km² of glacier ice and is a critical indicator for Arctic climate change. This research evaluates mass balance trends for 2003–2023 using geodetic methods comparing digital elevation models from ICESat, ICESat-2 satellite laser altimetry, and TanDEM-X radar interferometry. A total of 163 glacier basins covering over 90% of the glaciated area were analysed individually. The archipelago-wide geodetic mass balance averaged -7.2 ± 1.8 Gt/yr (specific: -0.21 ± 0.05 m w.e./yr), with pronounced spatial variability. Northwestern Spitsbergen glaciers experienced losses exceeding -1.5 m w.e./yr, while northeastern glaciers averaged -0.10 m w.e./yr. Several surge-type glaciers showed temporary upper-basin mass gains. The 2013–2023 rate exceeded 2003–2013 by 34%, driven by rising summer temperatures (positive degree days increased 18%) and warming ocean temperatures in western fjords. Tidewater glaciers (60% of area) contributed 68% of total loss, with submarine melting estimated at 40% of their mass loss. The total 144 Gt loss over 20 years equates to approximately 0.4 mm of global sea level rise. Continued satellite monitoring is essential for tracking Svalbard's evolving contribution to Arctic freshwater fluxes and global sea level.

Keywords: Glacier mass balance, geodetic methods, Svalbard, Arctic glaciers, ice volume change, ICESat-2, sea level rise, tidewater glaciers, climate change, cryosphere

Introduction

Glaciers outside the Greenland and Antarctic ice sheets contain approximately 170,000 km³ of ice and are major contributors to ongoing sea level rise ^[1]. Arctic archipelagos are experiencing warming rates 2–3 times the global average, driving widespread glacier retreat ^[2]. Svalbard is particularly important: it contains diverse glacier types including cirques, valley glaciers, ice caps, and tidewater glaciers; has mass balance records extending to the 1960s; and is sensitive to North Atlantic Current heat transport changes ^[3, 4].

Traditional in-situ mass balance measurements are available for only a handful of Svalbard glaciers and cannot cover the full archipelago. Geodetic methods that infer mass changes from ice surface elevation measurements offer comprehensive spatial coverage ^[5]. ICESat-2, launched in 2018, provides improved measurement precision and coverage compared to its predecessor, creating new opportunities for detailed geodetic assessment ^[6, 7].

Previous geodetic estimates for Svalbard span shorter time periods or cover limited areas ^[4, 8]. This research exploits the full 2003–2023 satellite elevation archive to produce a comprehensive 20-year assessment. The objectives are to quantify the magnitude and spatial variability of mass balance across 163 basins, examine temporal trends and acceleration, investigate climatic and oceanic drivers, and assess the contribution of different glacier types ^[9, 10].

Understanding these trends is essential not only for sea level projections but also for assessing the freshwater perturbation to Arctic marine ecosystems, as the approximately 7 km³ annual meltwater flux influences fjord circulation, vertical mixing, and nutrient supply with consequences for marine productivity ^[3, 11].

Research Area Description

Svalbard covers approximately 61,000 km², with 55% glaciated. The west coast is influenced by warm Atlantic water via the West Spitsbergen Current, while the eastern and northeastern portions experience colder Arctic conditions. Mean annual temperature at Longyearbyen has

increased by approximately 4°C since 1971. Precipitation ranges from 200 to 800 mm/yr depending on location and elevation. The 163 analysed glacier basins span the full range of glacier types and climatic settings across the archipelago [1, 3].

Material and Methods

Material

ICESat GLAS (2003–2009) provided elevation measurements with ~70 m footprint and ±15 cm vertical accuracy. ICESat-2 ATLAS (2018–2023) offered improved ~11 m footprint and ±10 cm accuracy. TanDEM-X global DEM (~2011–2014) provided spatially continuous elevation data bridging the two altimetry missions. ERA5 reanalysis at 0.25° resolution supplied surface air temperature and precipitation. Copernicus Marine data provided ocean temperature in adjacent fjord systems [6, 7, 12].

Methods

Repeat-track analysis compared altimetry at crossover points with cross-track slope corrections from TanDEM-X. Regional elevation change–altitude regression models were

fitted per basin to extrapolate point measurements to full glacier areas. Volume changes were converted to mass using 900 kg/m³ (ablation zone) and 600 kg/m³ (accumulation zone) following established density assumptions [5]. Surge-type glaciers were identified and treated separately. Summer temperature indices and ocean temperatures were analysed as potential drivers [8, 9].

Submarine Melting and Freshwater Fluxes

The residual between total geodetic loss and modelled surface mass balance was attributed to submarine melting and calving, accounting for approximately 40% of tidewater glacier mass loss. This is consistent with warming subsurface waters in western Spitsbergen fjords, where Atlantic-derived water at 3–5°C has increased its penetration over the past two decades. The annual meltwater flux of approximately 7 km³ concentrated from June to September can influence fjord circulation, suppress vertical mixing, and alter nutrient supply to surface waters [3, 11, 13].

Results

Table 1: Mass balance by region and period

Region	2003–2013 (Gt/yr)	2013–2023 (Gt/yr)	Change (%)
NW Spitsbergen	−2.8	−4.1	+46
NE Svalbard	−0.8	−1.0	+25
SE Svalbard	−1.2	−1.8	+50
S Spitsbergen	−1.0	−1.7	+70
Total Svalbard	−5.8	−8.6	+34

Table 2: Contribution of glacier types to total area and mass loss

Glacier Type	% Total Area	% Total Loss	Specific Balance (m w.e./yr)
Tidewater	60	68	−0.27
Land-terminating	32	26	−0.17
Cirque/Niche	8	6	−0.35

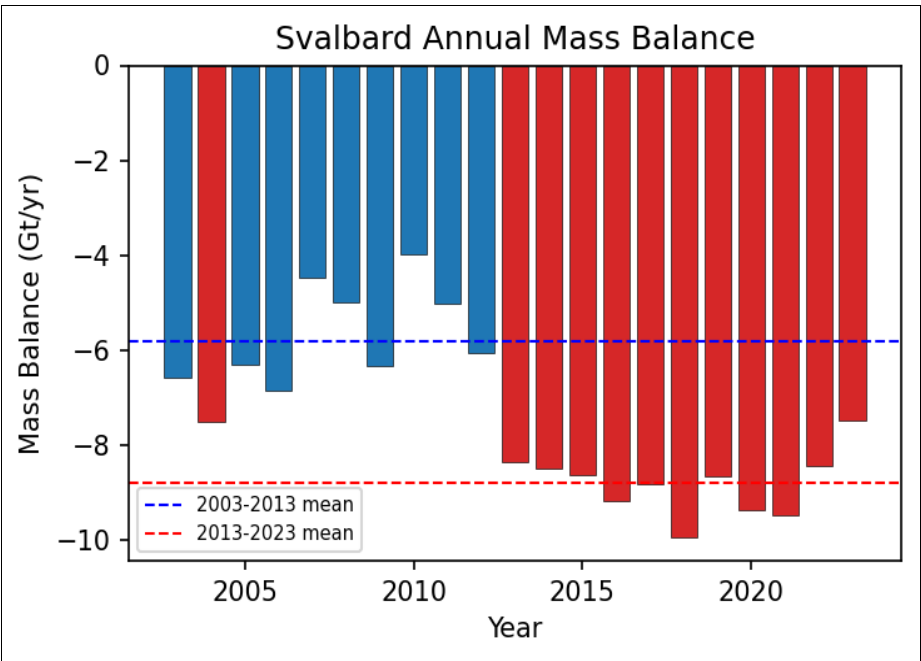


Fig 1: Annual geodetic mass balance for the Svalbard archipelago, 2003–2023

The 34% acceleration from the first to second decade is evident (Figure 1), with dashed lines indicating decadal

means. Years with exceptionally warm summers (e.g. 2016, 2020) show the most negative balances.

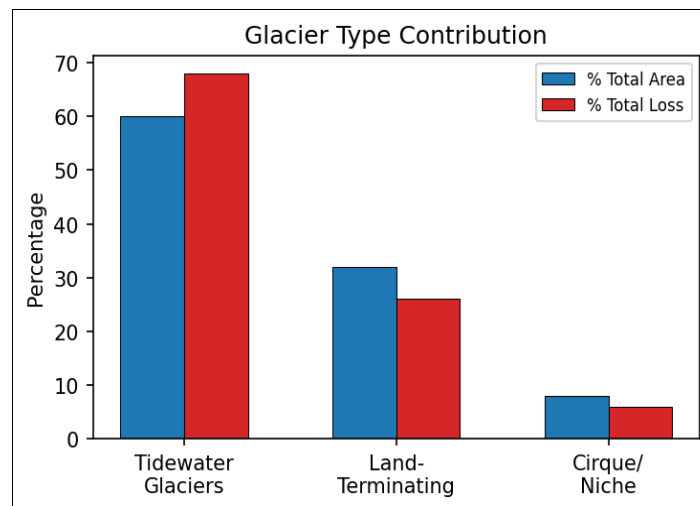


Fig 2: Contribution of glacier types to total area versus total mass loss

Tidewater glaciers contribute disproportionately to mass loss (68% of loss from 60% of area) due to the additional calving mechanism. Small cirque glaciers show the most negative specific balance and face complete disappearance within decades.

Comprehensive Interpretation

The spatial pattern of mass loss—most rapid in northwestern Spitsbergen—reflects exposure to warm Atlantic-derived waters. The temporal acceleration is primarily driven by increased surface melting (positive degree days rose 18%) supplemented by ocean warming in western fjords. Surge-type glacier behaviour locally complicates the signal but does not alter the archipelago-wide trend.

Discussion

The -7.2 Gt/yr estimate is broadly consistent with GRACE gravimetric estimates ^[1, 4]. The 144 Gt total loss equates to approximately 0.4 mm global sea level rise—modest individually but significant when combined with contributions from other Arctic glacier regions. The growing importance of submarine melting presents challenges for mass balance projections, as ocean-glacier interactions are poorly represented in current models ^[8, 13]. The freshwater perturbation from accelerating mass loss has potential ecosystem consequences through altered fjord stratification and nutrient cycling ^[11]. Future work should extend the analysis to include calving flux measurements from satellite imagery time series and develop coupled ocean-glacier models that can project marine-terminating glacier evolution under warming ocean scenarios ^[10, 14].

Conclusion

Svalbard is losing ice at approximately 7.2 Gt/yr with significant 34% acceleration over the past decade. Tidewater glaciers contribute disproportionately through both surface melting and submarine/calving losses. The spatial pattern reflects combined atmospheric warming and ocean thermal forcing.

Continued satellite geodetic monitoring is essential for tracking the evolving contribution to Arctic freshwater fluxes and global sea level rise. The identification of submarine melting as a major mass loss component highlights the need for ocean temperature monitoring in

glaciated fjords.

Small cirque glaciers face the most imminent threat of complete disappearance, representing irreversible loss of ice mass and the freshwater, habitat, and landscape values they provide.

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Contributions Not Qualifying for Authorship

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