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Tidewater glacier retreat on Svalbard in the past, present and future

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Tillbakadragandet av tidevattenglaciärer på Svalbard i dåtid, nutid och framtid

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Tidewater glacier retreat on Svalbard in the past, present and future

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Master thesis, 30 credits, in *Physical Geography and Ecosystem Science*

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Abstract

Tidewater glaciers on Svalbard are sensitive indicators of climate change and play a crucial role for Arctic ecosystems. The widespread retreat of tidewater glaciers across Svalbard highlights the need to quantify retreat rates and project when these glaciers will become land-terminating. This study investigates tidewater glacier retreat during historical (1936–1990) and present (2012–2024) periods, examines spatial variability in retreat acceleration, and projects the timing of transition from tidewater to land-terminating glaciers under multiple retreat scenarios. Using glacier front positions derived from historical maps and recent satellite imagery, retreat rates for 209 tidewater glaciers were calculated. This was done by measuring distances from parallel retreat lines, besides the glacier's centreline, to the intersection points with glacier front positions. Surge events were excluded to isolate climate-driven retreat. Later, parallel lines were intersected with two bedrock elevation models (Fürst et al., 2018; van Pelt & Frank, 2025). Present-day retreat rates were observed highest along the western coast of Spitsbergen – especially for larger glaciers within fjords, which are experiencing increased inflow of warm Atlantic water, highlighting the link between ocean temperature and frontal ablation. No glacier was found to have an advancing trend in any of the two periods. Statistical analysis revealed a significant increase ($p = 8.00 \times 10^{-23}$) in mean retreat rates across all of Svalbard from 47 m yr^{-1} historically to 111 m yr^{-1} – more than twice the speed at present rates, with maximum rates rising during these periods from 251 to 613 m yr^{-1} . The acceleration factor varied spatially, with Nordaustlandet showing the highest factor (on average >6 times as high). The rest of Svalbard showed a strong increase in retreat as well, with 2.5 to 3 times higher rates today. Additionally, Monte Carlo simulations projected future glacier front positions under four retreat scenarios: historical, present, mean, and doubled present retreat rates. This indicated that tidewater glaciers on Spitsbergen are most vulnerable and will, despite considerable uncertainty, most probably become land-terminating within the next decades. Projections indicate that by 2050, approximately 56% of Svalbard's tidewater glaciers will have become land-terminating, increasing to 75% by the end of this century. Climate change will further accelerate retreat, with applied double present-day retreat rate scenarios showing that these estimates decrease accordingly. The spatial variability underlines the influence of local bedrock topography on retreat patterns. While uncertainties remain due to surge exclusion and bedrock model variability, the results provide a baseline for forecasting tidewater glacier change on Svalbard and connections to other climate variables.

Keywords: Physical Geography and Ecosystem Science; Tidewater glaciers; Svalbard; Glacier retreat; Glaciology; Bedrock topography; GIS; Python; Marine ecosystems; Climate change

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1. Introduction

Arctic regions are warming at more than three times the global average rate, resulting in widespread and rapid changes in climate-related processes (AMAP, 2021). These changes have led to more frequent extreme weather events, and affect arctic communities, as well as both terrestrial and marine ecosystems (AMAP, 2021). Shifts in vegetation zones, community composition and food web structure, as well as species loss and migration of new species can be seen and are expected to continue influencing Arctic ecosystems in the future (Callaghan & Jonasson, 1995; Ingvaldsen et al., 2021). Besides this, one of the most well-documented effects of ongoing climate change in these regions is glacier retreat, which has been widely observed in both land-based and marine-terminating glaciers (Kohler et al., 2007; Geyman et al., 2022).

Svalbard is among the most glacier-rich regions in the Arctic, experiencing significant glacier retreat (Błaszczuk et al., 2021). Over 1100 individual glaciers cover more than half of Svalbard's land surface (Nuth et al., 2013). Approximately 20% of these are classified as tidewater glaciers, terminating in the sea (Van Pelt & Frank, 2025). These marine-terminating glaciers are especially relevant for both hydrological and ecological systems, as around 70% of Svalbard's glacier area drains through tidewater fronts, delivering freshwater from melting snow/ice and summer rain into fjords and coastal waters (Nuth et al., 2013).

Tidewater glaciers are characterized by their fronts extending into the sea, either along open coasts or within fjords (Torsvik et al., 2019). Their massive ice fronts can reach thicknesses up to ca. 200 metres, where a few tens of metres extend above sea level. Most of Svalbard's tidewater glaciers are located in fjords, though around a fourth of their total length borders open water, particularly along the extensive ice caps on the larger eastern islands. Unlike floating ice shelves in Antarctica, Svalbard's tidewater glaciers are grounded below sea level, which leads to small but frequent calving events (Luckman et al., 2015). In summer, the subglacial meltwater emerging at or just above the seabed creates buoyant freshwater plumes in fjords. These plumes contribute to vertical mixing, bringing nutrients from deeper layers into the euphotic zone, and drive sub-surface circulation by pulling in warmer, nutrient-rich waters from the outer fjord (Torsvik et al., 2019). This makes glacier fronts important ecological hotspots for fish, seabirds, and marine mammals (Lydersen et al., 2014). In contrast, land-terminating glaciers do not support this upwelling process (Meire et al., 2017).

With continued retreat, many of the marine-terminating glaciers are expected to lose contact with the sea. As glacier fronts retreat onto land, subglacial and supraglacial meltwater no longer directly discharges into the fjord. This weakens the strength of fjord circulation and the upwelling of nutrients, lowers ecosystem productivity, and may increase sea ice formation due to the presence of low-salinity surface water (Torsvik et al., 2019; Vonnahme et al., 2023). In addition to changes in fjord systems, glacier retreat also leads to physical transformations of the landscape. For example, in southern Spitsbergen, the continued thinning and retreat of Hornbreen and Hambergbreen may eventually result in a connection between Hornsund and Storfjorden, leaving Sørkapp Land as its own island (Grabiec et al., 2018).

Glacier mass loss has been ongoing in Svalbard since the 1960s and has accelerated since the early 2000s (Schuler et al., 2020; Van Pelt et al., 2019). This trend is consistent with observations from other Arctic regions, such as Greenland, Arctic Canada, and the Russian Arctic, where almost 90 % of tidewater glaciers have shown significant retreat over the last fifty years (AMAP, 2021; Straneo & Heimbach, 2013; Tepes et al., 2021). With continued warming and the increased inflow of warmer Atlantic waters into the fjords (AMAP, 2021), Svalbard's

tidewater glaciers are expected to keep retreating, leading to a further reduction in the number and size of marine-terminating glaciers (Kavan & Strzelecki, 2023). However, the extent of future retreat will also be influenced by subglacial bedrock topography (Grabiec et al., 2012). Svalbard's topography beneath the ice is largely unknown, with only restricted areas of ice-penetrating radar estimates of ice thickness from either airborne or ground-based campaigns (Fürst et al., 2018). Hagen et al. (1993), Huss and Farinotti (2012) and Martín-Español et al. (2015) estimated ice thickness distribution for Svalbard glaciers using statistical approaches. More recently, Fürst et al. (2018) and Van Pelt & Frank (2025) created bedrock elevation maps, using a mass-conservation inverse glacier modelling approach involving input parameters of surface elevation, surface velocity and modelled mass balance. Glacier bed grounded below sea level was estimated to be 13% and 4.6%, respectively, highlighting the differences between the two models.

Previous studies have investigated the area and volume changes of glaciers on Svalbard (e.g., Nuth et al., 2010, 2013; Geyman et al., 2022), as well as historical or seasonal front position changes for short periods of time, or selected regions (e.g., Błaszczyk et al., 2021; Braun et al., 2011; Kavan & Strzelecki, 2023; Li et al., 2025). Understanding when and where tidewater glaciers will become land-terminating is essential to predict the future of Svalbard's fjord systems, ecosystems, and landscape. Kohler & Moholdt (2023) present a first study on possible future tidewater glacier front position retreat over all of Svalbard, using the observed historical retreat rate for data ranging from 1936 to 2023, and the SVIFT1.0 bedrock elevation map from Fürst et al. (2018).

The release of a new bed topography map (Van Pelt & Frank, 2025), as well as the digitizing of more satellite images from the 1960s and 1990s and a refined front position retreat analysis approach provide a new opportunity to calculate more precise estimates of historic, present and future tidewater glacier retreat. This study aims to quantify the retreat rates of Svalbard's tidewater glaciers from the 1930s to the present, and to project when their fronts will become land-terminating under different retreat rate scenarios. This will be achieved by analysing available front position data for tidewater glaciers on Svalbard on a per-glacier basis, using a centreline and parallel method and incorporating two bedrock elevation maps for Svalbard: one from Fürst et al. (2018) and a more recent map from Van Pelt & Frank (2025).

The study will address the following research questions:

1. What have retreat rates been for Svalbard's tidewater glaciers for the historical (1936–1990) and present (2012–2024) periods, and do the two time periods differ significantly?
2. When will these tidewater glaciers become land-terminating, and how does this vary spatially? How large is the uncertainty in future retreat?

It is expected that this study's approach will provide more accurate estimates of the development in retreat rates and may indicate an earlier land termination compared to previous studies. These estimates are assumed to differ spatially, with earlier land termination for glaciers along Svalbard's western coast where inflow of warm Atlantic water dominates. Further, the two time periods are hypothesized to differ significantly, with global warming possibly accelerating rates in the present period. Additionally, the year of land termination is assumed to contain a moderate level of uncertainty, due to bedrock uncertainties and the response of tidewater glaciers to future atmospheric and marine warming.

2. Background

2.1. Study Area

The Svalbard archipelago is located about halfway between mainland Norway and the North Pole, at 74 °N to 81 °N and 10 °E to 35 °E (Figure 1). It is divided into four main islands: Nordaustlandet, Barentsøya, Edgeøya and Spitsbergen; and approximately 150 smaller islands (Błaszczyk et al., 2009). Svalbard's total area is around 60 000 km², of which around 57% is covered by glaciers (Błaszczyk et al., 2009; 1993, Nuth et al., 2013). More than 1100 glaciers are larger than 1 km² in area. However, 56% of the total number of glaciers on Svalbard are smaller and mainly just perennial snow patches, covering only 1% of the glacier area (Hagen et al., 1993). The total ice volume is estimated to be around 6,199 km³, with half of it being located in the two ice caps Austfonna and Vestfonna on Nordaustlandet (Fürst et al., 2018). Glaciers are of subpolar type and are characterized by large continuous ice masses on Spitsbergen, Edgeøya and Barentsøya, but small cirque and valley glaciers on central Spitsbergen and large ice caps on Nordaustlandet (Błaszczyk et al., 2009).



Figure 1. Study area showing Svalbard, its glacier cover (white areas) and distribution of tidewater glaciers (orange areas). Land areas are generated from the 2020 coastline for Svalbard (Moholdt et al., 2021b); glacier cover from the 2020 glacier inventory (Kohler et al., 2021) and tidewater glacier distribution from the Svalbard tidewater glacier front database (Kohler et al., 2018).

Climatic conditions can be described as relatively mild for its polar location, shaped by ocean currents and prevailing air masses. The West Spitsbergen Current brings warm and humid air masses to the western part of the archipelago, whereas the eastern part is strongly influenced by cooler and drier Arctic air masses (Möller & Kohler, 2018). The western parts show an average annual air temperature of about -6°C along the coast, with maximum values of 6°C in summer and -15°C in winter (Hagen et al., 1993). Further inland, temperatures are colder, and precipitation is lower. The highest precipitation rates are observed to the East and are generally higher over glaciers due to orography (Hagen et al., 1993).

Over the past 50 years Svalbard's mean temperature has increased by 4°C , significantly higher than the global average (0.8°C) during the same period (Wickström et al., 2020). This has led to more frequent extreme weather patterns, such as rain-on-snow events in connection with the increased occurrence of more extratropical cyclones bringing warm and moist air to Svalbard during winter (Rinke et al., 2017). Temperatures are expected to increase by around 10°C at the end of the century, and precipitation is expected to increase as well (Førland et al., 2012).

2.2. Tidewater glaciers

Tidewater glaciers typically terminate in fjords or along coastlines and are most commonly found in polar regions (Dowdeswell, 1995). These glaciers are different from land-based glaciers because their behaviour is directly influenced by both atmospheric and oceanic factors, such as inflow of warmer waters, so called Atlantification (Foss et al., 2024; Vonnahme et al., 2023). One of the dominant processes driving their dynamics is frontal melting and calving, where large pieces of ice break off from the glacier's front and fall into the sea (Błaszczyk et al., 2009). Contributing to around a third of the total mass loss, frontal ablation (sum of frontal melting and calving) is a major source of mass loss for tidewater glaciers on Svalbard (Błaszczyk et al., 2009). Calving rates can be accelerated by warming ocean temperatures, rising sea levels, deeper waters at the glacier front or shifts in the glacier's internal flow dynamics (Foss et al., 2024). Błaszczyk et al. (2009) and Nuth et al. (2013) classified around 165 tidewater glaciers on Svalbard, with half of the total tidewater front length being located in Spitsbergen, while Kohler et al. (2018) classified 201 glaciers as tidewater glaciers, with the difference reflecting how glaciers are defined.

Generally, tidewater glaciers show much higher velocities than land-terminating glaciers (Błaszczyk et al., 2009). Flow velocities are typically 10s of metres per year for those on land, but often on average around ten times greater for calving glaciers. Kronebreen, a tidewater glacier in Kongsfjorden, is considered the fastest flowing glacier on Svalbard, with speeds near the front of up to ca. 800 m/yr (Käab et al., 2005).

The total mass balance (TMB) of tidewater glaciers is defined as the sum of the climatic mass balance (CMB) and frontal ablation (FA) (Schuler et al., 2020), where CMB is the sum of mass inputs (accumulation due primarily to winter snowfall) and losses (ablation due primarily to summer snow and ice melt), and FA comprises mass loss from calving and ice melt along the glacier front, both above and below sea level (Figure 2). Positive TMBs lead to advancing glaciers in the long-term, whereas glacial retreat is often indicated by a negative TMB regime. For land-terminating glaciers, there is no FA, so TMB is equal to only the CMB.

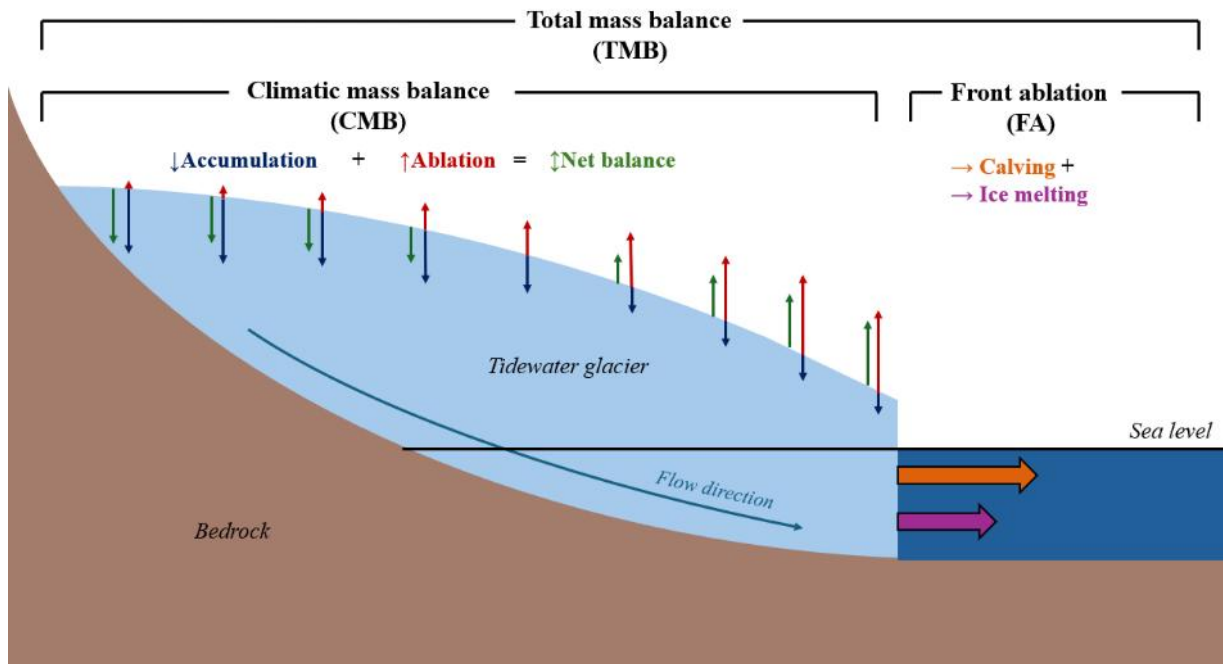


Figure 2. Terminology for mass balance of tidewater glaciers, adapted from Kohler & Moholdt, (2023).

2.3. Controls on tidewater glacier front positions

The position of a tidewater glacier front is mainly controlled by two factors: the rate of FA and the glaciers velocity, i.e. at which speed the ice flows towards the glacier front. Luckman et al. (2015) show that sub-surface ocean temperature is the key control on FA, followed by water depth, ice thickness and ice speed. Intrusions of warm waters can thus lead to faster melting and retreat of the calving front position (Straneo et al., 2010). Svalbard's fjords on the west coast are strongly influenced by warm Atlantic waters transported with the Norwegian Atlantic Current (NAC) and West Spitsbergen Current (WSC) (Vonnahme et al., 2023). To the east, the East Spitsbergen Current (ESC) transports cold waters that originate in the Arctic Ocean. However, the cold current is influenced by Atlantic water as well, as the warm water cools and subducts north of Svalbard. The ongoing warming of inflowing Atlantic water has led to increased sea surface temperatures and a decline in sea ice around Svalbard (Skogseth et al., 2020). This increase in temperature has also been linked to the loss of sea ice in the northern Barents sea (Lind et al., 2018).

The second factor controlling the front position, ice velocity, is partly related to the long-term CMB trend, where other mechanisms such as accumulation through snowfall in winter and ablation due to summer melt play a major role. Generally, glacier fronts retreat when CMB is negative, and the ice flux to the front is less than the rate at which ice is being removed by melting. For tidewater glaciers, even an overall positive CMB can lead to frontal retreat if FA rates cannot be compensated for (Luckman et al., 2015).

Whilst sea temperature and water depth controls FA rates, glacier dynamics are also characterized by the subglacial bedrock topography, which plays a crucial role in whether, when, and to what extent retreat will occur (Grabiec et al., 2012). Especially tidewater glaciers are strongly influenced by bed topography: subglacial ridges or ice-covered islands can allow the front to remain at a stable point for long periods, even as ice flux rates decrease (Truffer &

Motyka, 2016). Eventually, the glacier can retreat upglacier of such a stable point in a year where FA is extreme for example, putting the calving front into deeper water. Deep water leads to increased FA, triggering further retreat until a new position is attained where the bed topography allows establishment of a new quasi-stable position (Frank et al., 2022). Despite increasing temperatures due to global warming, a glacier that is partly stranded on land can remain stable for several years, only to suddenly and rapidly retreat over long distances. Some of Svalbard's tidewater glaciers reveal bays when retreating, often characterized by small ridges reaching out into the fjord at the bay's entrance, followed by deep water continuing for several kilometres. Nonetheless, over the long-term trends there is a close link between climate change and glacial retreat (Möller & Kohler, 2018).

2.4. Surge-type glaciers

The continuous retreat of glaciers on Svalbard is occasionally interrupted by glacier surges, in which the glacier front advances rapidly over a short period of time, from months up until a few years (Sevestre, 2015). Surging glaciers alternate periodically between passive and active phases, remaining at a low velocity over long periods of time (passive phase) and suddenly increasing in speed in their active phase. Indications of an impending surge are increased surface flow velocity and crevassing, typically with upper glacier thinning and lower glacier thickening (Sevestre, 2015).

During the surge, the dramatic increase in flow speed transports ice from the upper part of the glacier downwards, compressing more stagnant ice underneath (Sevestre, 2015). This causes the front to advance, sometimes far beyond its initial front position. Usually, surges are initiated at the top of the glacier, though some surges from tidewater glaciers have been recorded to propagate upstream from the glacier front (Sevestre, 2015; Rolstad et al., 1997). When velocities slow and the front does not advance further, the surge is over, and the frontal retreat begins anew.

2.5. Glacial retreat on Svalbard

Historical data shows widespread and accelerating glacial retreat on Svalbard since the Little Ice Age, with notable differences between land-terminating and tidewater glaciers (Geyman et al., 2022). Land-based glaciers generally show a steady, climate-driven retreat, while tidewater glaciers indicate more variable patterns due to dynamic processes such as calving and surging behaviour (Luckman et al., 2015). Between 1936 and 2010 Svalbard's glaciated area has decreased by approximately 7% (Nuth et al., 2013). A closer look indicates that the more recent period from 1990 to 2010 showed a larger retreat than the historical period. Geyman et al. (2022) provide a long-term perspective on Svalbard's glacier change, showing that around 15% of glacier volume has been lost since the early 20th century; loss rates are projected to double by 2100, if current warming continues.

Retreat rates are highest for tidewater glaciers. For example, Kronebreen and Nathorstbreen, tidewater glaciers in northwestern and southern Spitsbergen, have retreated 11 and 14 km, respectively, since the late 19th century (Błaszczyk et al., 2009; Schellenberger et al., 2015). Frontal position datasets spanning from the early 1900s to the present (Moholdt et al., 2021) show that many tidewater glaciers have been retreating rapidly since the early 2000s, most likely driven by increasing air and ocean temperatures that reflect amplified Arctic warming

(AMAP, 2025). In contrast, land-terminating glaciers, while also retreating, often do so at a slower and more uniform pace (Błaszczyk et al., 2020).

2.6. Glacier retreat assessment

There are several ways to assess glacier changes, depending on the scale, time period, and type of glacier change being studied. The most widely used method is to assess the climatic mass balance (CMB), which on Svalbard has been measured both directly, using stake networks and snow pits (e.g. Hagen et al., 2003), and indirectly through remote sensing (e.g. Nuth et al., 2010) or model simulations (e.g. Van Pelt et al., 2019). Kohler et al. (2007) used surface elevation data from a few well-documented glaciers to show that mass balance has been increasingly more negative over recent decades. Nuth et al. (2010, 2013) combined aerial photographs and digital elevation models to calculate glacier thinning since the 1960s. Later studies by Moholdt et al. (2010a) and Schuler et al. (2020) confirmed these patterns using satellite and climate data. More recently, Geyman et al. (2022) mapped widespread and accelerating ice loss across Svalbard over the last century, highlighting strong regional differences.

While mass balance measurements provide the best insights into the overall health of glaciers, changes in glacier front positions are more easily measured using remote sensing data, and are useful for tracking dynamic responses, such as that of tidewater glaciers, which can retreat rapidly due to calving and interactions with ocean water (Luckman et al., 2015). Glacier front position analysis is a standard method for monitoring tidewater glacier retreat (Braun et al., 2011; Błaszczyk et al., 2021; Kavan & Strzelecki, 2023; Kohler & Moholdt, 2023; Li et al., 2025) and is especially useful because historical front positions can be reconstructed from old aerial photos and satellite images (Geyman et al., 2022). This method is based on linear vector data that represent where the glacier front was at specific points in time. When analysing retreat on an annual or decadal basis, each line usually represents a particular year, typically from late summer, when glaciers are at their seasonal minimum. Most of these front positions come from interpretation of aerial images, or starting in the 1960s, from satellite data (e.g., Corona, Landsat, Sentinel). By measuring the distance between front lines, we can estimate how much the glacier has retreated (or advanced) over time (Błaszczyk et al., 2021; Kavan & Strzelecki, 2023).

A previous unpublished study (Kohler & Moholdt, 2023) analysed changes along single centrelines of Svalbard tidewater glaciers. The new feature in this study is the use of parallel lines drawn perpendicular to these centrelines, to allow better characterization of the typically irregular retreat along a glacier front, allowing a more consistent estimation of retreat even in complex fjord systems characterized by varying bedrock and water depths that affect glacier retreat. Furthermore, a number of newly digitized historical front positions allows an improved estimate of the past retreat rates.

2.7. Uncertainty of tidewater glacier retreat rates -case studies

Estimated retreat rates must be interpreted with caution, as glacier dynamics and behaviours can vary substantially. Figure 3 illustrates four specific glacier behaviours that require different ways of handling the data:

- a) Linear retreat, representing the most straightforward and ideal scenario for analysis;
- b) Surging glaciers, which rapidly advance during short surge periods and then retreat during long inactive periods;
- c) Partially stranded glaciers, where parts of the glacier front have already retreated onto land, while other parts are still in contact with the sea and continue to retreat; and
- d) Likely stranded glaciers, with front positions that barely change, indicating that they have most likely terminated on land, although not visible in satellite imagery.

Two representative examples are presented for each glacier behaviour category. Linear retreat has been observed for Deltabreen, on Edgeøya (Zone E), and Emiljanovbreen, in southern Spitsbergen (Zone D) (Figure 3a). Both glaciers have undergone continuous retreat since 1936, with front positions having shifted landwards by 6.5 to 7 km and 7 to 7.5 km, respectively. No surge behaviour has been observed. While Deltabreen has a similar trend for both historical and present periods, Emiljanovbreen shows an acceleration in retreat in recent years.

In contrast, surging has been identified for Blomstrandbreen (Zone A) and Tunabreen (Zone B) (Figure 3b), with two and three surges, respectively, over the past 100 years. Blomstrandbreen surged in 1960-1966 and 2009-2012, advancing by about 1 km in each event. However, during the second surge the glacier only advanced in its central part. Tunabreen, Svalbard's most surging glacier in the past 100 years, surged in from 1966-1971, 2001-2004, as seen in Flink et al. (2014), and most recently from 2016-2018, with advances between 1.5 to 2 km during the two most recent events.

Since glacier retreat does not occur uniformly and bedrock topography plays a crucial role in retreat patterns, a glacier can also partially become stranded on land even as parts of the front remain in the sea and continue to retreat (Figure 3c). This is the case for the southern front of Kongsbreen and Kollerbreen, both located in northwestern Spitsbergen (Zone A). Kongsbreen provides a clear example, with only a small part of the glacier still retreating northwards into a narrow part of the fjord. Similarly, Kollerbreen appears most likely stranded on its southern part, but continues to retreat on the northern edge.

Finally, there are glaciers that most likely to be fully stranded (Figure 3d). Nordre Buchanisen (Zone A) and Glintbreen (Zone B) show slight variation in front position, though the general trend is stagnant. Nordre Buchanisen retreated 1.1 to 1.6 km between 1936 and 1990 but has remained mostly stable since. On the other hand, Glintbreen has only shown minor variations, with advances up to 200 m, and retreats of no more than 100 m.

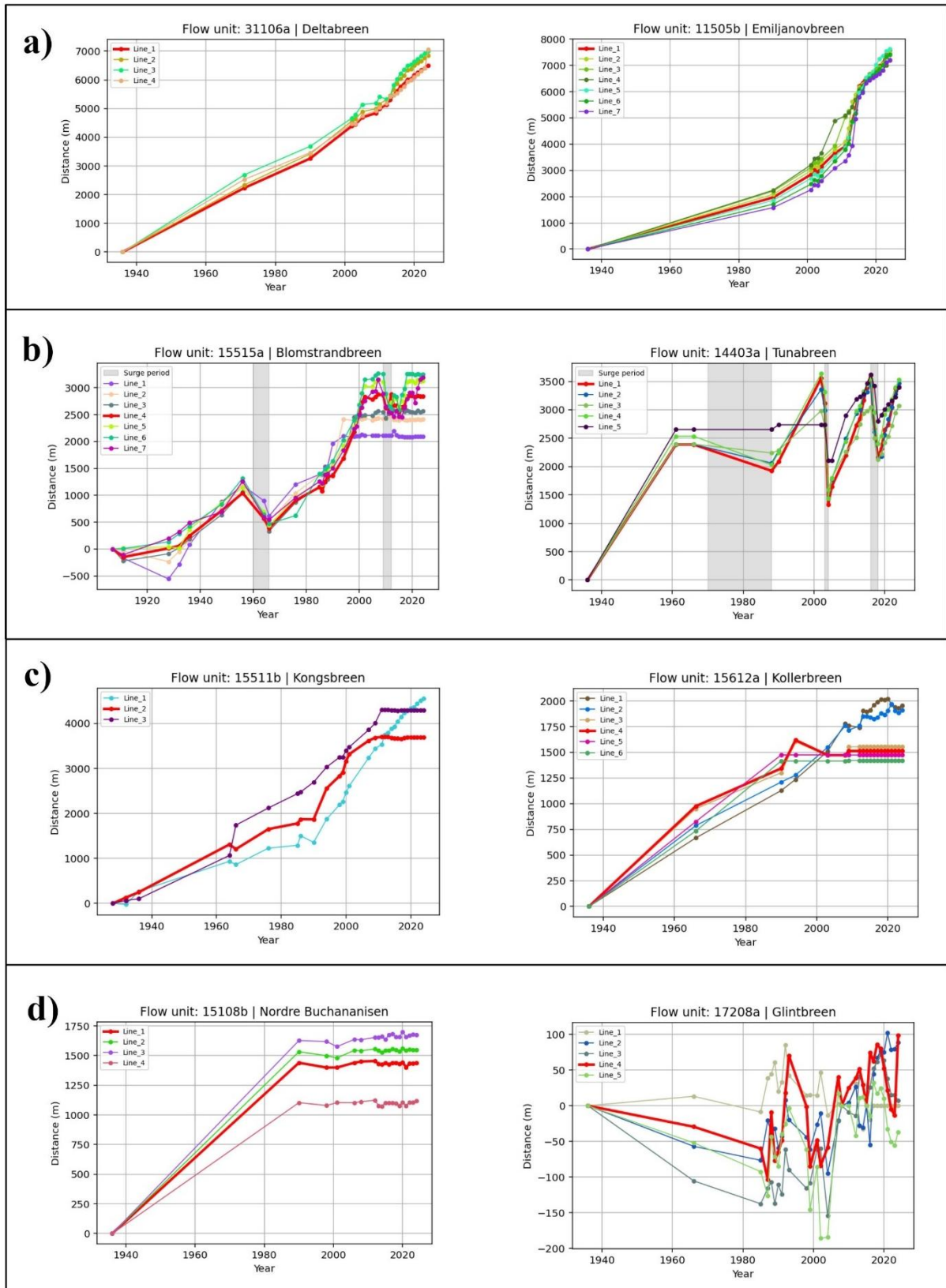


Figure 3. Case studies of tidewater glaciers showing different behaviour: a) linear retreat; b) surging glaciers; c) partially stranded glaciers; d) likely stranded glaciers. Y-axes show cumulative retreat distance (m), differing for the different glaciers, and x-axes show time (years).

2.8. Impact on marine ecosystem

Tidewater glacier fronts are important ecological hotspots, as subglacial discharge of freshwater into the ocean from melting creates upwelling places (Torsvik et al., 2019) that are rich with plankton and attract higher trophic levels like seabirds and marine mammals (Lydersen et al. 2014). These include species like kittiwakes (*Rissa tridactyla*) and ringed seals (*Pusa hispida*) that rely on these areas for feeding, especially in the "brown zone," an ice-free area in front of calving glaciers with suspended sediments (Lydersen et al., 2014). The reduction in the number of tidewater glaciers and of the extent of their calving fronts leads to habitat loss for these species (Lydersen et al., 2014). This could alter feeding behaviour, and cause changes in food web structure and potential population loss. Particularly species that depend on glacier-related fast-ice when sea ice is not available would be affected, such as ringed and bearded seals using glacier ice especially during spring as breeding or resting sites (Lydersen et al., 2014).

Apart from that, the impact on Arctic food webs is also driven by the changes in chemical and physical composition of sea or fjord water. Tidewater glaciers shifting to land-termination influence circulation, salinity, and nutrient availability (Losapio et al., 2025). Subglacial discharge plumes are created by the input of less dense, sediment laden freshwater from the glacier (Darlington, 2015). This is more buoyant than the deeper saline fjord water, increasing vertical mixing and upwelling, ultimately bringing nutrients from deep layers to the surface during summertime (Meire et al., 2017; White et al., 2025). Glacial meltwater from tidewater glacier fronts contributes to about 32% of the overall fraction of nutrients derived from upwelling in early spring (Vonnahme et al., 2021), with subglacial upwelling from marine bottom water (53%) and horizontal transport through surface water (15%) accounting for the rest. Similarly, Fransson et al. (2020) found that subglacial outflow contributes to 30% - 60% of upwelling at a tidewater glacier front in Tempelfjorden, central Spitsbergen. Despite local variation, this highlights the importance of the link between marine-terminating glacier fronts and vertical mixing in the fjords.

Meltwater beneath the glacier transports nutrients and organic matter from upstream glacial and terrestrial ecosystems. It can reduce photosynthesis due to the increase in turbidity as seen in a study by Darlington (2015) in Kongsfjorden. However, under low disturbance, the input of nutrients results in phytoplankton blooms enhancing local productivity (Losapio et al., 2025). Glacial meltwater supply of nutrients such as iron, silica and manganese (White et al., 2025) plays a crucial role in promoting primary production and species such as Antarctic krill (*Euphausia superba*) and Arctic copepods (*Calanus glacialis*, *C. hyperboreus*) (Losapio et al., 2025). Further, benthic communities can be disturbed by calving glaciers, initiating new succession processes and affecting carbon cycling (Losapio et al., 2025).

As tidewater glaciers thin and retreat further onto land, the timing, location, magnitude and composition of freshwater discharge can change in non-linear ways. Discharge points moving to higher elevations further away from the fjord alter freshwater input locations from direct subglacial discharge into the fjord to surface runoff (Hagen et al., 2003). Enhanced melt and less refreezing impact the increase in surface runoff further (Van Pelt et al., 2019) and seasonal discharge patterns are also expected to shift, with earlier melt onset and changing peak flow timing (Van Pelt et al., 2019).

3. Data and Methodology

3.1. Data

Long-term observation data for the analysis of retreat rates of tidewater glaciers is crucial to be able to identify trends. Before Geyman et al. (2022) published a glacier extent dataset for the years 1936 and 1938 from orthomosaic images, only a few glaciers were covered with data reaching that far back in time (e.g., Kongsbreen, Recherchebreen, Nordenskiöldbreen). Further front datasets, digitized from aerial photographs, orthophotos, satellite images and maps are available for several years in the 1960s, 70s, and 90s (Table 1). Non-georeferenced aerial images from the Norwegian Polar Institute's (NPI) S90 airborne campaign were also added to the front dataset in this study. Further, NPI has digitized annual frontlines of tidewater glaciers from available satellite imagery and the institute's own aerial imagery for mid-August to mid-September since 2012 (Moholdt et al., 2021). The front dataset for this study was complemented with front positions from Li et al. (2025) from 1985 to 2007, for glacier's not covered by the already existing data. All glacier front positions have been obtained as shapefiles.

Additionally, two bedrock elevation models covering all of Svalbard were used in this study (Füerst et al., 2018; Van Pelt & Frank, 2025). Füerst et al. (2018) include available radar derived sounding data within their inverse model, whereas Van Pelt & Frank (2025) only use their inverse method, including state-of-the-art ice flow models, to obtain the underlying glacier bed and assess the uncertainty by comparing to the radar-derived ice thicknesses. Both models provide good estimates of the bedrock topography; however, uncertainty is still high, which can be seen in the mean average error of 77.5 m of Van Pelt & Frank's (2025) final bed map and Füerst et al.'s (2018) error estimates, which exceeds 200 m in places.

Further data for the analysis included centreline and parallel line data to describe the flow of tidewater glaciers, as well as glacier inventories, topographic maps and the tidewater glacier database and reference polygon to identify glacier ID numbers and names. Surge data was available from Sevestre (2015) and recent observations from NPI (Table 1).

Table 1. Overview of datasets used in this study.

Category	Dataset	Source	Description
Glacier front positions	Years 1936, 1938	Geyman et al. (2022)	Glacier extents from orthomosaic, coverage: Svalbard
	Years 1960, 1961, 1966, 1969, 1970, 1971, 1990, 1992, 2000-2010	König et al. (2013)	Glacier area outlines, coverage: Svalbard
	Years 1990, 1991, 1992	Luda (unpublished)	Front positions from S90 maps and aerial images, helicopter survey and Landsat imagery, coverage: Svalbard
	Years 2007–2009, 2012–2024	Moholdt et al. (2021a)	Annual frontlines, coverage: Svalbard
	Variety of years, 1899-2022	Błaszczuk et al. (2023)	Coverage: Hornsund area
	Variety of years, 1869-2022	Liestøl (1988), Kohler (unpublished)	Coverage: Kongsfjorden
	Variety of years, 1896-2015	Allaart (2016)	Coverage: Nordenskiöldbreen
	Variety of years, 1830-2021	Zagórski et al. (2023)	Coverage: Recherchebreen
	Years 1985–2023	Li et al. (2025)	Calving front dataset for marine-terminating glaciers in Svalbard generated with deep learning
Glacier Geometry & Retreat Analysis	Tidewater glacier centrelines	Nuth et al. (2013)	Centreline data from the Svalbard Glacier Database
	Parallel lines	Lafont (2024, unpublished)	Parallel flow lines to the main centrelines on a per glacier-basis
Topographic & Background Data	Svalbard tidewater glacier front database	Kohler et al. (2018)	Tidewater glacier fronts with glacier geometries and attributes
	Glacier inventory (2020)	Kohler et al. (2021)	Glacier outlines and metadata
	Bed topography and ice thickness maps	Van Pelt & Frank (2025)	GeoTIFF files covering all of Svalbard
	SVIFT – Ice-free topography & bathymetry	Fürst et al. (2018)	NetCDF files for bed elevation with bathymetry data
	Coastline (2020)	Moholdt et al. (2021b)	Shapefile as reference for land-sea boundary
	Svalbard land area (S100)	NPI (2014)	Shapefile for general reference
	Tidewater glacier front reference polygon (2024)	Moholdt (unpublished)	Shapefile as reference layer for defining tidewater glacier extent, IDs, Names
	Satellite image mosaic (2020)	NPI (2023)	Background imagery for mapping and visual validation
	Orthophotomosaic Svalbard 1936	Geyman et al. (2021)	Background imagery for mapping and visual validation
	Topographic maps, TopoSvalbard	NPI (2025)	Norwegian Polar Institute’s topographical map service (https://toposvalbard.npolar.no)
Glacier Dynamics	Svalbard surge glacier database	Sevestre (2015) / NPI (2021, 2025)	Register of known surge-type glaciers in Svalbard and observed surges

3.2. Methodology

3.2.1. Research design overview

This study uses a partly novel and thorough method to analyse and project the retreat of Svalbard's tidewater glaciers. First, larger glaciers are subdivided into multiple flow units, which are analysed individually, rather than as a glacier-wide average. This allows the assessment of spatial variability in retreat behaviour, which is especially relevant for tidewater glaciers with multiple fronts (e.g. Stonebreen) or those that are wide in extent, where retreat may vary substantially between units. A set of flow lines, parallel to the glacier's centreline was drawn for each flow unit and intersected with mapped glacier front positions from the 1930s to 2024. This multiple line-based approach captures the variability in glacier front retreat across time and space, providing a more spatially representative view than centreline-based methods, which typically reflect only one retreat pathway and cannot capture lateral differences along the front. Moreover, surge periods were chosen to be excluded from retreat rate calculations, as they can interfere with the assessment of glacier behaviour (Błaszczyk et al., 2013). This was performed to isolate background retreat trends more reliably, offering a clearer view of glacier response to climate forcing.

To project future retreat, parallel lines were intersected with two independent bedrock elevation models as grounding-lines for land termination (Fürst et al., 2018; Van Pelt & Frank, 2025). Projections were made under four retreat scenarios: historical, present, mean of the entire study period, and double present-day retreat rates. Using different scenarios shows the glacier's sensitivity to climate change, as well as variability and uncertainty in future retreat projections. The combination of these methodological choices forms a research design that advances existing glacier retreat analyses by emphasizing spatial precision (flow unit-level detail), consistency over time (exclusion of surge periods) and climate sensitivity (scenario-based land-termination projections) across all of Svalbard's tidewater glaciers.

3.2.2. Data collection & Preprocessing

3.2.2.1. Front positions

Glacier front position data was collected (Table 1), harmonized and merged in ArcGIS Pro (Version 2.7.0, Esri, 2020; Redlands, California, USA) to create one dataset of available front positions for all tidewater glaciers on Svalbard, for a total of 5108 front lines between 1830 to 2024, covering 232 tidewater glaciers (Figure 4). Each glacier front line is characterized by a glacier ID (as defined by Hagen et al. (1993) and updated by Nuth et al. (2013)), name, year and source corresponding to the period in which the survey was made. Of these, 23 glaciers were excluded from further analysis, due either to there being no observed retreat in recent years, and thus to most likely being stranded, or to the fact that there were too few historical frontlines available. This resulted in a total of 209 tidewater glaciers being analysed in this study. In addition to the previously available front position data, aerial imagery from the Norwegian Polar Institute's 1990 campaign (S90) was georeferenced with ground control points taken from a modern orthophoto (NPI, 2023) and fronts were digitized for 38 glaciers not previously compiled, to yield 137 glacier fronts for 1990 across the archipelago. This work was carried out as part of the present study. Further unpublished datasets based on NPI aerial imagery from the 1960s and 1990s were incorporated as well.

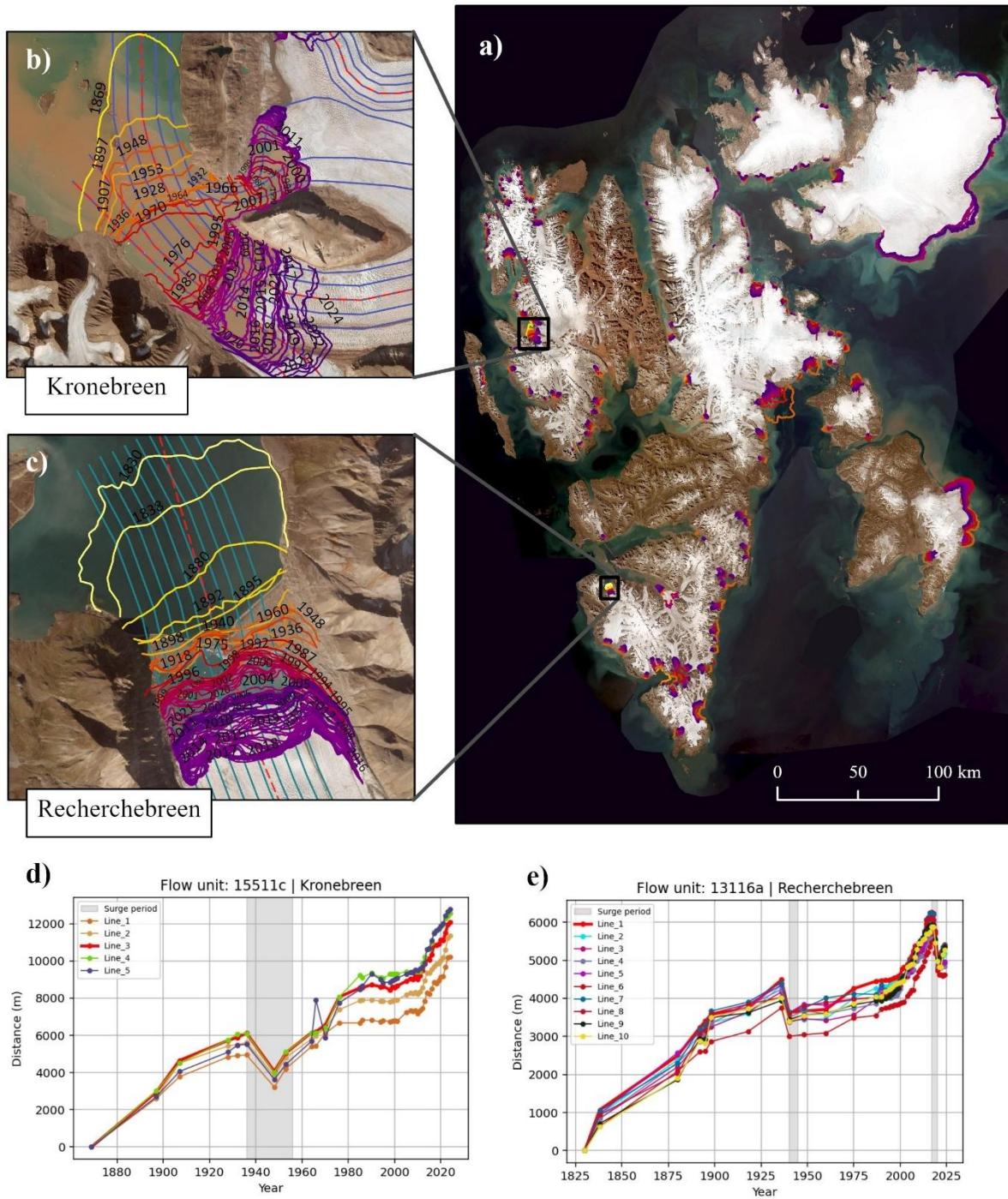


Figure 4. Distribution of front positions data across Svalbard (4a), close-up of Kronebreen's historical record (4b), as well as of Recherchebreen (4c). Cumulative retreat distance is also shown for the two glaciers (4d and 4e), including surge periods.

3.2.2.3. Parallel flow lines

This study's approach, using multiple parallel flow lines to the glacier's centreline (Figure 5), was initiated during the summer internship of Nathan Lafont at NPI in 2024 (unpublished data). Accordingly, a linear vector layer of parallel lines and predefined flow units was available. Svalbard was divided into 5 zones: A (northwestern Spitsbergen), B (central/eastern Spitsbergen), C (Nordaustlandet), D (southern Spitsbergen) and E (Barentsøya and Edgeøya) (Figure 5). At least three parallel lines per flow unit were used, however, the number was based on the glacier's size and geometry, indicating that larger and more extensive glacier fronts were described by more flow lines, and smaller ones by less. The flow lines were adjusted to fit this study's long-term analysis, extending to at least the previous glacier extent in 1936, as well as far beyond the most recent 2024 front position for the analysis of future bedrock intersection. Here, current glacier extent and topography was considered, mostly following the glacier's centreline further inland. Since the glacier flow does not always correspond exactly with the hand-drawn centrelines, in a few cases the parallel lines are not strictly sub-parallel. However, the glacier frontline is determined by the way the glacier flows, highlighting the importance of using these parallel lines, in addition to the centreline.

3.2.2.4. Flow units

Flow units are defined as the group of parallel lines defining the glacier's flow. One flow unit usually corresponds to one glacier, however, in a few cases one glacier could also have two or more flow units. Stonebreen serves as a good example: the glacier has two marine-terminating glacier fronts (Figure 5), separated by a small strip of land. Moreover, several glaciers can also share the same glacier front, as e.g. in larger fjords such as Lilliehöökfjorden, or along the extensive ice flow units of Austfonna. The flow unit number consists of the glacier's ID and a letter, with a glacier having several flow units continuing this identifier alphabetically (i.e., a, b, c...). By computing the distance between the annual front positions, the speed at which the glacier is advancing or retreating can be calculated. In order to follow the glacier's flow, intersection points between the frontlines, centre and parallel lines were created, linked to each specific flow unit.

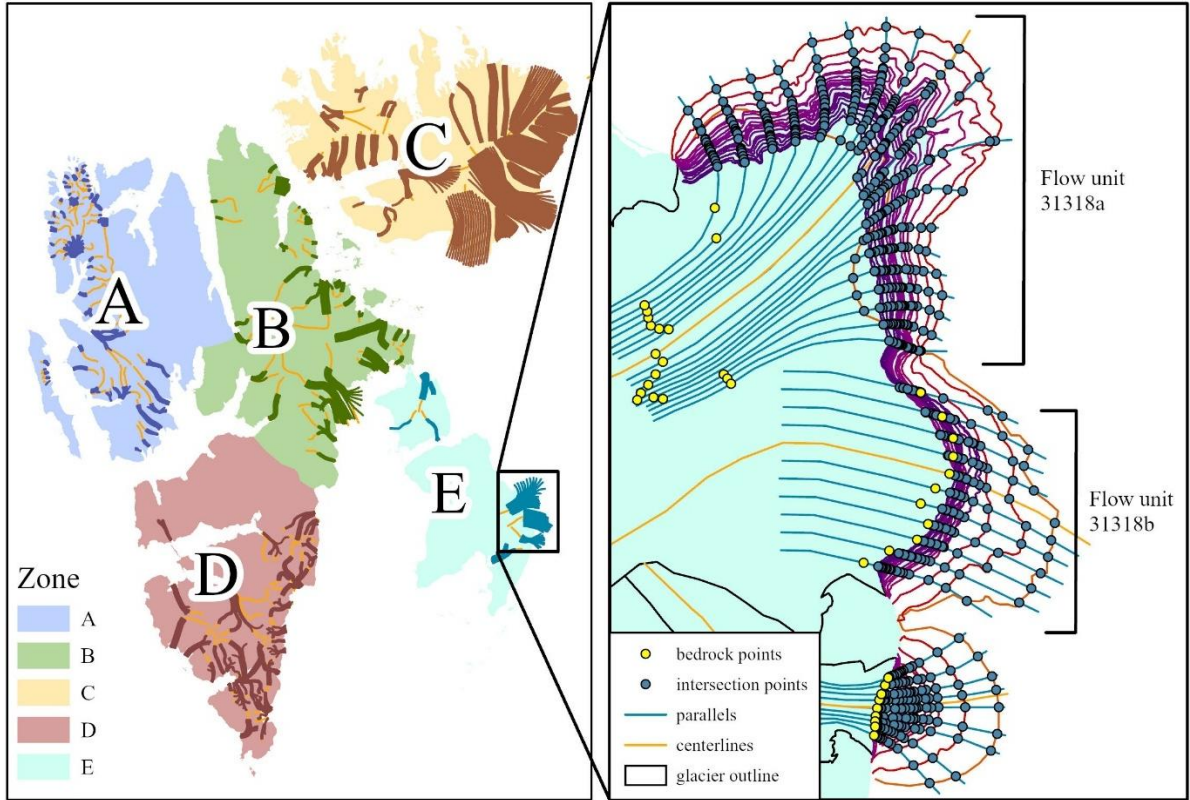


Figure 5. Map of the different implemented zones of the study area (Zones A, B, C, D, E) and a close-up of Stonebreen, divided into two flow units due to its two calving fronts at different positions. Intersection points between front position lines and flow lines, as well as bedrock points (estimated point of land termination) are also shown.

3.2.2.5. Surging glaciers

Surge data was added to all flow units and compiled from Sevestre's surging glacier dataset for Svalbard (2015), as well as from more recent observations from NPI. Major recorded surges from the two data sources, but also minor surges, especially identified prior to larger surge events, were included in the analysis. A total of 89 surge-type glaciers, with 70 glaciers surging once, 23 surging twice and only 6 glaciers surging three times within the observational time period, were recorded. Tunabreen in central Spitsbergen is the most prominent example of a frequently surging glacier on Svalbard. However, other glaciers such as Austfonna basin-6, Rijpbreen N and Crollbreen were also observed to have 3 surges, although of minor extent. Currently surging glaciers encompass Borebreen in northwestern Spitsbergen, Petermannbreen in central Spitsbergen, Nordsysselbreen, Hansbreen, Paulabreen and Skobreen in southern Spitsbergen and the northern part of Deltabreen on Edgeøya.

3.2.2.6. Bedrock intersection points

To determine the remaining time of a glacier being tidewater, or when it becomes land-terminating, the bedrock needs to be taken into account. Two bedrock topography maps are used in this study's analysis. The first one, SVIFT (Fürst et al., 2018), has been used previously in other studies (Van Pelt et al., 2019; Schuler et al., 2020; Allaart et al., 2020; Geyman et al., 2022; Frank et al., 2023; Kavan et al., 2023; Foss et al., 2024; Li et al., 2025). The second, is the recently published bedrock map of Van Pelt & Frank (2025). Bathymetry data, which helps

to understand past retreat, was added to the SVIFT dataset by Kohler & Moholdt (2023), but not for Van Pelt & Frank's (2025) data. For both bedrock raster layers, areas above sea level were extracted, and inland "holes" or depressions, areas below sea level situated inland and not connected to the ocean, were filled. A dissolved polygon layer was created for each of the bedrock maps, serving as the reference for land termination.

Then, intersection points between the parallel lines and the Fürst et al. (2018) bedrock were created. In cases where the parallel line intersected several times with the bedrock, only one intersection point per parallel line was kept. This step created some issues, as in a lot of cases the glacier fronts had retreated past the bed intersection points, which was validated with recent satellite imagery from the 2020 satellite image mosaic. In these cases, where the reference polygon of Fürst et al. (2018) did not represent reality, Van Pelt & Frank's (2025) bedrock polygon was considered, and intersection points adjusted accordingly. If, however, both bedrock maps did not align with observed tidewater glacier front retreat past the theoretical land-termination point, an uncertainty zone was taken into consideration (Figure 6). This uncertainty zone was established from the mean average error (MAE) of 77.5 m over the bedrock map of Van Pelt & Frank (2025). In reality, the errors can be much greater, however, this indicates that areas up until 77.5 m could possibly be classified water. This applies directly to low-lying areas where tidewater glaciers terminate in the sea, suggesting potential future pathways within fjords or valleys. The bed intersection points were then moved along the parallel lines to the edge of this uncertainty zone.

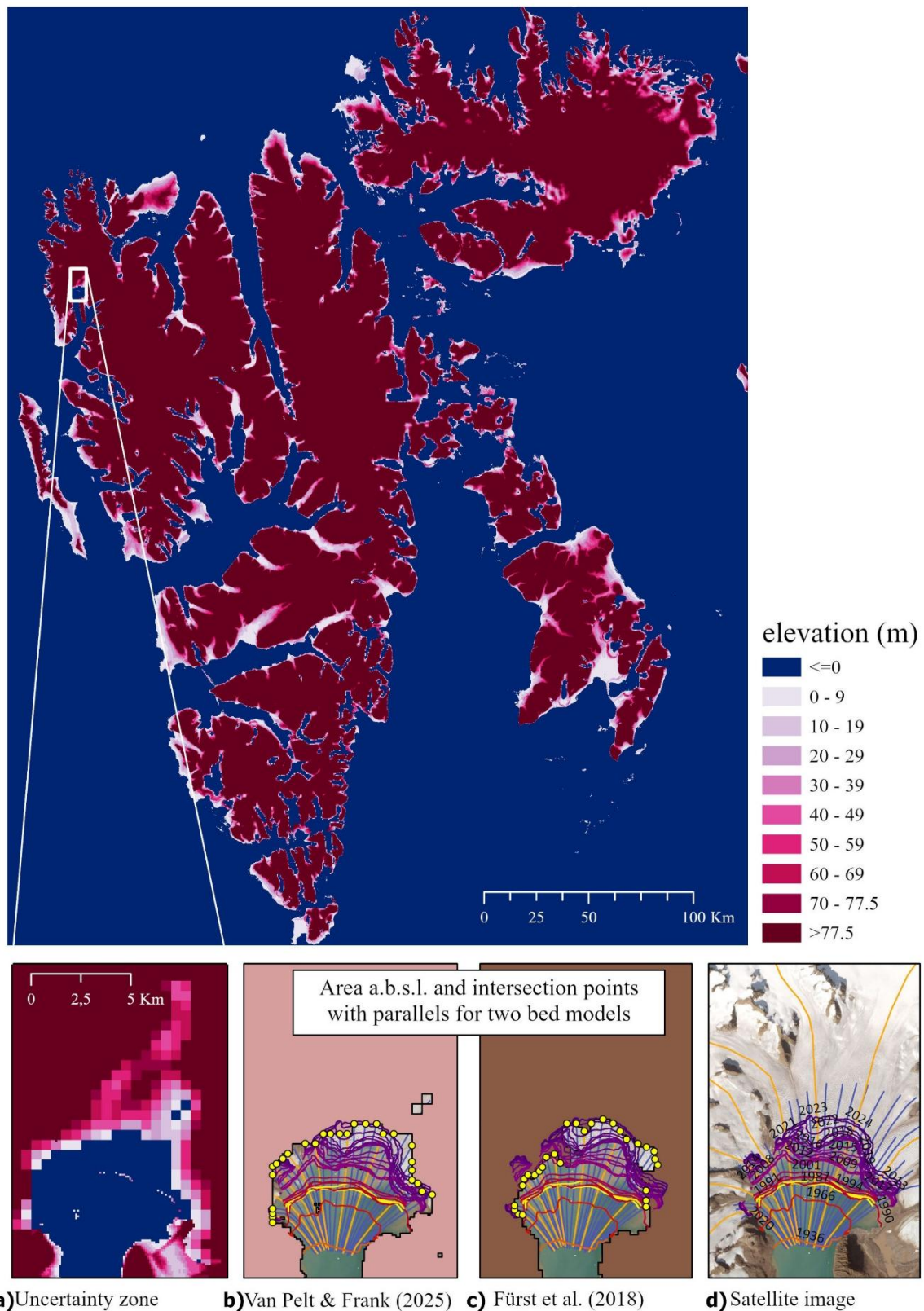


Figure 6. Indication of uncertainty of the two bedrock elevation models used in this study. Fürst et al. (2018) estimate an average error of 77.5 m over the whole area of their model (large map). A close-up of Lilliehöökreen is shown for a) the applied error estimate, alongside b) the Van Pelt & Frank (2025) and c) Fürst et al. (2018) models. The difference in bedrock point locations (yellow), are shown as intersection points between each model and the front lines. The glacier front has been observed to further retreat and still be marine-terminating, however, both models show wrong estimates of the bed in these areas. To the right, d) shows the 2020 satellite image for visual validation.

3.2.3. Retreat Rate Calculation

Retreat rate calculations were performed in Spyder 6 (Spyder Development Team, 2025) using Python (v3.11.11). The Python script computed distances from intersection points between glacier frontlines and parallel lines, along each parallel within a flow unit. The method used vector-based geospatial data and estimated linearly fitted retreat rates for three time periods: mean (entire observation period), historical (1936-1990) and present (2012-2024), excluding known surge periods. These two major time periods were chosen based on availability of data and representativity. While present data is available on an annual basis, historical data is rather sparse, with front data usually available for 1936, the 1960s, and the 1990s. In addition, an acceleration in retreat could be observed visually during data pre-processing for many glaciers within the past 15 years, by interpreting cumulative retreat distance plots. The retreat rate calculation was performed on a per-flow unit basis across all zones.

The script used two main inputs in the form of a GeoDataFrame: a lines layer for the parallel flow lines, including a numeric line ID, glacier name and ID number, flow unit ID and surge periods, as well as the intersection points layer, containing line ID, year of frontline and glacier ID. Both layers also included an attribute if the parallel line, or the line the point is lying on, is a centreline or not, to differentiate between centreline and other parallel line behaviour in graphs shown later.

Outputs included retreat plots per flow unit showing accumulated glacier front retreat over time per parallel line, as well as observed surge periods (Figures 3 and 4). Furthermore, CSV files were produced, summarizing retreat rates per line for the entire observation period (all available data), the historical and present period, as well as the average over all lines per flow unit. A CSV file presenting the mean retreat rates across lines for each flow unit within a zone was also generated (zone-level summary).

The main processing can be divided into 6 main steps:

1. First, input attributes were retrieved, flow units, and glacier fronts from input GeoDataFrames were extracted and the chronological ordering of glacier front positions was ensured.
2. Second, retreat distances were calculated for each parallel line: intersection points were projected onto the line to compute retreat distances along the parallel. The initial (earliest) distance was subtracted to measure relative retreat from the starting position. This retreat distance calculation (eq. 1) between two glacier frontlines along the same parallel line, assuming the glacier retreats in the direction of the flowline, can be described by:

$$D_{xy} = d(P_y) - d(P_x) \quad (\text{eq. 1})$$

Where:

D_{xy} = retreat distance between year x (earlier year) and y (later year)

P_x, P_y = intersection points of parallel with glacier fronts from year x and y

$d(P)$ = distance from point P to the starting point of the parallel line.

If $D_{xy} > 0$, the glacier retreats, if $D_{xy} < 0$, it advances.

3. Surge periods were identified and removed by extracting the years for known surge periods per flow unit from the lines layer. Retreat distances from surge-affected years were filtered out, while keeping the last point before the surge started. The start and end years for segments not including surge periods were stored for linear regression.
4. Retreat rates were calculated for each time period (full record/mean, historical, and present). A linear least-squares regression (scipy.stats.linregress v1.15.2) calculating the slope was applied to the segments. Mean retreat rates for the 3 different time periods were computed for each flow unit by first calculating the retreat rate along each parallel line and then averaging these rates across all lines within the flow unit, to provide a robust representation of glacier front change at the flow unit scale (eq. 2). The resulting mean flow unit retreat rate can be described by:

$$\bar{R} = \frac{1}{N} \sum_{i=1}^N R_i = \frac{1}{N} \sum_{i=1}^N \frac{D_{i,t_2} - D_{i,t_1}}{t_2 - t_1} \quad (\text{eq. 2})$$

Where:

$\bar{R}$ = Mean retreat rate for the flow unit (m yr⁻¹),

R_i = Retreat rate along the i -th parallel line,

D_{i,t_1}, D_{i,t_2} = Retreat distances at times t_1 and t_2 for the i -th line,

N = Number of parallel lines in the flow unit

5. Plots per flow unit were created showing cumulative retreat distances over time for all flow lines, excluded points were marked in red to check which points were excluded, and which segments were used. Finally, all outputs were saved and further processed in MS Excel (Version 2505; Microsoft Corporation, Redmond, WA, USA) and ArcGIS Pro for visualization, evaluation and the making of maps.
6. A paired, two-tailed t-test was chosen for the comparison between historical and present retreat rates. Glaciers with values for both periods were included in the statistical test (184 glaciers), linking the historical and present observations. The null hypothesis assumed the mean difference between the pairs to be zero. The alternative hypothesis would be accepted if there is a difference in means, showing that there has been a change between the two time periods.

3.2.3.1. Paired t-test

To assess whether glacier retreat rates on Svalbard differ significantly between the historical and present period, a paired, two-tailed t-test was conducted in Python. This test compares the means of two related groups and is appropriate given that retreat rates were measured for the same glacier units across the two periods. Only glaciers with available values for both periods were included in the test ($n = 184$).

Normality between the pairs was assessed visually using a histogram and Q-Q (quantile-quantile) plot of the differences. The distribution of the mean difference was roughly symmetric (Appendix, Figure S1) and with the help of the central limit theorem the use of the paired t-test

was justified given the relatively large sample size ($n > 30$), and the sampling distribution of the mean difference was approximately normal (Rogerson, 2019).

The null hypothesis (H_0) stated that the mean difference in retreat rates between the historical (1936–1990) and present (2012–2024) periods was zero. The alternative hypothesis (H_1) was that a significant difference existed, indicating a change in retreat behaviour between the two periods. A significance level of $\alpha = 0.05$ was used, following standard practice in glacier and climate-related studies, indicating a 5% risk of a Type I error (Jiskoot et al., 1998). The test was two-tailed, as the analysis aimed to detect any significant difference in either direction.

3.2.4. Bedrock Intersection Analysis

The calculated retreat rates were further implemented into the bedrock intersection analysis, where the time remaining for a flow unit to terminate on land was computed in Python. The analysis can be divided into two main steps: 1) calculation of distances from the last front position to the bedrock intersection point and 2) application of calculated retreat rates to estimate years remaining until land termination.

For the first step, similarly to the retreat rate calculation (Section 3.2.3), the analysis used parallel lines and glacier front points from GeoDataFrames as inputs. In addition, a bedrock intersection points layer, indicating where each parallel line becomes land-terminating, was added, matching the attributes of the other point layer. The difference between the last available glacier front point and the bedrock intersection point represented the remaining retreat distance. Linear regression was applied to the retreat distance time series for each line. Outputs included plots showing retreat lines and future intersection with the bedrock, and a CSV file per zone containing the remaining distance.

Then, the estimated years until land termination were computed with the remaining distance CSV files for each glacier flow unit and retreat rate summary CSV files, containing historical, mean and present retreat rates. A new retreat rate scenario was added: double the present rate, representing a hypothetical future acceleration at twice the present rate for sensitivity analysis. Both files for the same flow unit were used to calculate the number of years until land-termination by dividing the remaining retreat distance by the retreat rate for the four scenarios, each scenario output stored separately after calculating. Once all individual parallel lines within a flow unit were processed, the last point reaching land was filtered out and considered as the time until total land termination for a flow unit. The values for all flow units were summarized and saved in a CSV file and further processed in ArcGIS for map visualization and summary statistics.

3.2.5. Uncertainty assessment: Monte Carlo simulation

To quantify uncertainty in projections of glacier retreat, a Monte Carlo simulation approach was applied to estimate the distribution of years until land termination (YULT) for each glacier flow unit across the five defined zones of Svalbard. This kind of simulation was chosen for its ability to handle uncertainty and variability influencing future retreat projections, such as uncertainties in the topography beneath the ice at glacier front positions and climatic and sea temperature fluctuations. In contrast to single-scenario approaches that produce only one possible outcome, the Monte Carlo method captures a range of potential results and provides probabilistic

estimates of when glaciers are expected to become land-terminating. For example, Möller et al. (2016) use a well-defined Monte Carlo approach for modelling the mass loss of land-terminating glaciers under a future climate scenario.

The simulation was implemented in Python using the NumPy and Pandas libraries. For each flow unit, input data included:

- The distance from the latest glacier front to the bedrock intersection point (i.e., the remaining retreat distance before the glacier becomes land-terminating),
- Retreat rates under four different scenarios:
 - Mean retreat rate (overall mean from available historical data to the present),
 - Historical rate (1936-1990),
 - Present rate (2012-2024),
 - Double present rate, as a sensitivity test.

To account for natural variability in retreat behaviour, glacier retreat rates were treated as normally distributed variables in the simulations, with a mean and standard deviation derived from observed retreat data (excluding surge periods). These standard deviations reflect the observed variability and differences between different time periods and scenarios. More recent and future scenarios have shown bigger standard deviations, indicating the observed acceleration in retreat and the larger uncertainties expected for future conditions.

For each retreat rate scenario and each glacier flow unit, 1000 runs were performed. In each run, a random retreat rate was drawn from the defined normal distribution and YULT was calculated as:

$$YULT = \frac{\text{distance to bedrock}}{\text{retreat rate}} \quad (\text{eq. 3})$$

The Monte Carlo simulation was performed independently for each of the five zones across Svalbard to account for spatial variability in glacial retreat. For each zone, the combined dataset of all glacier flow unit Monte Carlo simulations was used to generate boxplots for comparative visualization within each zone and across zones. Summary statistics included mean, standard deviation, median (50th percentile), interquartile range (25th and 75th percentiles), and upper and lower confidence intervals.

4. Results

4.1. Retreat rates

The average historical retreat rate across all of Svalbard was 47 m yr⁻¹, differing significantly from the present average rate of 111 m yr⁻¹ (Table 2). Median values also reflect this transition, increasing from 37 m yr⁻¹ historically to 89 m yr⁻¹ in the present, indicating that the overall trend is not only influenced by a few rapidly retreating glaciers but reflects a widespread pattern. A paired t-test reveals that the difference between the historical and present period for 184 tidewater glaciers, that had data in both time periods, was statistically significant ($p < 0.001$) and lower than the chosen significance level, rejecting the null hypothesis. The p-value of $p = 8.00 \times 10^{-23}$ indicates a very strong difference and a clear acceleration in glacier front recession.

Retreat rates between the historical and present period were moderately correlated ($r = 0.60$), suggesting partial agreement in spatial retreat patterns. This means that even if they differ in

magnitude (mean), glaciers with a high retreat rate in the historical period tend to have a high rate in the present period as well.

No glacier was found to have an advancing trend in any of the three periods. While the minimum retreat rates remained low across both periods (2 and 1 m yr⁻¹, respectively), the maximum retreat rate rose significantly from 251 m yr⁻¹ during the historical period to 613 m yr⁻¹ in the present. The number of glacier flow units included was comparable between periods, with 192 and 191 entries for the historical and present datasets, respectively, and 209 for the combined mean (Appendix, Figure S2).

Table 2. Summary of historical (1936-1990), present (2012-2024) and mean (entire observation period) retreat rates for all tidewater glaciers (n=209) on Svalbard.

	Historical retreat rates (m yr ⁻¹)	Present retreat rates (m yr ⁻¹)	Mean retreat rates (m yr ⁻¹)
mean	47	111	76
median	37	89	65
min	2	1	7
max	251	613	453
count	192	191	209

4.1.1. Historical retreat 1936-1990

During the historical period (1936-1990), 192 tidewater glaciers were analyzed, with retreat rates ranging from 2 to 251 across all of Svalbard's tidewater glaciers (Figure 7). Retreat rates varied not only between zones but also within them, with some tidewater glaciers indicating high retreat near more stable ones.

The 3 highest retreat rates occurred in Zone B, with Negribreen (251 m yr⁻¹), Petermannbreen (239 m yr⁻¹) and Ordonnansbreen (219 m yr⁻¹) all having their glacier front in the same bay between Barentsøya and central Spitsbergen. A retreat just below 200 m yr⁻¹ was observed for a few glaciers in Zone D, Polakkbreen and Nathorstbreen, eventually also sharing the same glacier front. Further, tidewater glaciers along the east coast of southern Spitsbergen, the Hornsund area (Zone D), as well as the Kongsfjorden area (Zone A) indicated a more moderate retreat around 100 to 150 m yr⁻¹. Most tidewater glaciers on Edgeøya (Zone E) showed retreat rates between 50 and 100 m yr⁻¹. A comparable rate of retreat is also observed for several glaciers across Spitsbergen (Zones A, B, and D), as well as for a few glaciers terminating in Wahlenbergfjorden on Nordaustlandet (Zone C).

However, the majority of glaciers, approximately 60% (120 glaciers), retreated at relatively low rates, less than 50 m yr⁻¹. Roughly 40% (49 glaciers) of these more slowly retreating glaciers were located in northwestern Spitsbergen (Zone A), followed by Zone B, C and D, with a similar percentage. Minimal retreat of less than 10 m yr⁻¹ was observed for 15% (29 glaciers) of all tidewater glaciers, mostly situated around the northern edge of northwestern Spitsbergen (Zone A) and western Nordaustlandet (Zone C). Overall, glaciers in Zone B experienced the most rapid retreat, while those in Zones A and C showed the slowest average rates.

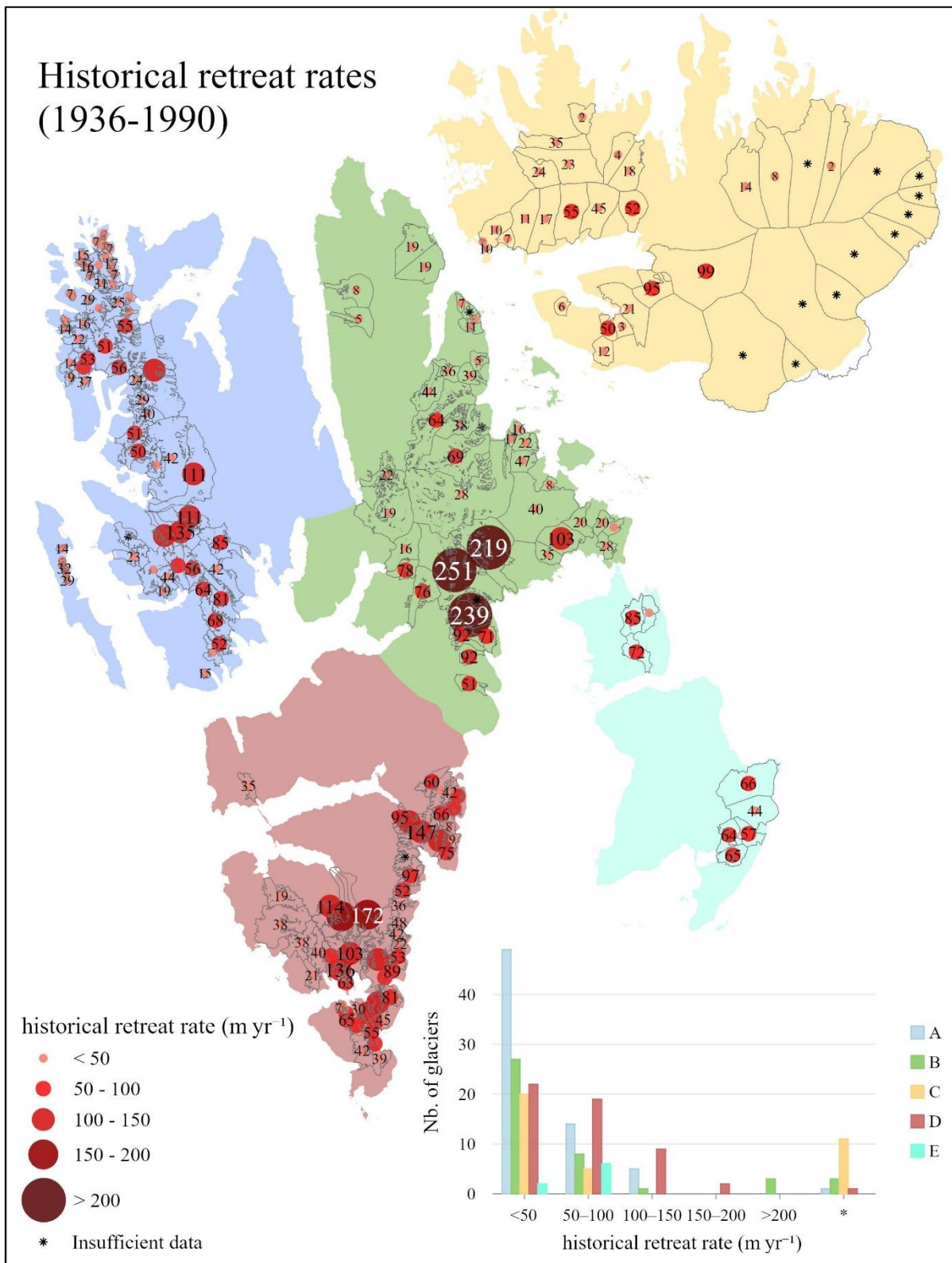


Figure 7. Retreat rates of 198 tidewater glaciers during the historical period (1936–1990), mapped across Svalbard. Higher rates are concentrated in central and southern Spitsbergen, while most glaciers retreated at slower rates, particularly in the northwest and on Nordaustlandet.

4.1.2. Present retreat 2012–2024

Figure 8 shows the retreat rates during the present period (2012–2024), where 191 tidewater glaciers were analysed, with retreat rates ranging from 1 to 613 m yr⁻¹ across Svalbard. As in the historical period, retreat rates varied both between and within zones, with some rapidly retreating glaciers located near more stable ones.

The highest retreat rates were recorded in Zone D, with Ordonnansbreen (613 m yr⁻¹) and Zawadzkiibreen (577 m yr⁻¹) showing exceptional retreat. Located in the central and southernmost part of Spitsbergen, both glaciers share their glacier front with another tidewater glacier, Negribreen and Nathorstbreen, respectively. These also show high retreats, but only about 25 to 50% as much (256 and 148 m yr⁻¹).

A total of 23 tidewater glaciers (12%) had retreat rates of between 200 and 400 m yr⁻¹, with most being situated in southern and along the northwestern coast of Spitsbergen. The highest retreat in Zone A occurred at Kongsvegen and Kronebreen (337 and 279 m yr⁻¹), while Zone C also featured high retreat; Storisstraumen on Austfonna reached the overall fourth highest rate with 503 m yr⁻¹. Additionally, one of the glacier fronts of Stonebreen on Edgeøya retreated 306 m yr⁻¹.

Retreat rates between 150 and 200 m yr⁻¹ were observed in 24 glaciers spread out over all of the archipelago. The majority having moderate retreat, between 100 and 150 m yr⁻¹, was observed in southern Spitsbergen (Zone D), with ca. 40% located in parts of Nordaustlandet (Zone C) and the fjords of northwestern Spitsbergen (Zone A). Glaciers on Edgeøya (Zone E) retreated mostly between 150 and 200 m yr⁻¹. However, about 55% (109 glaciers) had lower retreat rates below 100 m yr⁻¹, primarily located in Zone A, followed by Zones B, C and D. Minimal retreat, under 10 m yr⁻¹, was recorded for only one glacier, Portierbreen in northern Spitsbergen (Zone A).

Compared to the historical period, retreat rates have increased significantly, indicating a clear spatial shift in glacier dynamics under current climate conditions (Figure 9). Table 3 shows that on average, glaciers are now retreating at over three times the historical rate (mean factor: 3.3), with variation across zones. The most significant acceleration occurred in Zone C, where glaciers are now retreating about six times faster than during the historical period. Zone B also shows strong increases, with a mean change factor of 3.2. In contrast, Zones A, D and E experienced slightly more moderate changes, with average factors closer to 2.5–2.8. The three highest increases in retreat rate were recorded in Zone C: Rijpbreen (25.6 times the historical rate) (4 m yr⁻¹ historically, vs. 101 m yr⁻¹), Nilsenbreen (18.6) and Sabinebreen (18.5), all located along the northern coast of Nordaustlandet. Whilst most glaciers retreat at accelerated rates, 22 glaciers indicate a slow-down of retreat. Figure 9 shows that a few of those are situated around Hinlopenstretet between eastern Spitsbergen and western Nordaustlandet, as well as southern Spitsbergen. No significant relative change was observed for 8 glaciers, including Negribreen and Nordenskiöldbreen in central Spitsbergen; Indrebreen and Austjokulen in southern Spitsbergen; Sefströmbreen, Portierbreen and Esmarkbreen in northwestern Spitsbergen, and Etonbreen in central Nordaustlandet. These spatial variations suggest that all regions have become more impacted by recent climate forcing, particularly northeastern and north- and southwestern Svalbard.

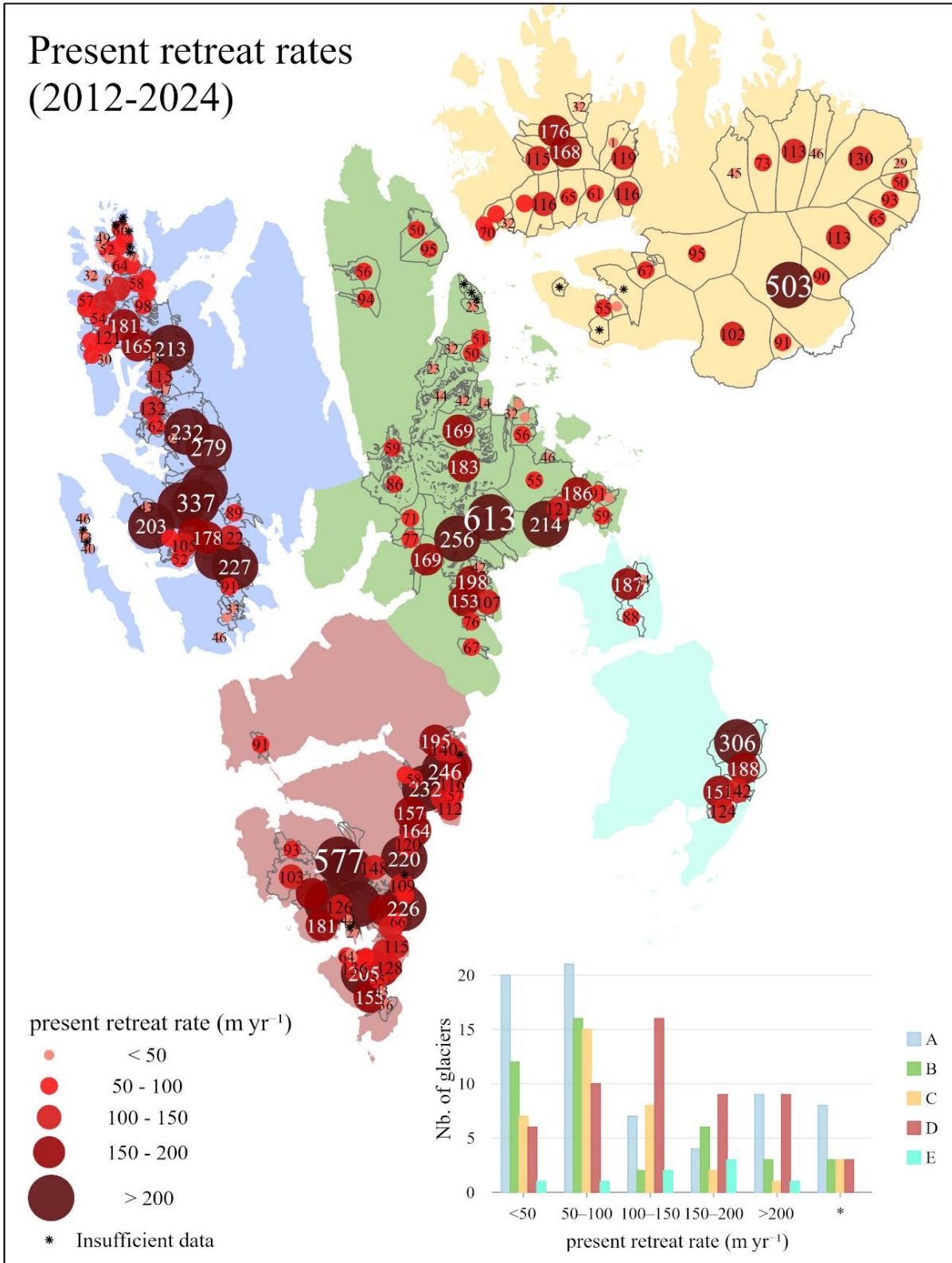


Figure 8. Retreat rates of 198 tidewater glaciers during the present period (2012–2024), mapped across Svalbard, colour-coded by the different zones.

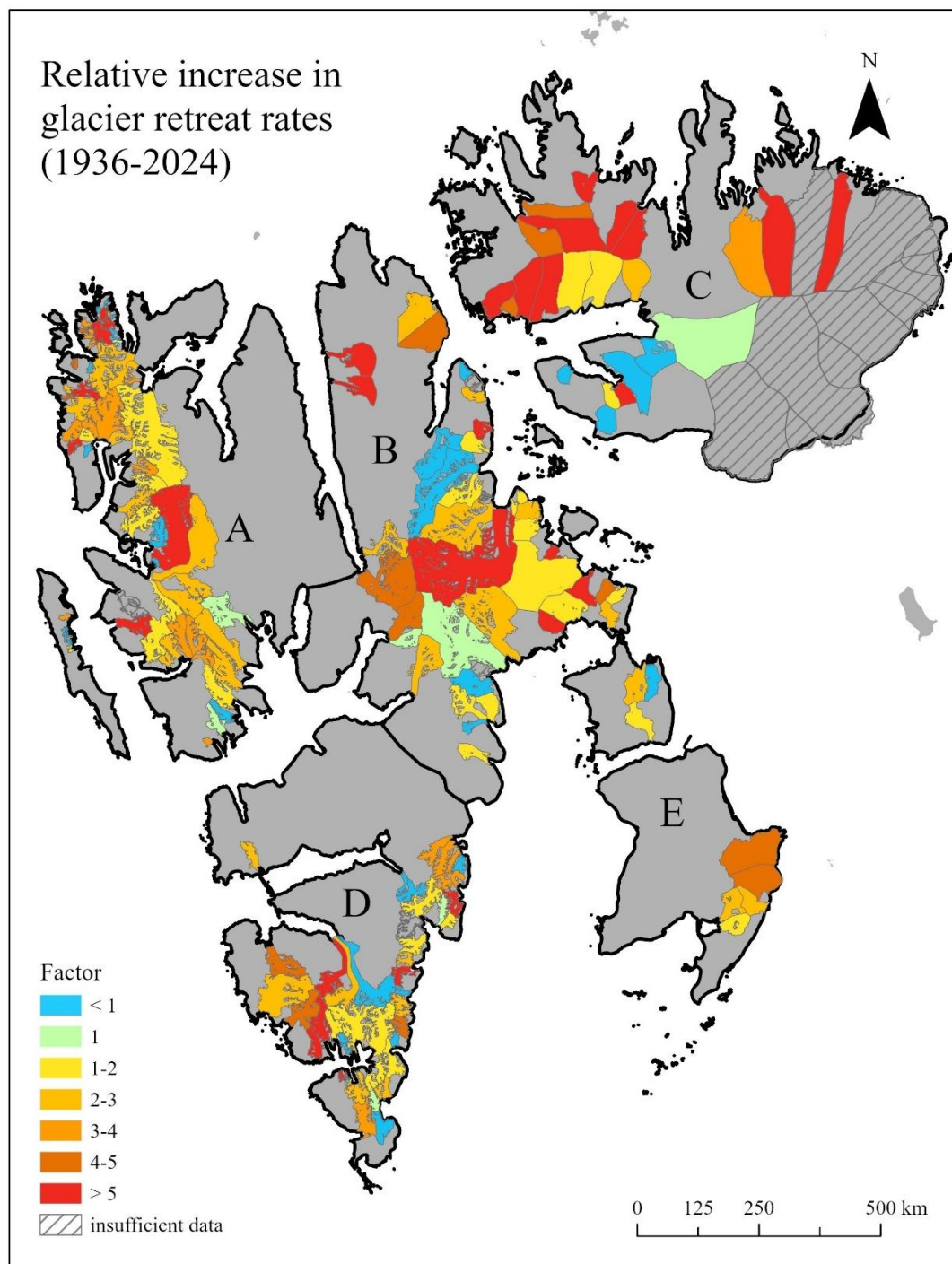


Figure 9. Increase in glacier retreat rates from the historical period (1936–1990) to the present (2012–2024), shown as a factor of change. Values represent the ratio of present to historical retreat rates across Svalbard and its regions. Glaciers with insufficient data for the historical period are shown with dashed lines.

Table 3. Relative increase from historical to present retreat rates (1936–2024), overall and for the different zones on Svalbard. A value <1 indicates a slow-down, whereas >1 shows acceleration of retreat rates.

	Overall	Zone A	Zone B	Zone C	Zone D	Zone E
mean	3.3	2.7	3.2	6.6	2.8	2.5
median	2.4	2.5	2	5	2.1	2.3
min	0	0	0	0	0	0.9
max	25.6	9.5	17.5	25.6	14.1	4.6
count	209	69	42	30	54	8

4.2. Future retreat

4.2.1. Glacier Retreat Projections

Projections of future tidewater glacier retreat based on present-day rates (2012-2024) show a progressive decline in the number of tidewater glaciers across Svalbard. The graph in Figure 10 quantifies the decrease in the number of tidewater glaciers from 2025 to 2200 under four retreat scenarios: historical, present, mean, and double present rates (Figure 10). In the historical scenario, around 40% of tidewater glaciers remain by 2100, while in the present scenario, this number drops to approximately 25%. Under the mean rate scenario, the decline is similar to the present rate scenario. The worst-case scenario, doubling the present retreat rate, shows a rapid decline, with only about 10% of glaciers remaining as tidewater by 2100, and nearly complete transition to land-terminating glaciers, with only about 5% left, by 2200.

The maps in Figure 11 indicate a clear pattern of tidewater glacier area change, particularly in northwest Spitsbergen, where it is predicted that most of these glaciers will be land-terminating by 2050. By the year 2100, extensive areas of southern and central Spitsbergen also reflect great change, indicating widespread loss of marine-terminating fronts on Svalbard. While projections in these maps are not zonally focused, there do appear to be some regional differences. Especially in Nordaustlandet, glaciers situated within the ice caps Austfonna and Vestfonna retain more tidewater fronts further into the century, compared to other parts of Svalbard. Otherwise, large glaciers such as Hornbreen and Hambergbreen in Sørkapp Land, as well as Stonebreen on Edgeøya and Hochstetterbreen and Negribreen in central Spitsbergen are estimated to be still marine-terminating by the end of the century.

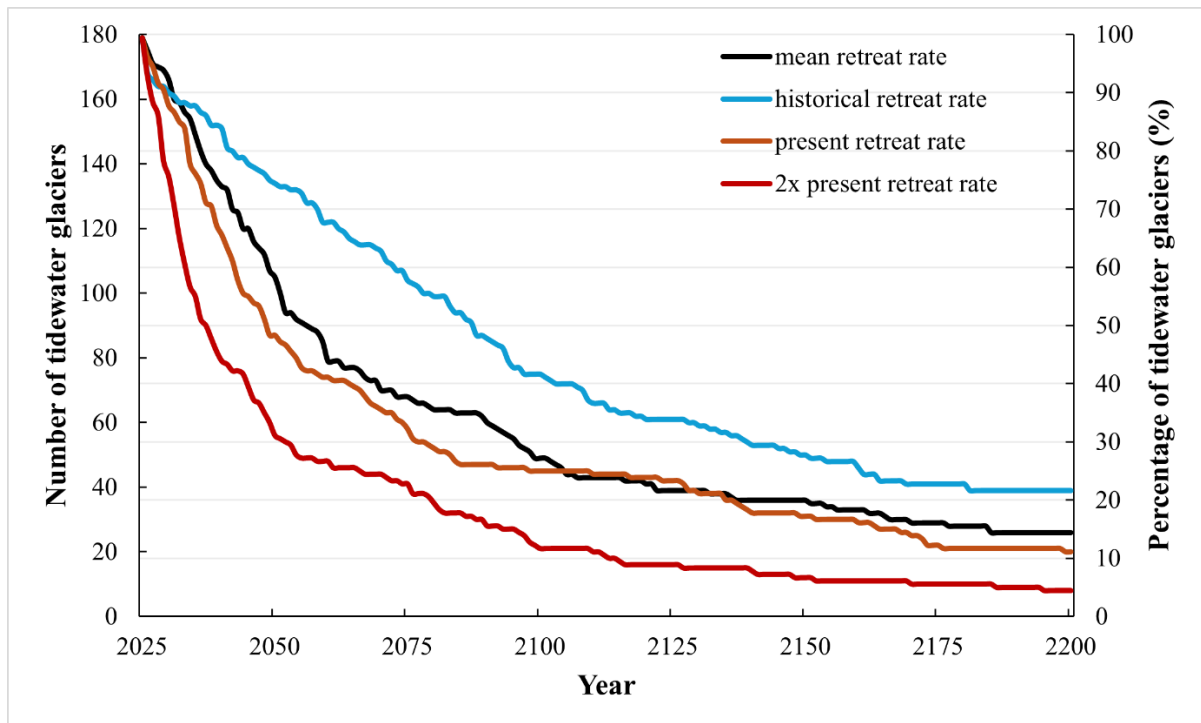


Figure 10. Projected number of tidewater glaciers under historical (1936-1990), present (2012-2024), mean, and double present retreat rates. Faster retreat scenarios show an earlier and sharper decline.

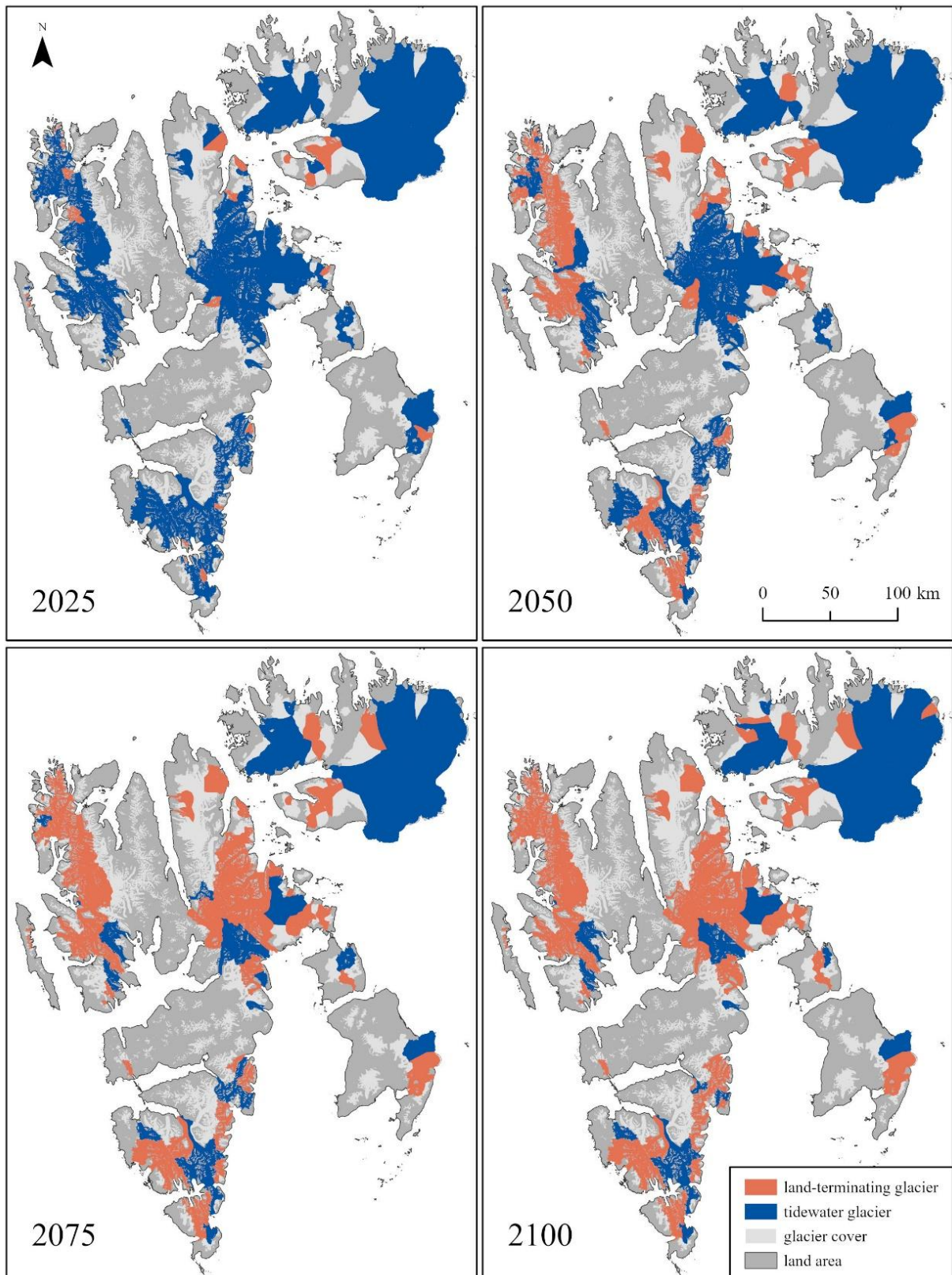


Figure 11. Projected distribution of tidewater glacier area on Svalbard for the years 2025, 2050, 2075, and 2100, based on present-day retreat rates. Orange indicates areas where glaciers are projected to terminate on land, highlighting a shift from tidewater to land-terminating glaciers over time.

4.2.2. Years until land termination based on historical and present retreat rates

Estimates of the number of years until land-termination (YULT) vary within and between zones, Figures 12 and 13 provide a general overview of the spatial distribution of glaciers projected to terminate based on calculations using historical and present retreat rates for each tidewater glacier across the archipelago. Overall, the projections show a significant acceleration in retreat under present rates compared to historical ones. While some glaciers are projected to remain tidewater for more than a century, many are expected to become land-terminating within the next few decades.

Short-term projections (<25 years, i.e. before 2050) show a marked difference between the two scenarios. Under present retreat rates, approximately 56% of glaciers (118 glaciers) are projected to reach land-termination by 2050, with about 25% (58 glaciers) transitioning within the next 10 years (before 2035). These glaciers are typically smaller in size and volume, and are primarily located along the northwestern coast of Spitsbergen (Zone A). In contrast, under historical retreat rates, fewer than 35% (68 glaciers) are expected to become land-terminating by 2050. The percentage of glaciers transitioning within 10 years drops to 20%, highlighting the slower change.

Medium-term projections (25-75 years, i.e. 2050–2100) show a continued shift toward land-termination, especially in Zones A, B, and D. Larger glaciers such as Lilliehöökreen, Kronebreen, Hinlopenbreen, Mittag-Lefflerbreen, Vestre Torellbreen, and Nordsysselbreen are projected to transition in this period. At historical rates, 30% (62 glaciers) will terminate on land by 2100, compared to only 22% (47 glaciers) under present rates, as many glaciers reach land-termination earlier.

Long-term projections (>75 years, i.e. after 2100) are dominated by large outlet glaciers in Zone C, particularly on Austfonna and Vestfonna, which show similar behaviour under both scenarios (26 vs. 23 glaciers >75 years). However, at historical rates, more glaciers, especially on Sørkapp Land and Nordaustlandet, are projected to remain tidewater for longer. Across Svalbard, the number of glaciers in the >75-year range declines from 49 (historical) to 22 (present), with the most notable change in southern Spitsbergen (Zone D), where glacier numbers halve from 22 to 12.

Variability within and in between zones is high. Under present rates, Nordaustlandet glaciers remain tidewater the longest, with a median YULT of 115 years, while other zones have medians ranging from 12 to 29 years, with Zone A showing the lowest values. This trend is also observed under historical rates, with glaciers on Nordaustlandet showing the highest median YULT (547 years), followed by Zones B, D, and E with median values between 50 and 60 years. This represents a 2.5- to 5-fold increase in time to land-termination compared to present-day projections.

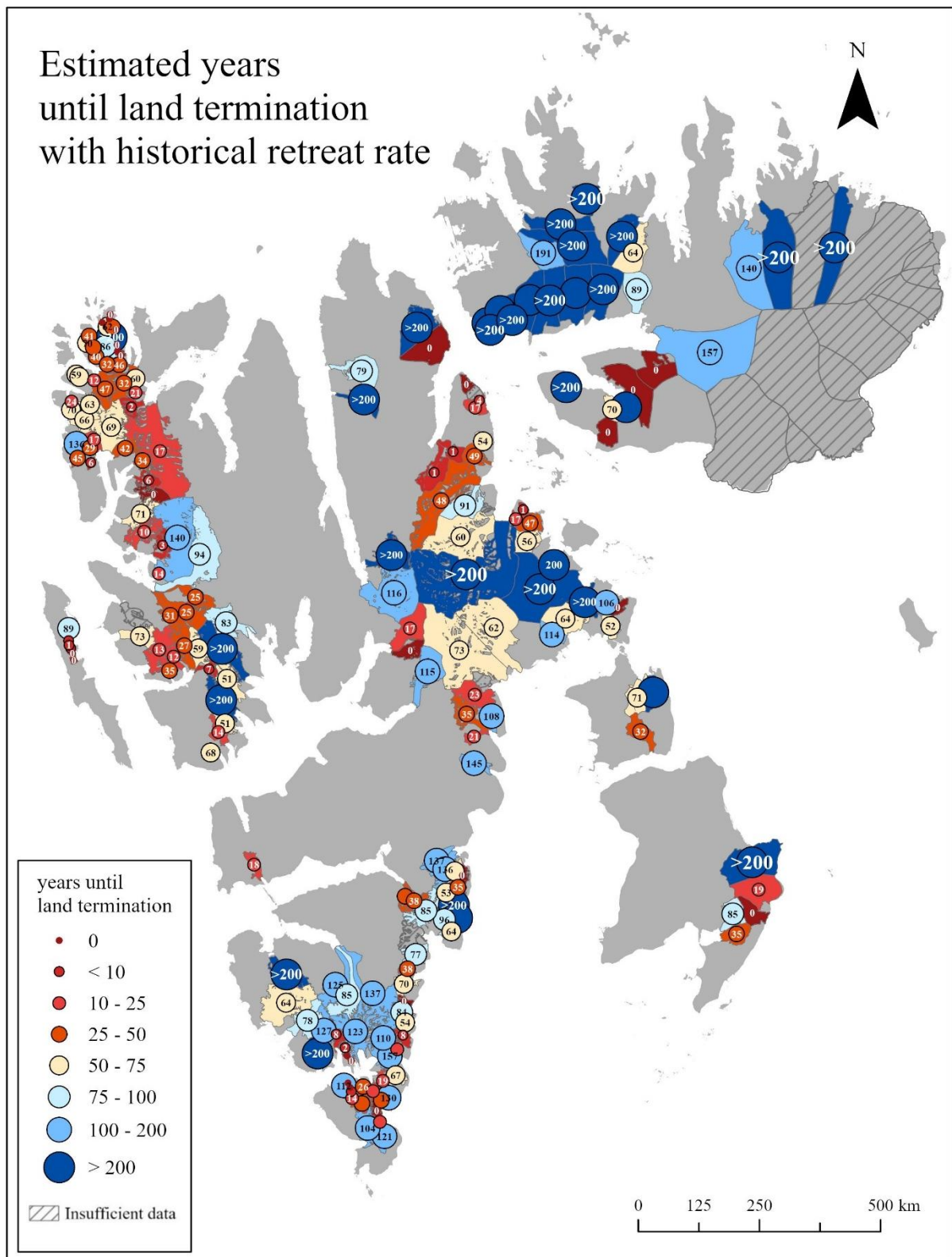


Figure 12. Estimated years until land termination with the applied historical retreat rate. Redder colours indicate earlier termination, whereas bluer colours show longer marine termination. Glaciers with insufficient data for the historical period are shown with dashed lines.

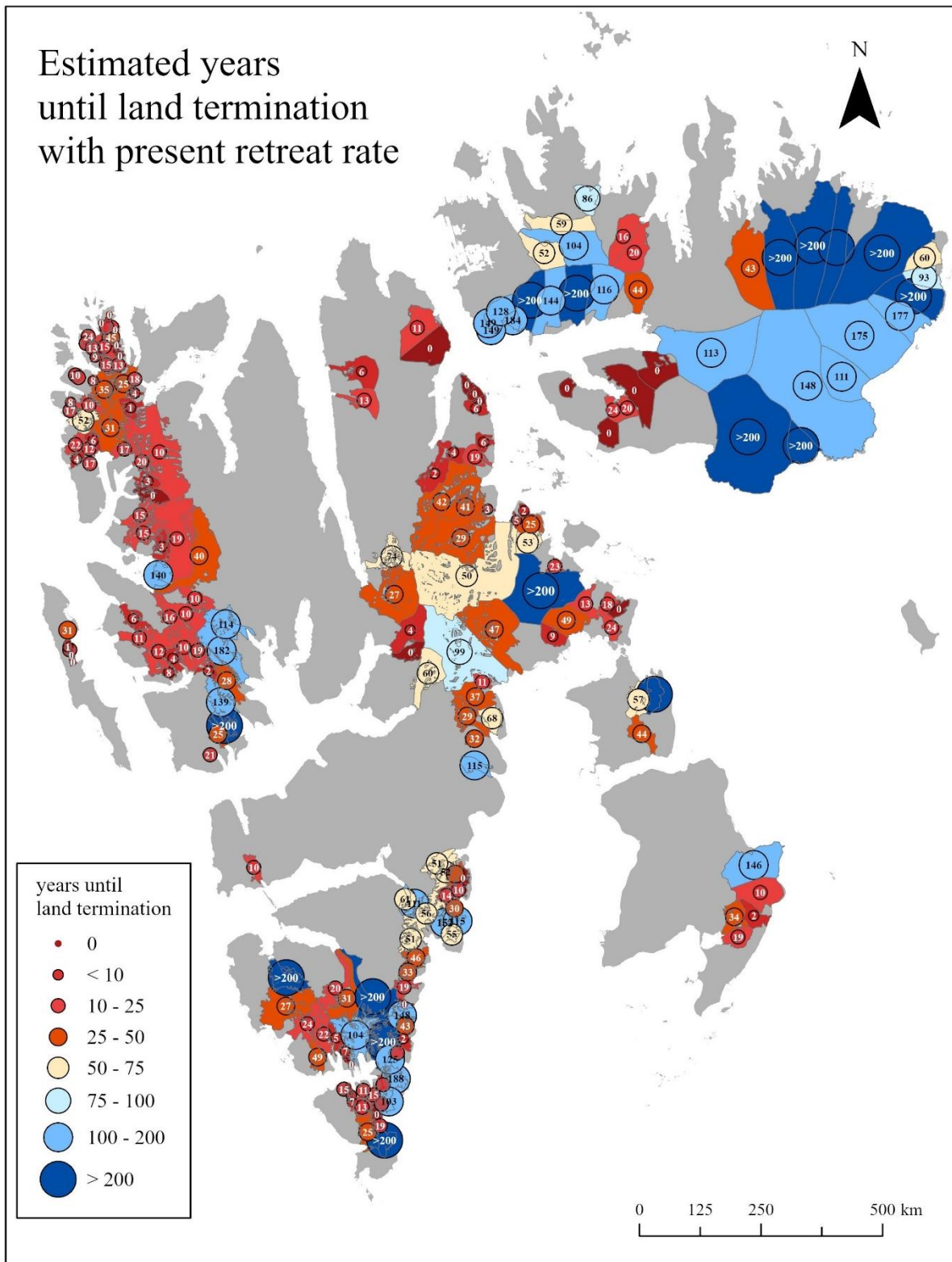


Figure 13. Estimated years until land termination with the applied present retreat rate. Redder colours indicate earlier termination, whereas bluer colours show longer marine termination.

4.2.3. Monte Carlo simulations

Under present and double present retreat rate scenarios, projected YULT show substantial spatial variability across all of Svalbard (Tables 4 and 5; Appendix, Figure S3). Generally, YULT decreases, and uncertainty narrows with accelerated retreat rates. Zone A (northwestern Spitsbergen) has the shortest projected timelines, with median YULT values as low as 2 years under the double present scenario and a small interquartile range of 0-6 years. Zones B and D also show relatively soon land termination, with YULT medians ranging in between 4 to 7 years. Confidence intervals (CI) are moderately narrow in these two zones, indicating more predictable transitions.

In contrast, Zone C (Nordaustlandet) stands out for having the longest projected YULT values, even under twice the present retreat rate. Median YULT remains around 24 years under the double present rate, but the interquartile range (IQR) and 95% CI remain wide, suggesting high internal variability among glacier flow units. Zone E also shows a broad range of outcomes under both present and double present conditions, with long upper tails and wide CI. This suggests that while many glaciers are expected to become land terminating within the next few decades, particularly in Zones A, B, and D, projections for Zones C and E remain more uncertain, even under high retreat scenarios.

These results are further supported by the full set of Monte Carlo simulation results, including mean and historical retreat rate scenarios, indicating larger IQR and CI, with the historical scenario projecting later land termination across all glacier zones (Appendix, Tables S1 and S2).

Table 4. Monte Carlo simulation results for YULT (years) with simulated present retreat rates (2012-2024) across the five zones of Svalbard.

Zone	Mean	Median	IQR	95% CI
A	42	4	0-12	27-58
B	85	7	0-29	65-105
C	235	47	9-104	195-275
D	123	15	3-35	71-174
E	98	16	1-59	75-120

Table 5. Monte Carlo simulation results for YULT (years) with simulated double present retreat rates across the five zones of Svalbard.

Zone	Mean	Median	IQR	95% CI
A	29	2	0-6	14-44
B	53	4	0-14	36-70
C	124	24	4-52	99-150
D	41	7	2-18	33-49
E	172	7	0-28	0-406

5. Discussion

5.1. Retreat rates

5.1.1. Doubling in retreat rates from historical to present period

The results show that there has been a significant acceleration in tidewater glacier retreat rates during the past 100 years. Present rates (2012-2024) are more than twice the historical rates (1936-1990), and none of the tidewater glaciers showed negative retreat rates (i.e. advance) during the study period, apart from the brief advances that occur during surges. The majority of studied tidewater glaciers show an increase from generally lower and more moderate rates historically, to substantially higher rates in the past few years. However, future trends are not fully predictive, as indicated by the moderate correlation ($r = 0.6$) between past and present rates.

Warming in the Arctic is especially pronounced, due to so-called Arctic Amplification, attributed in part to cloud and sea-ice feedbacks (Fox-Kemper et al., 2021). The estimated change in retreat rates in this study aligns with broader climate change patterns, where climate projections from CMIP6 suggest a temperature increase in the Arctic of 3 to 10 °C above the long-term average by the end of the century, depending on emission scenarios (AMAP, 2021). Only half a degree of global warming (1.5 vs 2 °C) will make an ice-free Arctic during summer 10 times more likely, indicating how sensitive Arctic regions, including Svalbard and its tidewater glaciers, are to climate change (AMAP, 2021). Even though warmer air temperatures lead to more precipitation, peaking in winter season, this may not occur necessarily as snow, but as rain-on-snow events, which would further impact ice melt (AMAP, 2021; Rinke et al., 2017). This is in line with the negative mass balance of glaciers globally, and on Svalbard since the early 2000s (Fox-Kemper et al., 2021; Schuler et al., 2020).

5.1.2. Retreat rates in other studies

In comparison with other studies, Kavan & Strzelecki (2023) and Kohler & Moholdt (2023) estimated a mean retreat rate of about 38 m yr⁻¹ and 50 m yr⁻¹, respectively, somewhat lower than this study's estimate (76 m yr⁻¹). Minimum observed mean retreat was -8 m yr⁻¹ (advance) for Kohler & Moholdt (2023), whereas this study calculated a minimum of 7 m yr⁻¹, showing that no advance was estimated when excluding surge periods. Maximum retreat differed greatly and was about 60% higher in this study, increasing from 280 m yr⁻¹ in Kohler & Moholdt (2023) to up to 453 m yr⁻¹. Differences are attributable to the incorporation of the additional parallel lines into the calculations, capturing more variability of the retreat at the glacier front, as well as to the increased number of historical front positions in the expanded frontline dataset. This is especially the case in comparison with Kavan & Strzelecki (2023), who used only two datasets, 1936 and 2019.

Li et al. (2025) investigated seasonal front rate changes, supporting the results of overall tidewater glacier retreat across Svalbard. For the period of 2014-2023, non-surging glaciers retreated on average 102 m yr⁻¹, and surging glaciers 192 m yr⁻¹. Whilst only looking at a total of 94 tidewater glaciers for these estimates, in contrast to 191 glaciers in this study, a mean retreat of 111 m yr⁻¹ in the present period was similar to Li et al.'s estimate for non-surging glaciers. Spatial variability was also reported, with southern Spitsbergen having the highest

average retreat rate. This is partially in line with this study's results, with half of the fastest retreating glaciers ($>200 \text{ m yr}^{-1}$) being located in southern Spitsbergen and the rest being situated in the Northwest. Kohler et al. (2007) and Moholdt et al. (2010b) also point out that western and southern Svalbard appear to be undergoing the highest mass loss. In addition, the highest retreat at Ordonnansbreen (613 m yr^{-1}) was about 50% more than for Li et al.'s highest estimate at Oslobreen (411 m yr^{-1}).

Błaszczyk et al. (2021) show that the retreat observed at Hansbreen in southern Spitsbergen has been increasing lately. The mean rate between 1991 to 2016 was 38 m yr^{-1} , with the highest annual rates being observed towards the end of the study period in 2013 (290 m yr^{-1}). Compared to this study, where rates for Hansbreen increased from 20 m yr^{-1} historically to 180 m yr^{-1} in the present period, mean rates were lower, which could be due to the inclusion of both summer (mainly retreat) and winter (mainly advance) fluctuations for Błaszczyk et al.'s study. Glaciers on the southern coast of Vestfonna have been retreating continuously, in agreement with Braun et al. (2011).

5.1.3. Higher retreat after surge periods

These results reveal that there is a clear spatial variability in retreat rates: highest retreat was observed especially for glaciers of larger size and volume. These are located in western Spitsbergen around the Kongsfjorden area, in southern Spitsbergen, at the central-eastern coast of Spitsbergen, on Edgeøya and Austfonna. Higher retreat in the present period for some of these glaciers could be due to the aftermath of recent surges. Storisstraumen on Austfonna experienced a massive surge from 2012 to 2020/22 advancing on average a total of 5 km during this period. During a surge, the ice flux rate increases dramatically and the glacier advances further into the sea (Luckman et al., 2015). The surge is over when velocity and the ice flux rate decreases and no more advancing occurs. This leads to the ice loss at the front through calving being extensively larger than the ice flux, with only a limited amount of ice available at the top of the glacier, ultimately resulting in an accelerated retreat. This pattern has been most commonly observed for surge-type glaciers during the study period.

5.1.4. Ocean temperature controls frontal ablation

Another reason for higher retreat rates in certain areas could be due to an increase in sea temperatures and greater influence of warm Atlantic water inflow in the fjords. The Barents Sea, touching upon Svalbard's southern and eastern coast, is considered a warming hotspot (Lind et al., 2018; AMAP, 2021). Enhanced surface melt and thinning contributes greatly to glacial mass loss; however, submarine melting and calving at tidewater glaciers fronts is also a major source of loss (Błaszczyk et al., 2009). Ocean warming is not only occurring in the Barents Sea. Atlantic water, reaching the western and northern coast and fjords of Svalbard is also undergoing rapid warming (Foss et al., 2024). Meredith et al., (2019) suggest that there is a high confidence in the increase of inflowing Atlantic warmer water since the 2000s, strengthened by the observed change in upper mixed layer temperature of $+0.5 \text{ }^{\circ}\text{C}$ per decade since 1982.

The largest relative increase in retreat rates was observed along the northern coast of Nordaustlandet. This could reflect the inflow of warmer Atlantic water from the West Spitsbergen Current into western Svalbard fjords (Vonnahme et al., 2023). On the other hand,

these fronts have been largely stable during the historical period, or have a scarcity of front data, resulting in larger relative acceleration during the well-documented present period. In contrast to glaciers in the northeast, tidewater glaciers in fjords on the western coast of Spitsbergen are expected to experience a greater influence of warm Atlantic water than anywhere else in Svalbard (Cottier et al., 2010). Results show that tidewater glaciers terminating in these areas, such as Hansbreen, Aavatsmarkbreen and Kongsbreen, show a twice to five times higher present retreat rate. Recent studies show that peak retreat rates coincide with months of highest ocean temperatures and changes in front position are highly correlated to subsurface ocean temperature (Foss et al., 2024; Li et al., 2025). Western Spitsbergen's tidewater glaciers are mainly located in two fjords: Kongsfjorden and, more southerly, Hornsund. Yet, retreat rates are higher for glaciers terminating in Kongsfjorden. This could be due to Hornsund also being strongly influenced by the cold Sørkapp Current (Cisek et al., 2017).

5.1.5. Bedrock topography influences decrease in retreat rates

A slow-down of retreat in the present period was observed for some glaciers, such as Glintbreen and Petermannbreen in central Spitsbergen, or Conwaybreen in northeastern Kongsfjorden. This could be due to the glacier being in close proximity to land and shallower water, gradually losing contact with water, leading to a reduced calving rate at the front (Błaszczyk et al., 2013). Kavan et al. (2023) show that despite the increase of air temperatures during the last century, a tidewater glacier's retreat rate can decline when it starts shifting from marine- to land-terminating. Whilst a tidewater glacier front can retreat more or less uniformly in deeper water, once bedrock topography comes into play when the glacier retreats into shallower water, retreat can become spatially variable (Kavan et al., 2023). Conversely, depressions in bedrock topography can accelerate retreat rates (Viel et al., 2002). This variability cannot be depicted that well in the long time frame of the historical period of this study, however, annual frontlines during the present period have shown tidewater glaciers, such as Stubendorffbreen or Nordenskiöldbreen, stabilizing at so-called pinning points and then retreating rapidly after passing those. Shallow sections of a fjord can function as a pinning point, often revealing new land once the glacier retreated beyond these points (Frank et al., 2022; Benn et al., 2007). Similar changes have been observed for Blomstrandbreen, in line with Burton et al. (2016).

5.1.6. Landscape changes due to tidewater glacier retreat

Not only does the retreat of tidewater glaciers uncover thousands of kilometres of new coastline in the northern hemisphere in the form of moraines, eskers and ridges, and creates new islands, it also can lead to the formation of glacial or ice-dammed lakes in depressions in the glacier bed, often situated along the outer edges of the glacier (Nehyba et al., 2017). When an ice dam collapses and the lake drains, new deltas and terraces can be formed, as seen in Adolfbukta, along the northern edge of Nordenskiöldbreen (Nehyba et al., 2017). In some cases, landscape changes encompass the creation of nearly closed-off bays as e.g., for Deltabreen, Stubendorffbreen, Andrebreen and Scheibreen. The new ridges separate the open sea from the fjord almost entirely, reducing the influence of currents and inflow of warmer water on the tidewater glacier's retreat. This causes less melting at the glacier front, showing that future retreat might not occur at the same rate as today (Kohler & Moholdt, 2023). Further, coastal erosion can be observed, especially for deglaciated terrain of sedimentary origin (Luetzenburg

et al., 2023). These areas are more vulnerable to erosion and create shallower and wider glacial valleys (Kavan et al., 2025), which can be seen at Besselsbreen, along the northern coast of Barentsøya. Whilst georeferencing the aerial image from 1990, it was hard to determine fixed ground control points due to the vast change that had occurred between 1990 and 2020.

An exciting case of changing landscape due to deglaciation is the retreat of Hornbreen and Hambergbreen in southern Spitsbergen. Grabiec et al. (2018) assessed subglacial topography to reveal the existence of the soon-to-be Hornsund Strait, which will leave Sørkapp Land as its own island in the near-future. This strait has been ice-free during the early-middle Holocene, prior to the Little Ice Age, clearly linking climate warming to glacial retreat (Osika et al., 2022). The results presented here show that both glaciers are retreating rapidly and will merge into one front within the next decades, if the observed retreat rates are representative for the future here. Despite its fast retreat since 1936, Hornbreen is expected to be marine-terminating for several hundreds of years more, as the subglacial topography indicates the fjord extending far into the area of today's Flatbreen.

5.2. Future retreat

5.2.1. Transition to land termination

Future retreat projections in this study show that the majority of today's marine-terminating glaciers are expected to lose their tidewater status by 2100 at present retreat rates. Estimated years until land termination show that glaciers in Nordaustlandet are expected to remain tidewater the longest, as well as a few glaciers lying within deep valleys elsewhere across the archipelago. Austfonna, one of the large ice caps on Nordaustlandet, has been radar-surveyed extensively between 1983 and 2008 (Moholdt et al., 2010a), providing higher confidence in the bedrock topography and therefore in these estimates.

Smaller and narrower glaciers are expected to transition to land-terminating first, with these glaciers located mainly in the northwest and along the eastern coast of Spitsbergen. These results are supported by the Monte Carlo simulations, showing lowest mean and median values in northwestern Spitsbergen, and relatively narrow uncertainty ranges under both present and double present retreat scenarios. Kavan & Strzelecki (2023) suggest that this could be due to the rapid adjustment of these glaciers, which are smaller in size and volume, to climate change. During the Little Ice Age, they advanced into the sea and with climate warming retreat quickly further inland. The results show the largest overall reduction in number of tidewater glaciers between today and 2050 (56%). From 2050 to 2100 the number decreases moderately to 22% of the total amount of glaciers terminating on land in this period. This trend is caused by the high amount of smaller marine-terminating glaciers transitioning in the near-future and larger glaciers remaining tidewater for a long time. Nordaustlandet, Barentsøya and Edgeøya show broader IQR and CI in the Monte Carlo simulations, and even under the most extreme retreat scenario, YULT values remain high, underlining the certainty of these glaciers remaining tidewater well beyond 2100.

Different retreat projections show scenario sensitivity, as faster retreat scenarios (e.g., doubling the present rates) reduces the amount of tidewater glaciers in 2100 by half. Historical rates show a moderate decrease, reaching the same number of glaciers remaining tidewater in 2100 for

present rates, 100 years later. This displays how sensitive tidewater glaciers are to global warming.

5.2.2. Uncertainty in future land termination

The main uncertainty in future retreat lies within bedrock topography estimations. Both Fürst et al. (2018) and Van Pelt & Frank (2025) quantify error estimates for their bedrock maps, ranging from about 20 m in radar-surveyed areas for Fürst et al. (2018), to a mean average error over the entire area of 77.5 m for Van Pelt & Frank (2025) and even several hundreds of metres for modelled areas in Fürst et al.'s (2018) map, with highest errors in low-lying areas. However, this study's approach using a combination of both bedrock maps and an uncertainty zone, as well as visual validation from the most recent satellite image of 2020, provides a good estimate for projections over entire Svalbard. Furthermore, the future response of each individual tidewater glacier to climate change remains uncertain to some extent, as shown by the Monte Carlo simulations. The linear retreat rate approach in this method makes it harder to capture a tidewater glacier's non-linear response to climate forcing, and its slowing down as it approaches landfall. This can be seen in the cumulative retreat distance plots, and in the comparison between historical and present period. The future rate of acceleration contains a certain degree of uncertainty. Future surges have to be considered as well, though these events remain hard to project (Sevestre, 2015).

5.2.3. Implications of land termination on marine ecosystems

The results of this study show a major future decline in the number of tidewater glaciers, particularly in northwestern and southern Spitsbergen. Meredith et al. (2019) suggest that global warming has affected marine primary production (*high confidence*), impacting Arctic marine ecosystems (*medium confidence*). This shift from tidewater to land-terminating glaciers influences the physical and biogeochemical state of these ecosystems (Kavan et al., 2023). Studies in Kongsfjorden have linked circulation changes (Torsvik et al., 2019), production within the marine food web (Hop et al., 2023) and species and habitat loss (Lydersen et al., 2014) to the retreating tidewater glaciers in the fjord. Fewer tidewater fronts lead to a reduced number of subglacial upwelling zones, which are important feeding areas for higher trophic levels (Lydersen et al., 2014). Today, subglacial outflow accounts for up to 60% of the upwelling at marine-terminating fronts (Fransson et al., 2020). As fronts retreat onto land, less subglacial meltwater enters the fjord at depth, reducing vertical mixing and causing nutrient-rich plumes and thus primary productivity at the fronts to decrease (Losapio et al., 2025; Knies et al., 2025). Van Pelt et al. (2019) support the shift from subglacial to surface runoff, by quantifying the decrease in firn areas, located in the upper part of the glacier. Available pore space for summer meltwater decreases, leading to higher drainage and a doubling in glacier runoff. These ecological shifts are especially concerning given that this study projects widespread land-termination in regions where productivity and species richness are currently high (Lydersen et al., 2014; Garcia-Lopez et al., 2019).

5.3. Future studies

Future studies could compare the two bedrock elevation models from Fürst et al. (2018) and Van Pelt & Frank (2025), by computing two bedrock intersection point layers and calculating remaining distances until land termination. This does not allow more precise estimates for

future land termination but can improve estimates of the uncertainty in comparison to the combined approach used in this study. Incorporating the available radar data into Van Pelt & Frank's model would also provide a better base for this comparison. Another aspect to consider for future analysis is to evaluate the existing results more carefully with available radar data, i.e. treating results of future land termination with higher confidence for areas that have been radar-surveyed, as shown in Kohler & Moholdt (2023).

Furthermore, georeferencing more satellite images and digitizing glacier fronts for the historical period would close temporal gaps in front position data, possibly revealing more insights on length of surge periods and capturing historical spatial variability more accurately. This study uses a large dataset of glacier front positions, AI-generated fronts from Li et al. (2025) to supplement existing data, among other things. During this study's analysis visual comparison under pre-processing of data showed some major differences between AI-generated and human-digitized fronts for the same years, with human-digitized fronts capturing irregularities at glacier fronts more precisely. Deep learning within the field of remote sensing and glaciology is still a novel approach, and further development within this field might provide new opportunities for future front position analysis (Bolibar et al., 2022; Li et al., 2025). Finally, and most importantly, more radar surveys in the future would help to improve the knowledge about the bed topography of Svalbard.

The results of this study present a strong base for future analysis of connections between tidewater glacier retreat and other climate variables. Air and ocean temperatures, precipitation, sea ice concentration and surface runoff could be compared, for example. Foss et al. (2024) and Li et al. (2025) found that all of these variables show positive correlation with retreat rates and frontal ablation, highlighting the relevance of improved future analyses. As tidewater glacier retreat is heavily influenced by ocean temperatures, adding specific climate projections and emission scenarios, such as the commonly used representative concentration pathways (RCPs) in climate modelling, would show the range of possible outcomes for future retreat rates within a changing climate (Moss et al., 2020). Besides physical indicators of glacier retreat, one could analyse the abundance of species, phytoplankton populations and productivity on a larger scale across the whole archipelago, coupling tidewater glacier retreat to observed changes and to help predict spatial patterns in the future.

6. Summary/ Conclusion

This study has investigated the retreat of Svalbard's tidewater glaciers with the aim of quantifying changes in retreat rates over time, assessing spatial variability, estimating when glaciers will become land-terminating and evaluating its uncertainty. The results show a clear increase in retreat from the historical (1936-1990) to the present period (2012-2024), with present rates being more than double the historical average. However, tidewater glacier retreat does not occur uniformly across the archipelago. Southern and northwestern Spitsbergen show most rapid retreat, which aligns with other observed changes, such as increasing inflow of warm Atlantic water from the West Spitsbergen Current and strong glacial thinning in these areas. This highlights spatial variability and the influence of local topographic and glaciological conditions on glacier retreat.

The analysis focused on when glaciers are likely to become land-terminating, using calculated retreat rates for both time periods and two bedrock datasets (Fürst et al., 2018; Van Pelt & Frank, 2025). To account for uncertainty in retreat rate estimates, a Monte Carlo approach was applied. This enabled the estimation of both central tendencies and confidence intervals for each glacier flow unit. Despite variability in timing between historical, present and future scenarios and between glaciers, the overall pattern shows that most tidewater glaciers are projected to become land-terminating by 2100. Only about 30% of today's tidewater glaciers are expected to be marine-terminating at that point, and with most likely further warming, an accelerated retreat rate of double the present rate shows a reduction to only 10% by the end of the century. Considerable uncertainty remains for the year individual tidewater glaciers will become land terminating due to bedrock topography uncertainty, potential future surges and the response of tidewater glaciers to climate change. However, the results are consistent with ongoing trends of mass loss and frontal retreat in Svalbard.

The retreat of tidewater glaciers has important implications for glacial environments and marine ecosystems. This study highlights how the transition from tidewater to land-terminating glaciers is already underway across large parts of Svalbard and to which extent it will intensify in the future. The method accounts for differences in retreat rates across glaciers, surge behaviour, and bed topography, and includes an uncertainty estimate using Monte Carlo simulations, which allows for a more robust assessment of when and where glaciers will become land-terminating. Future studies can build on these results, providing the opportunity for understanding tidewater glacier retreat in a warming Arctic and improving predictions of glacier-driven environmental change.

7. References

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8. Appendix

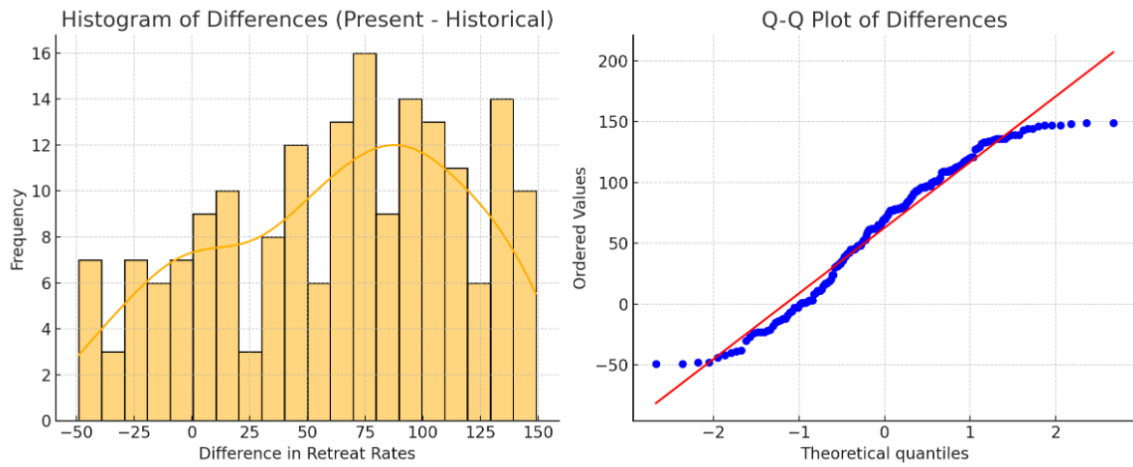


Figure S1. Normality assessment through visual interpretation of the histogram of differences, and the Q-Q plot, for the performed paired t-test between historical present rates. The histogram shows a unimodal and positive, slightly right-skewed distribution, with values in the range of -50 to 150 m yr^{-1} . The peak frequency is around 75-100, suggesting many glaciers have increased their retreat rate by that much in the present period compared to the historical one, only a small number of glaciers show negative values, meaning retreat rates have slowed down for those. Further, the Q-Q plot (to the right) compares this study's data to a theoretical normal distribution. The middle section follows the red line pretty well; however, it deviated greatly for higher and lower quantiles, especially the upper tail bends sharply upwards. This pattern indicates non-normality due to outliers mainly in the upper tail.

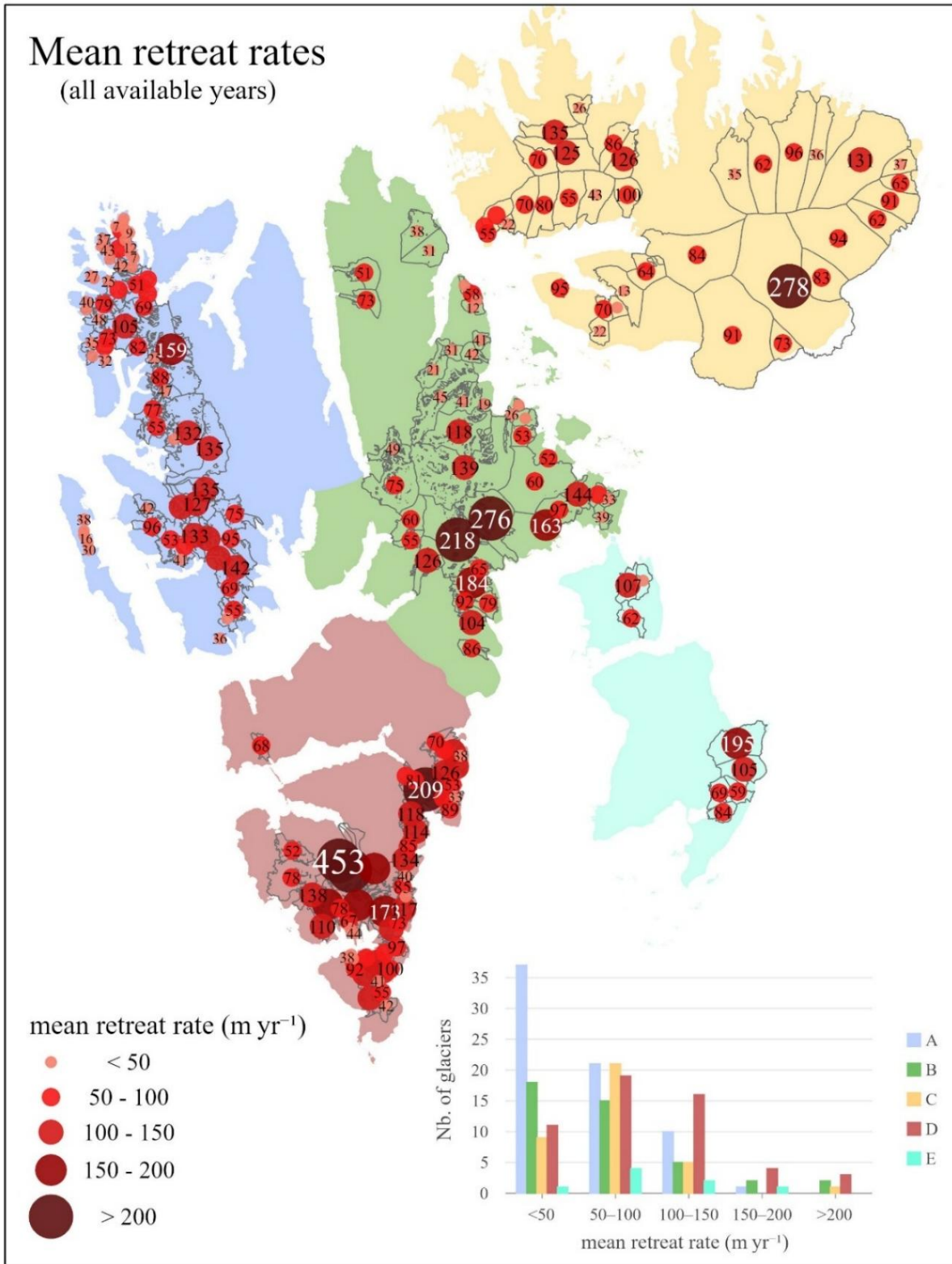


Figure S2. Map of mean retreat rates over the entire study period with all available front data for each flow unit.

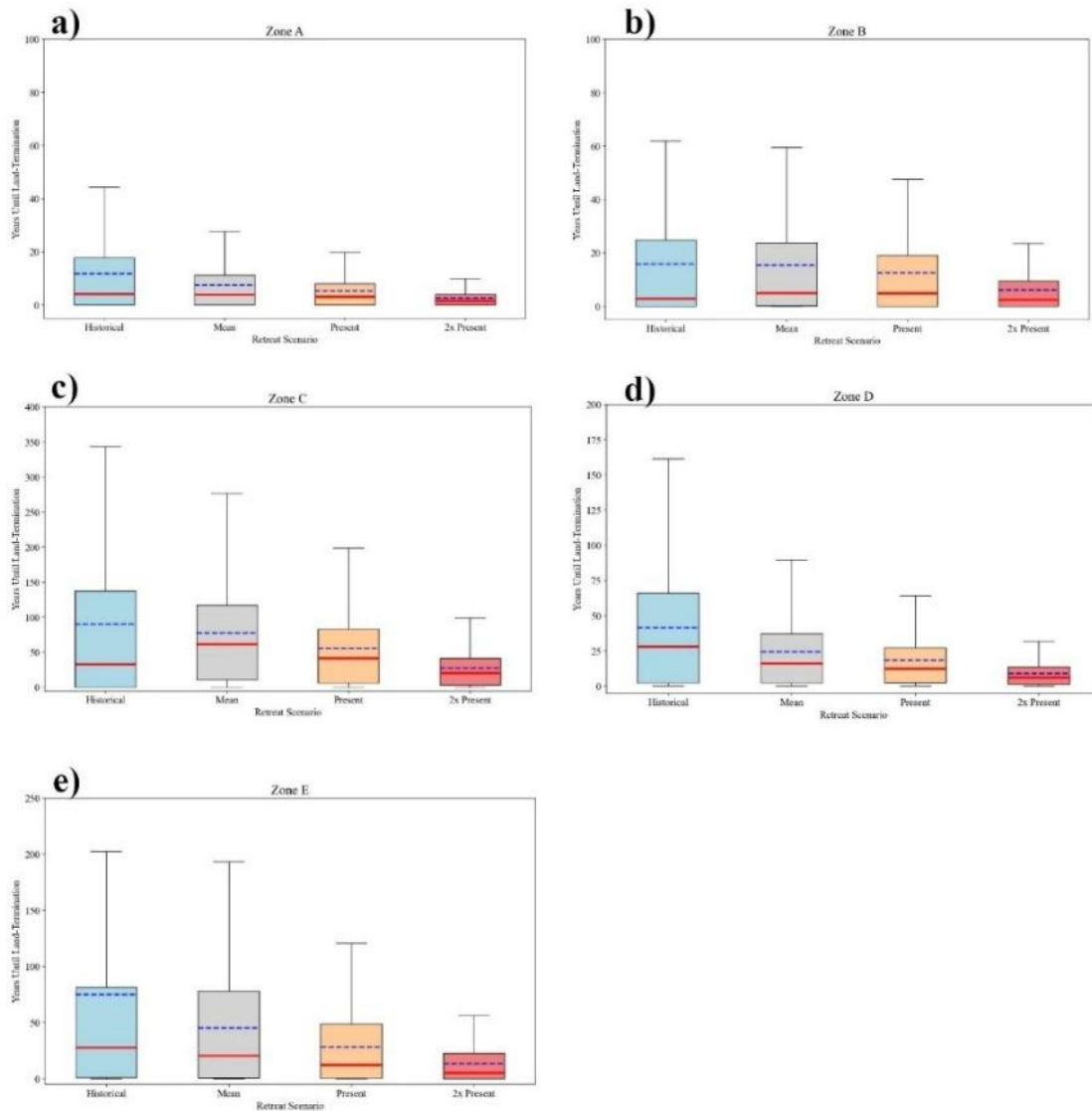


Figure S3. Results of the Monte Carlo are summarized for each of the five zones of Svalbard (a-e)). The boxplots show the distributions of projected years until land-termination (YULT) across four retreat rate scenarios: historical, present, mean, and double present. Each boxplot shows the median (red line), mean (blue dashed line), interquartile range, and 95% confidence intervals to reflect the range and uncertainty in the projections.

Table S1. Monte Carlo simulation results for YULT (years) with simulated mean retreat rates (entire observation period) across the five zones of Svalbard.

Zone	Mean	Median	IQR	95% CI
A	44	5	0-17	32-55
B	97	8	0-35	67-126
C	333	70	15-139	207-460
D	119	19	3-48	95-143
E	156	25	1-93	74-238

Table S2. Monte Carlo simulation results for YULT (years) with simulated historical retreat rates (1936-1990) across the five zones of Svalbard.

Zone	Mean	Median	IQR	95% CI
A	75	7	0-28	48-101
B	211	7	0-40	122-300
C	849	49	0-213	547-1152
D	179	33	4-80	146-211
E	644	31	1-177	0-1487