Environmental changes in Svalbard since the termination of the Little Ice Age: Towards a warmer and less icy future

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Abstract

Svalbard has experienced significant warming since the end of the Little Ice Age (LIA; around 1900 CE). Since the LIA, air temperatures have risen almost continuously, with even more accelerated warming trend recorded in recent decades. These climatic shifts have had serious impacts, particularly on the cryosphere but also on landscape dynamics, through an accelerated hydrological cycle and the intensification of various geomorphic processes. Surprisingly, Svalbard experienced a warmer climate for much of the Holocene compared to today, with only a few colder periods, the most pronounced being the LIA. In other words, Svalbard, as it was known to early polar explorers at the end of the 19th century, was at its maximum Holocene glacier extent. Nowadays, the environment is returning to its usual mode of operation, with a less glaciated landscape. However, the current rate of change is unprecedented. Here, we document the most striking landscape changes with a series of repeated photographs, comparing the landscape at the glacier's maximum extent (in 1908) with photographs taken at the same locations recently. We demonstrate the rapid evolution of glacier-connected geosystems and intense paraglaciation, where glacier-dominated processes are being replaced by fluvial, slope or aeolian forces. In contrast, landscapes that were not directly connected to glaciers appeared relatively stable and resilient to climatic forcings. As the landscape seeks to reach a new equilibrium after glacier retreat, this also triggers various natural hazards, such as slope failures, avalanches and floods, that may pose risks to human society and infrastructure. Together with the massive thawing of permafrost, these changes could endanger economic activities, tourism and even the traditional way of life of Indigenous communities in the Arctic.

Key words: Arctic, glacier retreat, deglaciated landscape dynamics, coastal processes, historic photographs

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Introduction

Svalbard experienced a significant cooling period during the late Holocene (approximately the last 3,000 years), known as the Neoglacial period (Farnsworth et al. 2017). The Little Ice Age (LIA), its latest and coldest phase, ended around 1900 CE (Szczucinski et al. 2009). Since then, the climate has warmed significantly, with serious consequences for the local environment. The end of the LIA marked the maximum extent of glaciers during the Holocene. From that point onwards, local glaciers began to retreat (Martín-Moreno et al. 2017).

The Arctic has been warming four times faster than the global average in recent decades, a phenomenon often referred to as Arctic amplification (Rantanen et al. 2022). Moreover, the Barents Sea region, including Svalbard, is warming twice as fast as the Arctic average (Isaksen et al. 2016, Nordli et al. 2020). This warming trend has a pronounced seasonal component, with greater warming during spring and summer, while significant autumn and winter warming has emerged only in the past few decades (Nordli et al. 2014). The accelerated warming in recent decades is attributed to multiple feedback mechanisms, such as sea ice reduction and altered regional oceanic and atmospheric circulation patterns (Isaksen et al. 2016).

The precipitation pattern across the archipelago is strongly influenced by the persistent ocean currents and variable sea ice extent, leading to wet western coastal areas, colder northern and eastern regions, and a drier continental interior (Przybylak et al. 2014). There has been an increasing trend in precipitation rates, with an estimated rise of about 8% per decade due to the intensified inflow of warm Atlantic water over recent decades (Forland et al. 2020). This trend is expected to continue, particularly affecting the windward western coastal areas (Wickström et al. 2020).

The landscape, previously dominated by glacial processes, is rapidly transforming into a paraglacial environment (Ballantyne 2002). Paraglaciation encompasses a suite of processes that reshape the landscape into a new equilibrium state, erasing the traces of glaciation. This transformation involves sediment cascades, wherein the former glacial landforms and sediments are eroded, transported and re-deposited by fluvial, slope, aeolian and coastal processes (Mercier et al. 2009, Ewertowski et al. 2016, Strzelecki et al. 2017). The glacier forefield, in particular, is among the most dynamically changing landscapes (Blaszkiewicz et al. 2023).

The present paraglacial landscape results from the LIA glaciers' advance and subsequent rapid retreat. Studying these dynamic processes in Svalbard is significantly advantageous due to the availability of relatively abundant historical instrumental records documenting landscape development since the LIA. This period coincides with the rise of the scientific and economic exploration of the archipelago (Liljequist 1993). Multiple reconstructions of glacier retreat are available, ranging from Svalbard-wide applications (*e.g.* Geyman et al. 2022, Kavan and Strzelecki 2023) to regional studies (*e.g.* Rachlewicz et al. 2007, Malecki 2016, Kavan and Haagmans 2021, Kavan et al. 2022a) and single glacier studies (*e.g.* Kavan 2020a, Holmlund 2021, Kavan et al. 2024a).

Unconsolidated glacial sediments left by retreating glaciers are highly susceptible to transformation by external forces, including fluvial and aeolian erosion and massive slope movements. These processes are exacerbated by permafrost degradation (Isaksen et al. 2022), leading to the development of thermo-erosion gullies and thaw slumps (Nicu et al. 2023). Land exposed after glacier retreat is rapidly colonised by pioneering organisms, such as microbes and plants, initiating soil formation (Bradley et al. 2014). The rate of initial soil development depends on time, environmental factors (geographic and climatic conditions) and substrate properties (*e.g.* soil texture, porosity, nutrient status, pH and mineralogical composition; Lazzaro et al. 2010). Glacier forefields exhibit high heterogeneity in geology, geomorphology, substrate availability and moisture, which influences nutrient levels. Greater nutrient availability can significantly accelerate early soil succession after deglaciation (Luláková et al. 2023).

Here, we present landscape changes in central Svalbard as documented through repeated photography of sites around Billefjorden. The original photographs, taken by Oscar Haldin during the Swedish expedition led by De Geer in 1908, were repeated in 2018. These images illustrate the evolution of the environment, highlighting the significant impact of past environmental processes on the current landscape. We discuss the implications of these changes for future development in a continuously warming Arctic and the potential consequences for human presence in the region.

Study site

Central Svalbard was almost entirely covered by the Barents Sea Ice Sheet during the Last Glacial Maximum (Hughes et al. 2021). The major ice stream in Isfjorden and its tributaries rapidly disintegrated at the Pleistocene–Holocene boundary, approximately 12,500–11,000 years BP (Mangerud et al. 1998). This rapid ice mass disintegration was followed by a significant sea-level rise (Forwick and Vorren 2009). The coastline in Billefjorden was about 60 m above the present sea level, as evidenced by whale bone remnants found at the highest (and thus oldest) marine terraces (Lulák et al., *this issue*).

With the cessation of ice sheet loading, the postglacial uplift of Svalbard began. The most rapid uplift occurred at the start of the Holocene, gradually slowing over time (Long et al. 2012). Ice-rafted debris found at several locations in central Svalbard indicates repeated episodes of marine-terminating glacier retreat and advance during the Holocene (Forwick and Vorren 2009).

The deglaciated landscape was initially dominated by permafrost active layer processes, complemented by colluvial, alluvial and fluvial processes, which were particularly concentrated along fjord and valley sides (Tomczyk 2021). Post-LIA deglaciation created polythermal glacier landsystems in the study area, characterised by features such as roches moutonnées, moraine mound complexes, fluted moraines, eskers, supraglacial debris stripes, prominent ridges of LIA maximum latero-frontal ice-cored moraines, glaciolacustrine and glacimarine deltas, and extensive glaciofluvial outwash fans and valley trains (*e.g.* Evans et al. 2012, Ewertowski 2014, Nehyba et al. 2017, Allaart et al. 2018). The retreating glaciers were quickly followed by plant colonisation on newly exposed moraine and till plains (Prach and Rachlewicz 2012, Těšitel et al. 2014).

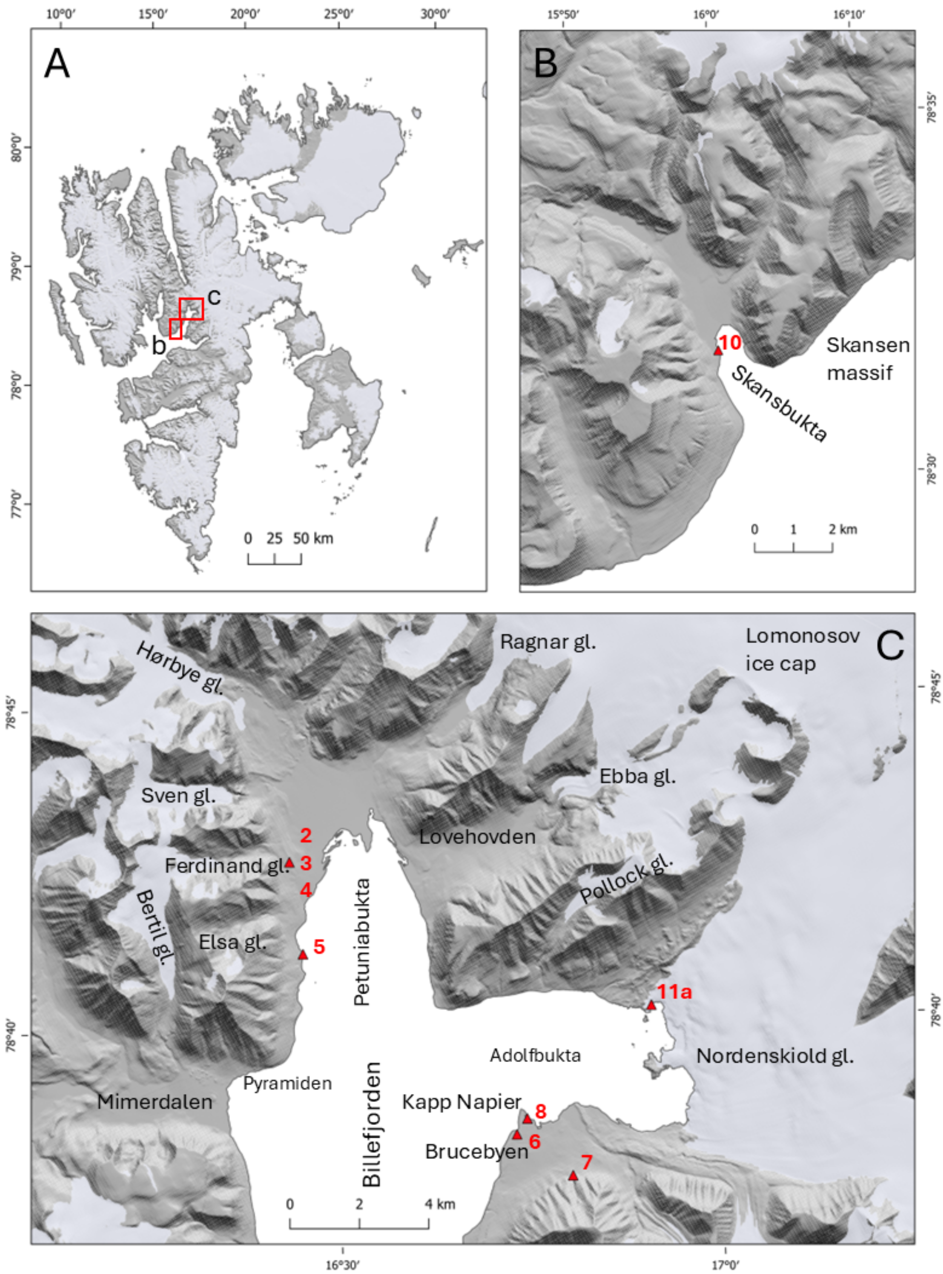

Fig. 1. (**A**) Svalbard with the study location indicated by the red rectangles; (**B**) Skansbukta and its surroundings; (**C**) northern part of Billefjorden; terrain model provided by ArcticDEM (Porter et al. 2023) glacier cover indicated by light blue shades; red triangles correspond to photo locations marked with the red numbers as figures in the following text.

Methods

We used historical photographs from the 1908 de Geer expedition (de Geer 1910) taken by Oscar Haldin to evaluate landscape changes. The photographs are available from the Alvin database of the Centre for History of Science, Royal Academy of Sciences, Sweden[1]. Most of the photographs were taken during the expedition in July 1908, except for the photograph of the Skansen massif (Fig. 10), which was captured during A. E. Nordenskiöld's expedition in 1872.

The locations of the original photographs were identified based on our detailed knowledge of the terrain, and we repeated the photographs during fieldwork in July 2018. Distinct terrain features, such as boulders and rock outcrops, were used to accurately determine the camera positions. Although the parameters of the cameras used in the original and repeated photographs (*e.g.* focal length) differ, it was relatively straightforward to compare the images and interpret the observable changes. We performed only a visual comparison as more sophisticated methods (*e.g.* photogrammetry) would require more photographic material or in detail analysis such as the examples in Kavan (2020a,b). Here, we wanted to simply emphasize the importance of historic photographs to reveal the key environmental processes shaping the post LIA landscape.

The coordinates of the locations where the photographs were taken are summarised in Table 1.

Figure	Latitude	Longitude	Alvin ID (link)	Alvin ID (general)	Source
2	78.70993°N	16.44279°E	15487	KVA PX 10-305	de Geer expedition (1908)
3	78.70993°N	16.44279°E	15489	KVA PX 10-304	de Geer expedition (1908)
4	78.70993°N	16.44279°E	15468	KVA PX 10-282	de Geer expedition (1908)
5	78.68599°N	16.45800°E	15529	KVA PX 10-355	de Geer expedition (1908)
6	78.63825°N	16.73234°E	15209	KVA PX 10-039	de Geer expedition (1908)
7	78.62737°N	16.80435°E	15491	KVA PX 10-309	de Geer expedition (1908)
8	78.64228°N	16.74583°E	15182	KVA PX 10-007	de Geer expedition (1908)
10	78.52830°N	16.00778°E	13771	KVA PX 01-054	A. E. Nordenskiöld expedition (1872)

Table 1. Detailed information on the locations and sources of the photographs.

Results and Discussion

Most of the changes observed when comparing the historical 1908 photographs with their recent counterparts are associated with glacier retreat and the areas directly surrounding the glaciers. Minor changes are also visible in the most active zones of steep slopes, where new landslides, mudflows and erosional thaw slumps are evident. These changes are complemented by variations in vegetation cover. In contrast, relatively flat surfaces, such as tundra vegetation zones and raised marine terraces, remain relatively stable despite the significant and abrupt climate warming trend. Below, we present the most striking examples of landscape changes observed in the paired photographs.

Ferdinand glacier

Ferdinand Glacier (Fig. 2), one of the smallest valley glaciers in the area, has undergone dramatic retreat, losing more than 90% of its LIA volume as reported by Kavan (2020a) comparable to other small valley type glaciers in central Svalbard (Mannerfelt et al. 2024). In the 1908 photograph, the glacier is visibly resting on its push moraine, marking its maximum LIA extent. The frontal section, shaped almost like an ice cliff, was approximately 50 metres thick (quantified in Kavan 2020a) and represents the typical maximum LIA geometry of local glaciers.

Fig. 2. Ferdinand glacier terminus in 1908 and completely deglaciated valley in 2018; the silhouette of the 1908 glacier indicated in the lower panel.

The prominent frontal lobe was supported by the bedrock configuration, which includes a significant transverse bedrock outcrop that caused ice deformation at the terminus. As the glacier retreated, it left behind a substantial amount of debris that had been frozen to the formerly cold-based interface between the glacier and its bed (Evans et al. 2012).

While the most obvious change is the disappearance of the glacier itself, it is noteworthy that the forefield alluvial fan remains largely unchanged. This stability is evident from the flow channels, which were already well-vegetated, as shown in the 1908 photograph. The alluvial fan in the foreground thus most likely originated before the Neoglacial cool phase. Its elevation suggests that it originated at the start of the Holocene, following the retreat of local ice streams when it was situated approximately at sea level (Strzelecki et al. 2018).

Hørbye glacier

The most striking change is the absence of the glacier snout in the 2018 photograph. While the terminus was not as steep as that of Ferdinand Glacier (Fig. 2), the frontal section of Hørbye Glacier at its LIA maximum extent was still relatively thick.The extent and thickness of the glacier during its LIA maximum are clearly indicated by the trim line visible in the 2018 photograph (*see* Fig. 3).

The glacial sediments in the forefield are characterised by a light grey colour, which contrasts sharply with the reddish bedrock visible in the background. In the 1908 photograph, the central moraine – originating at the confluence of the Sven and Hørbye glaciers – is clearly identifiable. This feature is also mapped in the geomorphological survey of the area (Evans et al. 2012).

Additionally, small valley-type glaciers located above Hørbye Glacier have almost entirely disappeared since the LIA, highlighting the rapid and extensive deglaciation in the region.

Petuniabukta delta with Ragnar and Ebba glaciers

The eastern side of Petuniabukta is dominated by the extensive Lomonosov Ice Cap, which feeds the local outlet glaciers, including Ragnar Glacier (on the left) & Ebba Glacier (on the right, Fig. 4). The ice cap is situated at high altitudes, reaching up to 1,000 m a.s.l. and even higher in some more distant areas. This configuration of the accumulation zone has contributed to the relative preservation of these outlet glaciers compared to the smaller valley-type glaciers on the western coast of Petuniabukta, which lack extensive accumulation areas. Consequently, thinning and areal retreat occurred later and at a lower rate, as noted by Rachlewicz et al. (2007).

Since the 1980s, the thinning and retreat of Ragnar Glacier have led to the development of a significant proglacial lake (1.5 km in length), dammed by the glacier's LIA maximum extent push moraine (Ewertowski and Tomczyk 2020). In addition to glacier retreat, the photographs reveal the dynamic evolution of the tide-dominated delta, which is fed by glaciofluvial sediment from the surrounding glaciers. Sediment input following the LIA has resulted in the formation of new barrier spits and lagoons in front of Ferdinand Glacier (Strzelecki et al. 2018). These features are visible on the right side of the delta, where they are prograding into the bay.

The development of new coastal landforms has been further supported by a glacio-isostatic uplift in the region (Kierulf et al. 2022), which stabilises existing landforms and aids in the creation of new ones.

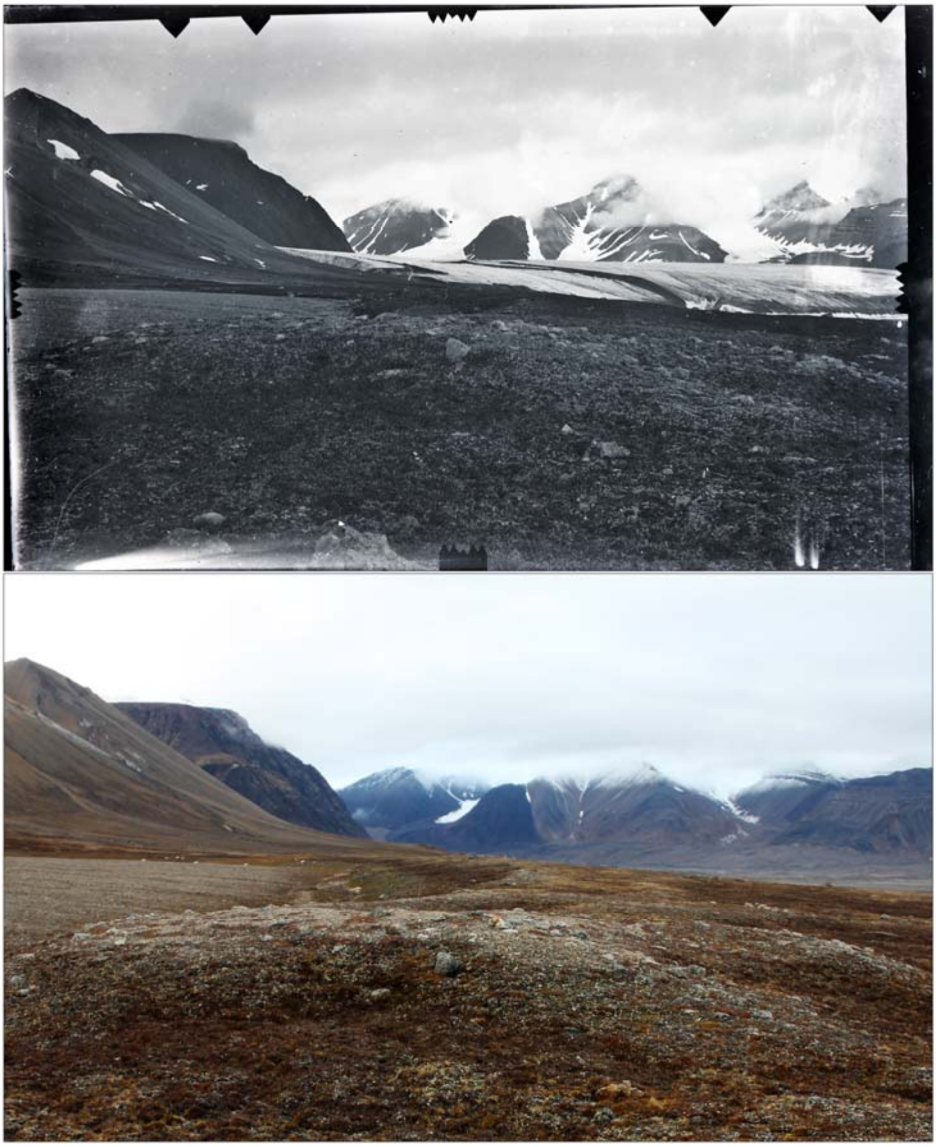

Fig. 3. Hørbye glacier terminus as seen from the south; the 1908 terminus is joint with the Sven glacier terminus approaching from the left side of the photograph.

Fig. 4. View on the eastern side of the Petuniabukta over a massive tide-dominated delta; the central feature is the Løvehovden massive, with Ragnar glacier on the left and Ebba glacier on the right.

Western coast of Petuniabukta: Research field station

This section highlights the enduring presence of research activities in the Petuniabukta area. In 1908, this coastal site served as a temporary base for the de Geer expedition, where a land party established a tent camp for several days to facilitate the exploration of the surroundings (Fig. 5). Since 2015, the same location has been home to two field research stations: the Nostoc Field Station (operated by the University of South Bohemia, Czechia) and the Adam Mickiewicz University Polar Station (Poznań, Poland).

A noteworthy observation from this photographic comparison is that the location was evidently regarded as an ideal site for landing and setting up a base. It also illustrates the impact of human activity on the local landscape, evidenced by terrain modifications. The area was taken over by the Russian state-owned company Arktikugol in the 1930s and underwent significant exploitation starting in the 1960s (Kavan and Halašková 2021).

The uplifted marine terrace, clearly visible on the left side of the 1908 photograph, was completely modified by heavy machinery. Additionally, newly constructed roads can be observed in the centre of the 2018 photograph and on the right-hand side in the background. Today, the site near the shore serves as a landing area for rubber boats, a fuel depot and a temporary atmospheric observation facility.

Brucebyen

Brucebyen is a historic mining settlement founded in 1909 by the Scottish Spitsbergen Syndicate (NPI 2024[2]). The four cabins, used as a logistical and accommodation base for local gypsum mining activities, were constructed between two major lakes, one of which is shown in the photograph (Fig. 6). Notably, the landscape and vegetation cover in the foreground have remained remarkably stable. No significant changes in vegetation cover were evident, which aligns with findings from comparative analyses of similar timespans in this locality (Klimešová et al. 2012).

Nonetheless, a significant decrease in the lake's water level is apparent. This is evident from the exposure of a non-vegetated shoreline zone, particularly on the left side of the lake, where a small peninsula has formed. A minor barren sediment zone was also visible along the shoreline in the background. This decrease in water level could be attributed to continuous permafrost thaw (Grünberg et al. 2024), which has resulted in active layer thickening at rates ranging from 0.7 cm/year (Strand et al. 2021) to over 2 cm/year (Isaksen et al. 2022) around Svalbard in the past two decades. Such thickening enhances communication between lake water and subsurface water storages, potentially leading to gradual drainage into adjacent swamps and subsurface aquifers. Nonetheless, lake water level lowering did not result in significant decrease in lake areal extent as the banks are quasi-vertical. This may however change in the near future as the lake is very shallow (less than 1 meter in the central part of the basin).

The transformation of the massive alluvial fan in the background (central part) is also clearly visible. While the active section (light grey on the left) appears relatively stabilised, the vegetated section visible in the 1908 photograph (on the right-hand side) shows evidence of fresh sediment deposits transported from the upper reaches near the reddish bedrock outcrop. This behaviour is characteristic of alluvial fans and cones found in Svalbard (*e.g.* Bernhardt et al. 2017, Tomczyk et al. 2019).

Fig. 5. Near-shore location on the western coast of Petuniabukta, currently occupied by field research stations of the University of South Bohemia (Czech Republic) and Adam Mickiewicz University (Poland).

Fig. 6. Brucebyen with its lakes on uplifted marine terraces.

Nordenskiöld marine-terminating glacier

The 1908 photograph marks nearly the maximum extent of the glacier, even though the marine-terminating glacier reacts more dynamically to climatic forcings. The maximum recorded position in 1896 was approximately 200–300 meters farther advanced (Kavan et al. 2024a). In this photograph, we can observe the crevassed glacier snout terminating in a cliff of tens of metres. Its land-based marginal part, however, appears to be cold-based, with no signs of crevassing, suggesting that it is most likely frozen to its bedrock. The true left lateral moraine visible in the 2018 image is just beginning to form in the 1908 photograph, as it is being deposited by supraglacial debris transported by the glacier. The trimline, which indicates the maximum glacier thickness (corresponding approximately to the 1908 photograph), is clearly visible in the 2018 image.

The current state of the glacier marks the transition from marine to land terminating with all the possible consequences on marine and terrestrial environments including shifts in nutrient cycling, permafrost dynamics, slope destabilisation, development of freshwater ecosystems and vegetation succession (Kavan et al. 2025).

View from Kapp Napier towards the true left margin of Nordenskiöld glacier

The presented pair of photographs (Fig. 8) depicts the same location illustrated in Fig. 7 but from a different angle. The true left margin of the Nordenskiöld glacier, with its marginal moraine formed by supraglacial debris being deposited, is a clear example of the development of a fresh proglacial landscape loaded with a large amount of unconsolidated sediments. The distance the glacier has retreated is not immediately apparent due to the frontal view of the terminus. However, the Retreat Island, visible on the left side of the 2018 photograph, began to be exposed only in the late 1980s.

The comparison, however, shows the dynamic behaviour of the coastal zone at the tip of Kapp Napier, where a system of beaches and barrier spits has cut off the lagoon and created a freshwater lake (Fig. 9). This is clearly visible in the 2018 photograph, where the former beach from 1908 is marked by the tiny pond in the foreground. Since then, tens of metres of beach complex have been deposited (*see* Kavan 2020b).

Skansbukta bird cliffs

Skansbukta is an embayment on the western side of southern Billefjorden protected by high and steep cliffs frequently inhabited by numerous birds, such as seagulls, puffins and guillemots. Seabirds are an essential source of nutrients transported from the sea to the land, enriching the terrestrial environment, which is often limited by nitrogen and phosphorus content (Ziólek and Melke 2014, Finne et al. 2024). This, combined with the favourable southern orientation of the slopes, has resulted in the development of rich and diverse vegetation. However, these ideal conditions are disturbed by highly dynamic slope processes.

Fig. 7. Ice calving front of the marine-terminating glacier.

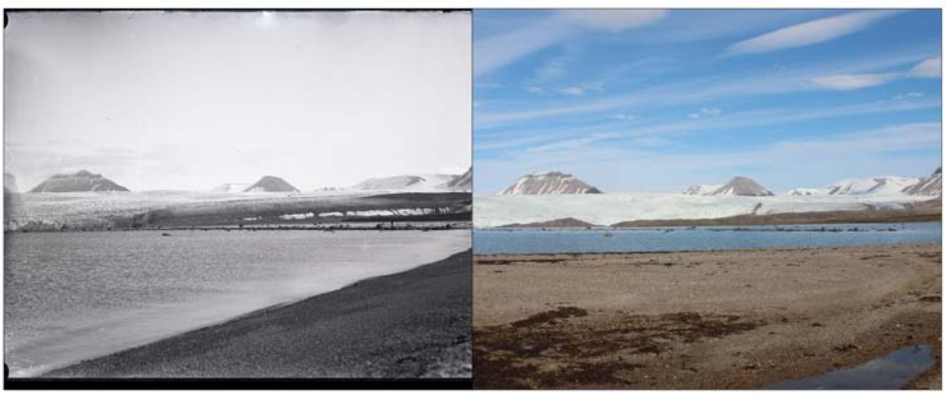

Fig. 8. View of the Nordenskiöld glacier from Kapp Napier.

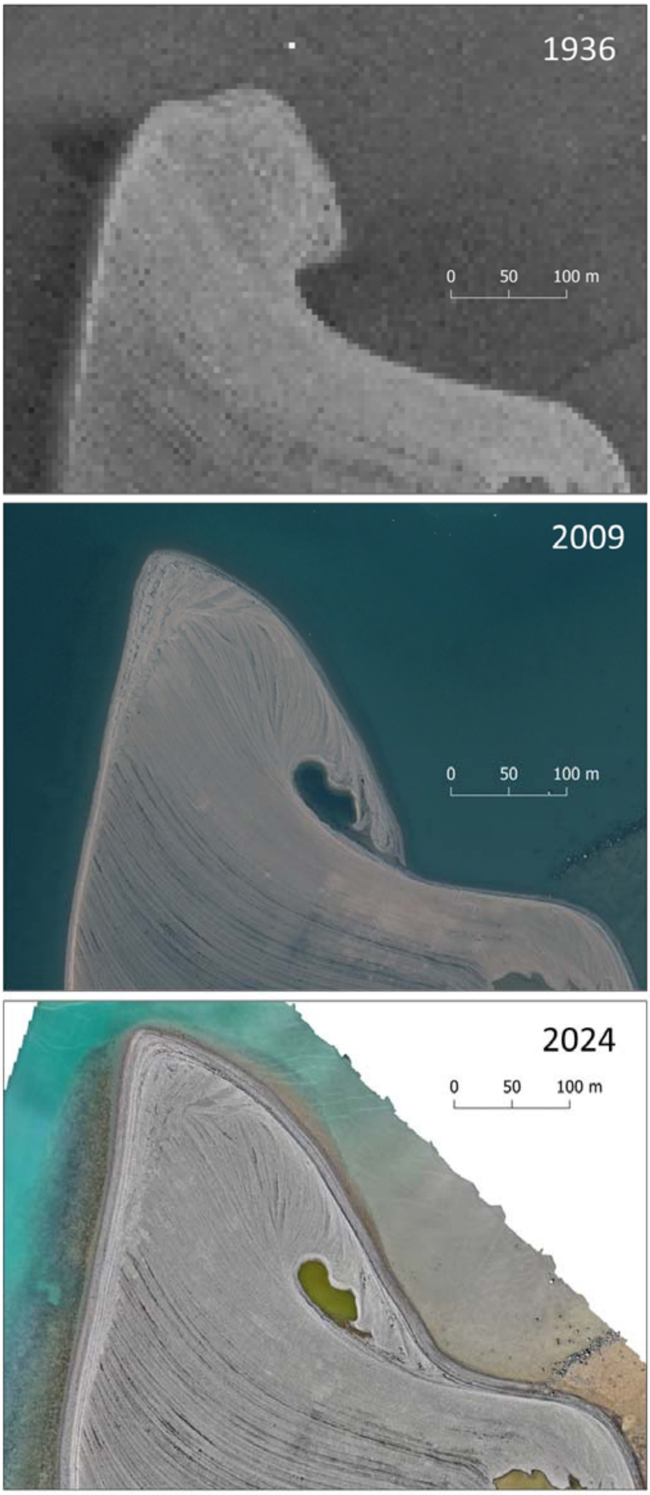

Fig. 9. Development of the freshwater lagoon out of the sea embayment from 1936 to 2024.

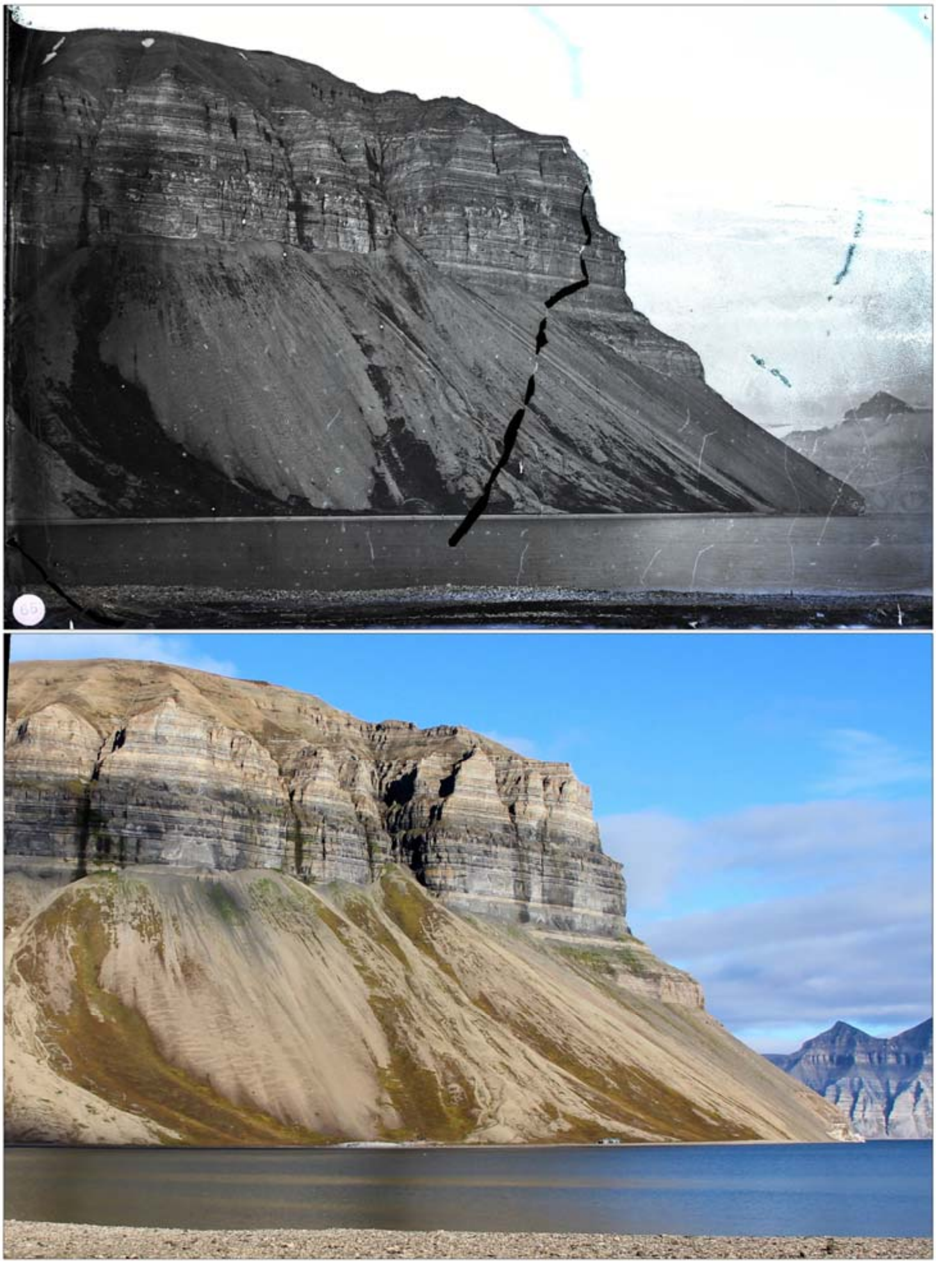

Fig. 10. Northern side of Skansbukta with steep bird cliffs and debris fans.

As a result, the vegetation cover is determined by high nutrient input and favourable microclimates but is also restricted by disturbances from slope dynamics. These two contradictory processes are well illustrated in the photograph pair. Most of the vegetation has spread notably on the right-hand side of the image. Meanwhile, in the far left-hand part of the image, slope erosion has limited the extent of vegetation.

Another feature visible in the image is the onset of mining activity in the coastal zone at the foot of the cliff. A gypsum mine (white, horizontally elongated shape) and a relatively large cabin to the right side of the mine were opened in 1918 and definitively abandoned in the early 1930s(Dallmann 2015, Kjærnett 2000).

Landscape development: A conceptual model Post-LIA to the beginning of the 21st century

The retreat dynamics of glaciers around Petuniabukta exhibit large spatial and temporal heterogeneity. The areal extent of larger valley-type glaciers (Hørbye, Bertil, Sven) remained relatively stable throughout the 20th century. Initially, glaciers lost mass by thinning, which did not cause major retreat in terms of areal extent. The glaciers were losing their massive convex snouts, which became thin and flat. Surface ablation resulted in continuous supraglacial debris deposition, which increased in areal extent and thickness. This marked the formation of frontal and lateral moraine complexes (Hørbye, Nordenskiöld). This was especially evident in the case of Hørbye glacier, which left the largest proglacial area with distinctive supraglacial debris stripes. Smaller glaciers (Ferdinand, Elsa) had retreated more significantly even earlier (since the 1960s). However, in general, vast proglacial areas started to be exposed in the 1980s. This was caused by a long period of thinning of relatively thick glacier snouts without marked retreat (Kavan 2020a).

The first half of the 20th century was dominated by sedimentation and slope processes in the terminoglacial zone of the thinning glaciers. The biggest accumulation of moraine material was concentrated around the LIA maximum extent limits. Frontal and lateral moraines originating during this period unambiguously mark the LIA maximum extent and can be used to date these maxima (*e.g.* Rachlewicz et al. 2007). These moraines were later transformed by slope processes and the degradation of dead ice buried within the moraine complexes. The intensification of redeposition and resedimentation processes can be observed in the second half of the 20th century, especially since the 1990s, when the warming trend accelerated in Svalbard (Nordli et al. 2020). As a result, large moraine-mound complexes can be found between the present glacier fronts and LIA moraines. The intensity of such reworking activity ceases towards the LIA moraines, as older surfaces tend to stabilise due to the gradual degradation and thaw of the buried ice within the moraines.

Fluvial erosion and sedimentation by proglacial streams correlate with meltwater production resulting from atmospheric warming. As a result, small valley-type glaciers (*e.g.* Elsa or Ferdinand) have already passed their peak meltwater production, as defined by Huss and Hock (2018), and the intensity of these processes is now decreasing. Large glaciers, which still hold most of their mass, have not yet reached the expected maximum meltwater production, and fluvial processes are still powerful enough to effectively remodel the landscape (*e.g.* Hørbye glacier or outflow glaciers from the Lomonosov ice cap on the eastern side of Petuniabukta). In the ice-free areas, the slopes are remodelled by gravitational processes, leading to the aggradation of talus cones, alluvial fans and debris accumulation (Tomczyk et al. 2019). A significant volume of material is transported down the slopes, transforming the previously glaciated landscape. This is supplemented by active layer degradation, leading to intensification of thaw slumps and thermokarst erosion gullies (Nicu et al. 2021a, 2023).

The input of terrestrial sediment material into the marine environment (*e.g.* Kavan et al. 2022b) leads to the gradual progradation of shallow, tide-dominated delta systems (Sessford et al. 2015), the accumulation of new barrier spits and beaches, and overall shifts in the actual shoreline position (*e.g.* Strzelecki et al. 2018, Kim et al. 2022). Similarly, due to a longer ice-free season, intensified coastal erosion and the redeposition of material have led to the activation of some coastal landforms, as documented from Kapp Napier, where almost a 100-metres shift in shoreline position was recorded (Kavan 2020b).

Massive glacier retreat has also led to the formation of new proglacial lakes across all of Svalbard (Wieczorek et al. 2023), usually dammed by the frontal moraine or by the glacier ice itself. Ragnar glacier (on the eastern side of Petuniabukta) has developed a proglacial lake, 1.5 km in length and more than 0.5 km² in area, since the early 1980s. The interaction between the lake environment and the massive frontal and lateral moraines has activated a number of minor landslides and slope instabilities (Ewertowski and Tomczyk 2020).

Current situation

Landscape evolution is driven by regional climate dynamics. Continuous warming throughout the 20th century up to the present has resulted in the loss of approximately 15% of the glacier volume and the exposure of vast areas due to glacier retreat since 1936 (Geyman et al. 2022). However, this overall trend is modified by local controls, such as bedrock geology, tectonics and local topography. As a result, we observe high spatial variability in the landscape's response to climatic forcings. Proglacial moraine-mound complexes and till plains undergo more intense and dynamic transformation in the forefields of glaciers located in narrow valleys with steep slopes (*e.g.* Bertil, Ferdinand and Pollock glaciers). In contrast, forefields located in large, flat valleys (*e.g.* Hørbye and Sven glaciers) are more stable. The most intense landscape transformation can probably be observed in the case of the nearly disappeared Ferdinand glacier.

The bedrock tectonic structure predisposed the formation of proglacial ice-dammed lakes in the northern marginal zone of Nordenskiöld glacier around 1990. Subsequent continual melting of the glacier resulted in the sudden drainage of these glacial lakes around 2010 (Nehyba et al. 2017). Such events can have serious consequences for coastal landscapes, leading to the origin of new deltas and the progradation of the actual shoreline (Fig. 11a). Glacial Lake Outburst Floods (GLOFs) may erase signs of long-term development in a particular area (*e.g.* Wołoszyn et al. 2022, Dudek et al. 2023). Similarly, a glacier surge may transform a glacier forefield evolving for decades or centuries in just a few years – an event typical of many Svalbard glaciers (Farnsworth et al. 2016, Benn et al. 2023, Kavan et al. 2024b; Fig. 11b).

Fig. 11. (**a**) New delta in the northern margin of Nordenskiöld glacier, which originated after the GLOF event around 2010 – photo taken by Martin Lulák (2018); (**b**) new delta in front of Recherche Glacier that formed in July 2020, photo taken by Jan Kavan (2023).

The most dynamic fluvial activity is located in front of larger glaciers with high volumes of meltwater production (*e.g.* Hørbye, Sven and Ebba glaciers), where large coalescing glaciofluvial outwash fans can be found. Colluvial and alluvial processes are likely the most abundant, recent landscape features, even though they are concentrated almost exclusively in areas with steep mountain slopes and available weathered material.

Towards a warmer and less icy future

The future development of glaciers and permafrost – the key components controlling the evolution of High Arctic landscapes – is largely dependent on climate dynamics. The expected warming trend (Hanssen-Bauer et al. 2019) will lead to continuous glacier mass loss (Geyman et al. 2022) and the intensification of multiple geomorphic processes, especially those connected to fluvial activity. The transformation of braidplains, alluvial fans and deltas, which are often cut off from the glacier (as a major source of water), will then rely solely on precipitation. This, however, is projected to be stable or increase in the future (van Pelt et al. 2019). Thus, we can expect that fluvial and slope processes will play an essential role in future landscape development.

We can assume that the oldest parts of the proglacial hummocky moraine complexes of Hørbye and Sven glaciers and the till plains of the terrestrial marginal zones of Nordenskiöld glacier will stabilise (Evans et al. 2012, Malecki et al. 2013, Ewertowski et al. 2016, 2019; Allaart et al. 2018), whereas the steep slopes of small valley-type glaciers (*e.g.* Bertil and Ferdinand) will continue to undergo intensive transformation as reported from different areas around Svalbard (*e.g.* Aradóttir et al. 2019, Allaart et al. 2021, Dudek et al. 2023). Fast-retreating glaciers (such as Bertil glacier, which faces south) will produce large amounts of meltwater, effectively transforming their proglacial zone and areas adjacent to the stream draining the glacier (compare with McCerery et al. 2024). The stable zones in flat areas will soon be colonised by numerous organisms, and initial soil genesis will begin (*e.g.* Luláková et al. 2023).

The landscape tends to find a new equilibrium state after the massive deglaciation since the LIA. Although Svalbard has experienced significantly warmer conditions during the Early Holocene (Mangerud and Svendsen 2018), the fluctuations might have been as extreme as what we are experiencing today (van der Bilt et al. 2019). As mentioned above, the role of extreme events is crucial in effectively remodelling the landscape. Although Hørbye glacier is considered a surge-type glacier (Malecki et al. 2013), there is no sign of any post-LIA surging activity in the vicinity of Petuniabukta (despite some geomorphic evidence from the pre-LIA period having been identified; *see* Farnsworth et al. 2016). However, as demonstrated in Nehyba et al. (2017), GLOF events were detected and are likely to occur again. Important glacial lakes identified around Svalbard (Wieczorek et al. 2023) include the vast Ragnar Lake. The ice-cored frontal moraine (Ewertowski & Tomczyk 2020) dams the expanding lake (a result of glacier retreat). An increasing volume of water in the lake and the destabilisation of the moraine may result in dam failure and abrupt drainage in the near future. Such a rapid GLOF event could significantly remodel the valley bottom and adjacent coastal zone. Currently, the lake serves as a major temporary deposition centre for fine-grained glaciolacustrine sediments (compare to Kavan et al. 2022b). In the event of lake drainage, these sediments would be suddenly exposed and prone to further remodelling. They may also become an important dust source, as the Ragnar/Hørbye glacier forefield has already been identified as an existing dust source, as glacier-driven catabatic winds are strong enough to lift fine mineral material (Kavan et al. 2020). The same is true for the neighbouring Ebba valley (Rymer et al. 2022, Rymer and Wachecka-Kotkowska 2024).

Permafrost degradation, intense fluvial processes and slope movements in the future may pose a serious threat to the infrastructure of the Pyramiden town, west of Petuniabukta (Kavan and Halašková 2021). Earlier snowmelt and a general decrease in winter precipitation may substantially limit the availability of drinking water supplies at the end of the summer season, as most current supplies rely on water derived from snowmelt. The infrastructure will also become more vulnerable to coastal erosion, as the prolonged sea ice – free period will lead to increased coastal erosion (Jaskólski et al. 2018, Nicu et al. 2021b).

Conclusions

We have demonstrated the dynamic response of the High Arctic landscape to post-LIA warming through a comparison of pairs of historic and recent photographs. The landscape has adjusted to new climatic controls through massive glacier retreat and the consequent intensification of paraglacial processes, particularly fluvial and slope processes, as well as permafrost degradation. We have also outlined the expected future development of the landscape, with still-retreating glaciers; highlighted the role of local controlling factors, such as geomorphology and tectonics; and pointed out the importance of extreme events. The rapid transformation of the landscape will pose serious challenges to human activities, especially in terms of maintaining infrastructure. The new, warmer and less icy future will bring both opportunities (*e.g.* new areas available for mining and new transportation routes) and threats (*e.g.* active layer destabilisation, avalanches or water shortages). Human activities currently present in the Arctic will need to cope with and adapt to these upcoming challenges.

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