Received: 2 November 2022 | Revised: 28 February 2023 | Accepted: 13 March 2023

DOI: 10.1002/ldr.4695

RESEARCH ARTICLE

WILEY

Glacier decay boosts the formation of new Arctic coastal environments—Perspectives from Svalbard

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Funding information
Norwegian Financial Mechanism 2014-2021: SVELTA—Svalbard Delta Systems Under Warming Climate, Grant/Award Number: UMO-2020/37/K/ST10/02852; Masaryk University project ARCTOS MU, Grant/Award Number: MUNI/G/1540/2019; SONATA BIS, Grant/Award Number: UMO-2020/38/E/ST10/00042

Abstract

The consequences of accelerating climatic warming on Arctic landscape evolution are far-reaching. In Svalbard, glaciers are rapidly retreating after the Little Ice Age, which leads to exposing new coastal landscapes from marine-terminating glaciers. Precise quantification of these changes was limited until the complete dataset of Svalbard glacier outlines from 1930's was made available. Here, we analyse the new Svalbard glacier change inventory data and demonstrate that glacier retreat led to a major shift from marine-terminating towards land-based glaciers in the last century. This retreat also led to the formation of 922.9 km of new coastline since 1930's creating pristine landscapes governed by paraglacial processes and sediment-rich nearshore fjord environments. Recent palaeogeographical reconstructions suggest that such a mode of coastal evolution was dominant over the extended periods of the Holocene. Transitions from marine-terminating to land-based glaciers have significant implications for fjord circulation, biological production, the state of marine ecosystems, biogeochemical cycles between land and seas and the CO_2 budget in coastal waters.

KEYWORDS

climate change, coastal evolution, fjord circulation, glacier retreat, Holocene, marine-terminating glaciers

1 | INTRODUCTION

The rapid mass loss of Svalbard glaciers reported since the 1930s (Geyman et al., 2022) has serious implications not only for the transformation of sediment cascades and the reshaping of landscapes but also for the functioning of the associated terrestrial and submerged ecosystems. Marine-terminating glaciers are widely reported to have retreated significantly over the whole northern hemisphere during the last two decades (Kochtitzky & Copland, 2022). The accelerated retreat of marine-terminating glaciers after 2000 was observed in the Canadian Arctic Archipelago (Cook et al., 2019). Similarly, Hugonnet et al. (2021) highlighted the acceleration of mass loss and thinning rates of glaciers outside ice sheet peripheries since 2000. Moreover, glaciers are highly sensitive to temperature which is likely to further increase resulting in continuous glacier retreat during the 21st century (Rounce et al., 2023). Svalbard marine-terminating glaciers dynamics have been previously described by Blaszczyk et al. (2009) using satellite observations from the years 2000 to 2006 with the identification of 14 glaciers turning from marine-terminating to land-based systems during this period. The extensive new dataset of historic glacier extent (Geyman et al., 2022) enables us to significantly extend the analysis and smooth the decadal variations caused by short-lived surge cycles and consequently also to present long-term trends in the dynamics of marine-terminating glaciers. The observed recession of glaciers and consequent exposure of the new coastal zones filled with glacial sediments provides an opportunity to improve interpretations of coastal evolution in the warmer phases of the Holocene characterised by the reduced extent of glaciers and

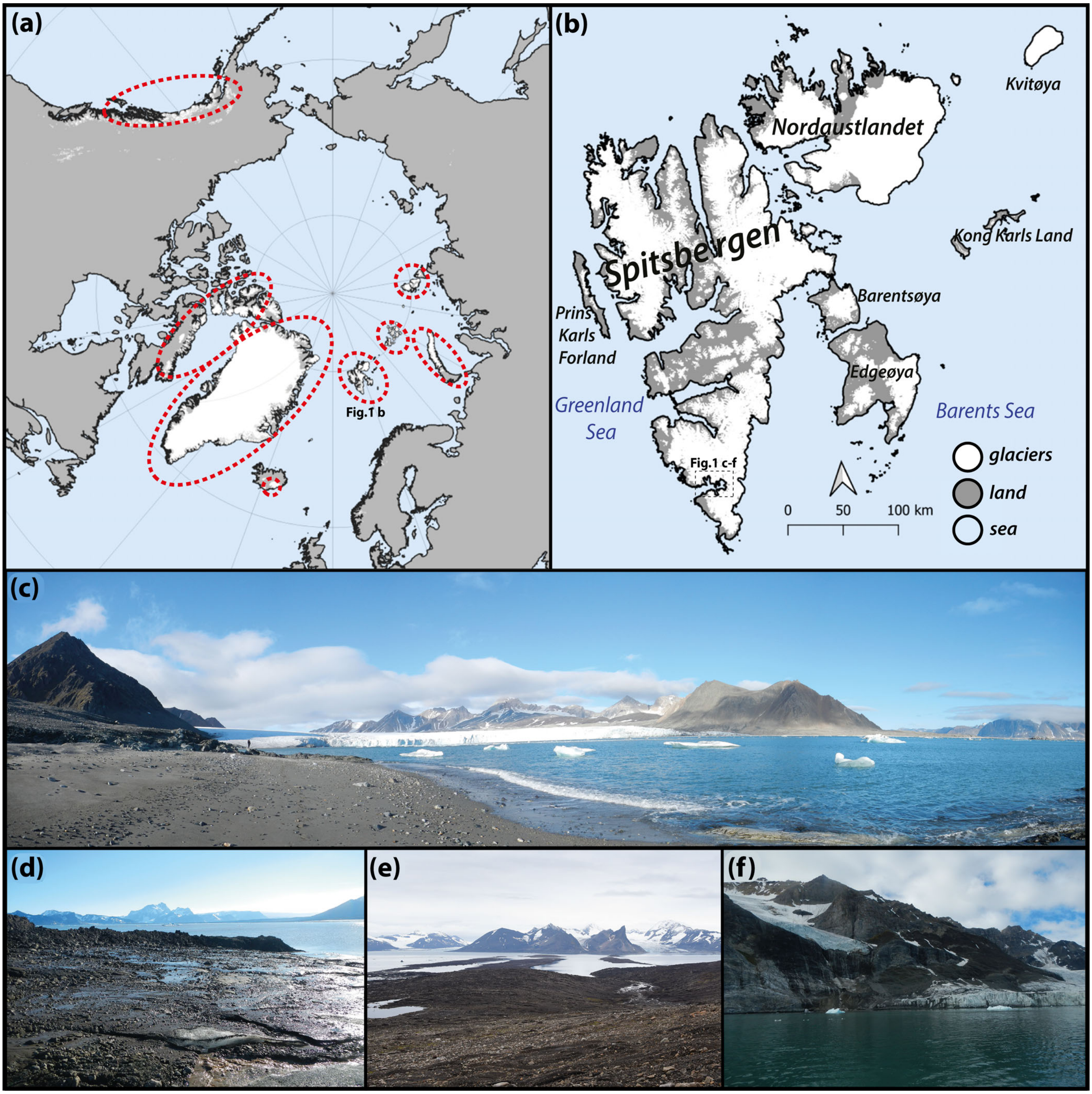

FIGURE 1 (a) Glaciated coasts of Arctic and sub-Arctic regions where degradation of marine-terminating glaciers drives coastal evolution; (b) Present-day glaciation of Svalbard Archipelago; (c) New coastal systems exposed after the rapid retreat of Svalbard glaciers in the last 80 years-mixed sand-gravel beaches formed in front of Hansbreen; (d) remnants of glacial landforms (crevasse-fill sediments) eroded and transformed by marine processes into pocket beaches in southern Spitsbergen; (e) lagoons, coves and quasi-barrier islands in Brepollen composed of sediments from the glacial landforms erosion; (f) plunging rocky cliffs revealed in Vestre Burgerbukta after the retreat of marine-terminating Paierlbreen and separation of small, tributary hanging glacier on steep fjord slopes. [Colour figure can be viewed at wileyonlinelibrary.com]

their role in transforming the landscapes (Farnsworth et al., 2020; Figure 1).

This study points out the importance of the reported past and projected future mass loss of marine-terminating glaciers as the key mechanism for boosting the formation of new coastal environments and the paraglaciation of nearshore zones in the Arctic.

2 | MATERIALS AND METHODS

The glacier areal extent delimited from the 1936/1938 aerial images (Geyman et al., 2022) was used as a base for comparison with the present state (5 m spatial resolution, WGS84/UTM zone 33 °N coordinate system). The present position of the glacier fronts and new coastline were derived from the set of Sentinel-2 images from August 2019 (10 m spatial resolution, WGS84 / UTM zone 33 °N coordinate system). The satellite images were downloaded via the Sentinel Hub EO browser. The images were already georeferenced, and the TIFF files were directly processed using the QGIS software. The comparison of glacier front positions from 1936/1938 to 2019 provided insight into changes in marine-terminating glaciers over 80 years. Based on these two datasets we manually delimited the positions of the glacier termini, the new coastline that appeared after the glacier retreat and calculated the average retreat rate along the glaciers' centerlines. The combined error resulting from the spatial resolution of both datasets leads to an uncertainty of ±21.2 m of the retreat corresponding to ca ± 0.3 m/year of calculated retreat rate.

3 | RESULTS AND DISCUSSION

3.1 | New coasts after glacier retreat

The new coast that resulted from the retreat of the marine-terminating glaciers (Figures 2a and 3c) amounts to 922.9 km which represents an increase of 16.4% from the original 1936/1938 Svalbard coastline length (including Spitsbergen, Edgeoya, Barentsoya, Prins Karls Forland and Nordaustlandet; excluding other small islands and rocks). To put it into the perspective, it is important to note that the post-Little Ice Age (LIA) deglaciation increased the length of the archipelago's coastline from ca 4700 to 5600 km. Two hundred fourteen marine-terminating glaciers were identified in the 1936/38 data

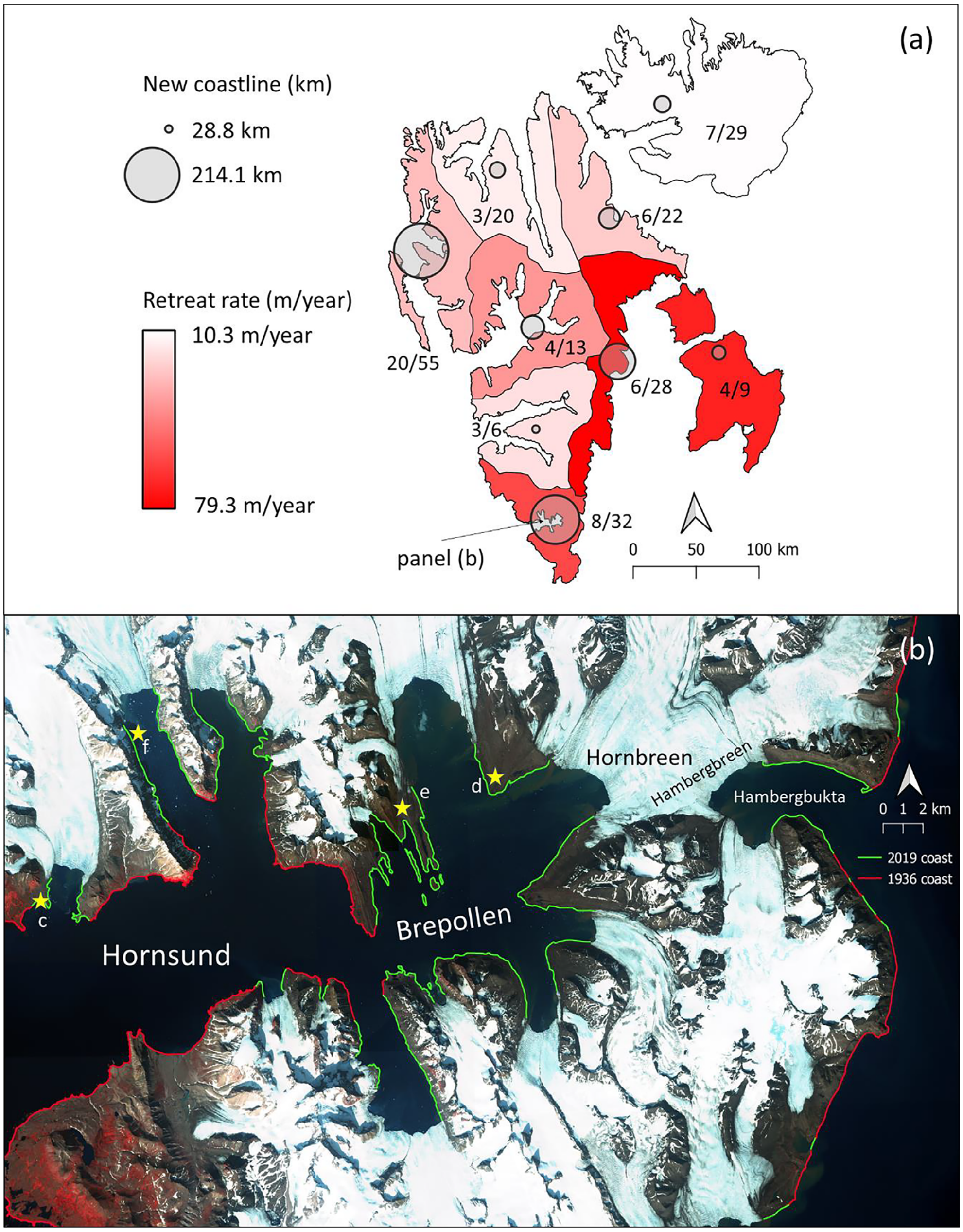

FIGURE 2 Retreat rate of marine-terminating glaciers since 1936 in coloured scale and length of the new coast since 1936/1938 in size illustrated for the glacier regions by Hagen et al. (1993), the numbers document the proportion of glaciers that switched from marine-terminating to land-based glaciers from the total number of marine-terminating glaciers in 1936/38 in the region (a); Sentinel-2 satellite image (July 28, 2019) of the Brepollen region with a large proportion of new coasts appearing. [Colour figure can be viewed at wileyonlinelibrary.com]

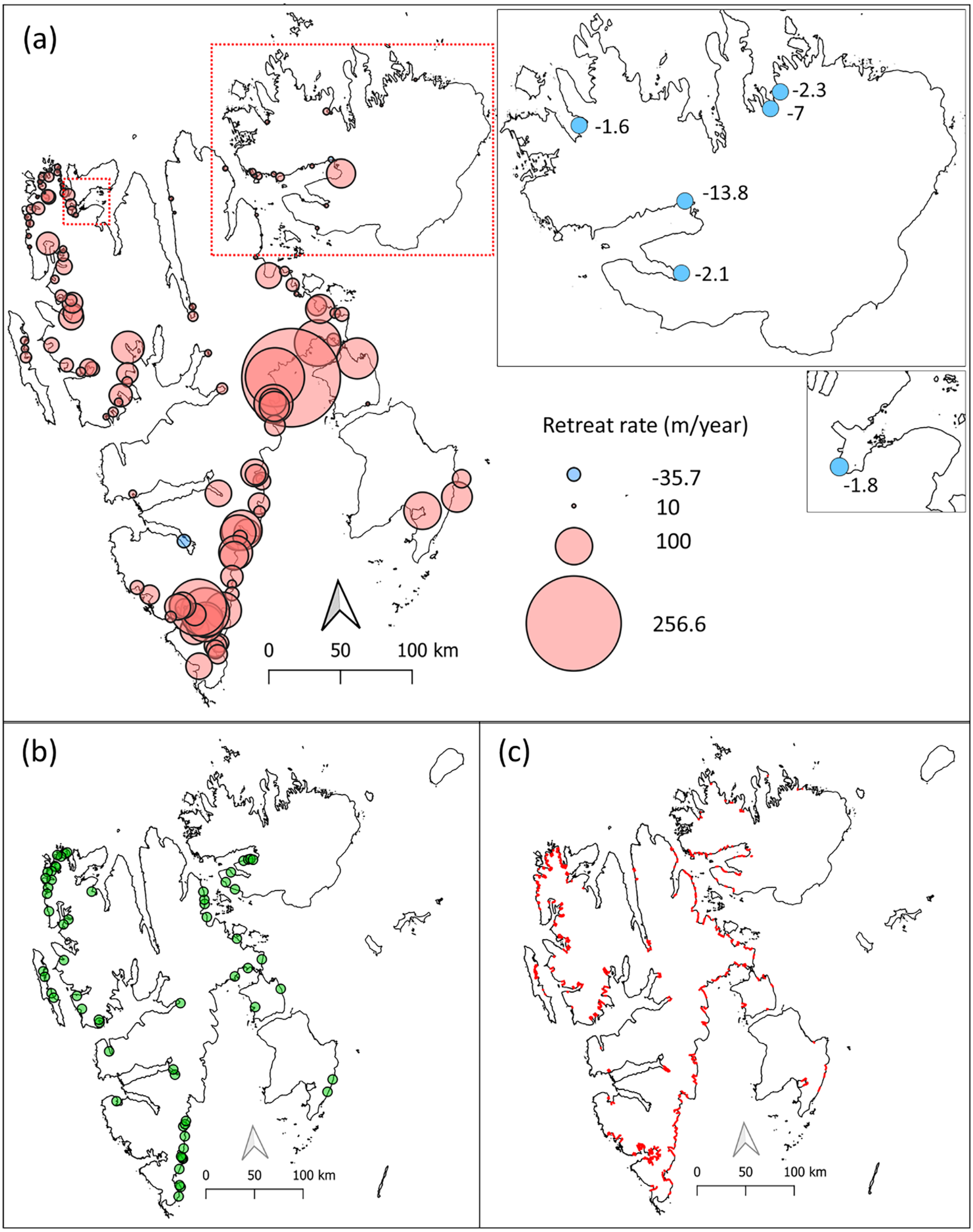

FIGURE 3 Location and retreat rate of marine-terminating glacier; the advancing glaciers (in blue) are highlighted in the detailed panels with numbers indicating their annual advance (a); location of glaciers that switched from marine-terminating to land-based (b); new coasts emerging after the glacier retreat (c). [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 3a) and of these 61 have developed into land-based glaciers by 2019 (Figure 3b). This represents 28.5% of the total amount of marine-terminating glaciers in 1936/1938. Most of these 61 glaciers are rather small (23.4 km^2 on average, 10.8 km^2 median) and as such are more sensitive to climatic warming in terms of mass loss. Forty-nine land-based glaciers were identified as main glaciers, 12 as tributary. The transition from marine-terminating to land-based glaciers was most evident along the southeast coast and in northwest Svalbard (Figure 2a). The likely explanation for this spatial pattern is the distribution and characteristics of marine-terminating glaciers. Glaciers in the northwest are rather small, but due to the relatively cold climate had reached the sea and temporarily became marine-terminating during the LIA. The effect of enhanced snowfall was probably responsible for a similar advance in the southeast. After the climate had warmed up, these small glaciers quickly adjusted to these new climatic conditions and retreated.

Most of the studied glaciers retreated between 1936 and 2019 with only seven glaciers experiencing advance—five in Nordaustlandet, one in northwest (Emmabreen) and the largest one, Nathorstbreen, in the southern part of Svalbard (Figure 3a). The advance of these glaciers could be probably associated with recent surging, as is the case of Nathorstbreen (Sund et al., 2014).

The average distance the glaciers have retreated is 3137 m, which gives an average retreat rate of 37.8 m/year. The most rapid retreat was observed in Negribreen on the east coast (22 km), although this glacier was surging just prior to the aerial photography campaign in 1936/1938 (Hagen et al., 1993), which captured glacier termini in its maximum position. The spatial pattern of the retreat rate (Figure 2a) reveals that the fastest retreat was observed in the southeast region of Svalbard. This corresponds well with the massive retreat of glaciers in the Brepollen region in Hornsund fjord (Strzelecki et al., 2020) or that observed along the southeast coast (Kavan et al., 2022). The high retreat rate along the southeast coast is in line with Svalbard-wide surface mass balance models (e.g., van Pelt et al., 2019). Also, the hypsometry of the glaciers with a large proportion of low elevated parts is favourable to large and fast retreats. Some of the large glaciers besides underwent surges before 1930s, such as the Negribreen, which produces disbalance favourable to large and fast retreat afterwards (see e.g., Hagen et al., 1993).

It is important to note that even without acceleration of the current glacier retreat rates, the southern part of Spitsbergen—Sørkappland—will most probably become a new island (with the areal extent of approximately 1300 km^2) of Svalbard Archipelago by the mid-21st century (Grabiec et al., 2018) when the collapse of Hornbreen-Hambergbreen glacier bridge is likely to happen (Figure 2b). The disappearance of the ice isthmus between Sørkappland and the rest of Spitsbergen will link the Barents Sea with the Greenland Sea and will have severe consequences for the marine environment.

3.2 | Remodelling of coastlines

The coastlines of the Arctic are probably some of the most dynamic environments due to ongoing climate change (Fritz et al., 2017). While much scientific effort has concentrated on understanding changes along ice-rich permafrost coasts of Alaska, Yukon or Siberia (Irrgang et al., 2022), the glacier retreat described by Geyman et al. (2022) allows us to identify that considerable shift in coastal environments may occur also in glaciated parts of the Arctic. Glacier retreat generates substantial amounts of unconsolidated sediments (Strzelecki et al., 2018) and unstable glacial landforms that become exposed directly to the operation of waves, tides and currents. As such, they are often vulnerable to intensive erosion and remodelling into new coastal features including beaches, barrier islands, spits, lagoons, or tidal flats. The retreat of marine-terminating glaciers often reveals glacially-overridden bedrock landscapes that evolve into new rock cliffs, shore platforms and skerries (Lim et al., 2020). Across the European Arctic and Greenland, glacier recession exposed at least 40 new bedrock islands in the last 70 years (Ziaja & Haska, 2023; Ziaja & Ostafin, 2019).

Enhanced runoff from melting glaciers (Huss & Hock, 2018) can increase rates of sediment transport from land to the sea. This may result in progradation of delta systems, as reported from the coasts of Greenland (Bendixen et al., 2017). The exposure of steep slopes of fjords by retreating marine-terminating glaciers leads to the activation of a number of extreme slope processes including rockfalls and rock avalanches that may trigger tsunami waves (Higman et al., 2018; Strzelecki & Jaskólski, 2020).

3.3 | Implications for the future

The doubling of ice mass loss by 2100 in Svalbard predicted by Geyman et al. (2022) portends a period of dramatic landscape and ecosystem change that will significantly impact the coastal zone, which serves as a geoecological buffer between the rapidly deglaciating land and the de-icing seas. Interestingly, recent geochronological studies of the region (Osika et al., 2022) suggest that the opening of the strait due to the glacier decay most probably occurred in the Hornsund area numerous times over the Holocene. The strait in Brepollen was opened when the climate was warmer than today, that is, during the Early Holocene (Mangerud & Svendsen, 2018) and the Medieval Warming Period (Divine et al., 2011). On the contrary, Neoglacial cooling between 3.9 and 1.3 ka BP and the most recent cold and wet phase of the Late Holocene—the LIA —had rebuilt ice bridge and filled the strait with advancing, often surging glaciers (Farnsworth et al., 2020; Noormets et al., 2021). This may suggest that the picture of Svalbard's coastal zone morphodynamics controlled by glacial activity we know from the last century of observations was to a large degree misleading. The post- LIA climate warming and associated deglaciation (Martín-Moreno et al., 2017) result in the return of Svalbard's coastal landscapes to the operation in analogous conditions which controlled their evolution in the earlier periods of the Holocene. The further development of Svalbard's coast depends to a large extent on the amount and availability of sediments produced during the LIA.

Another unknown is the glacioisostatic response to the massive post-LIA ice mass loss leading to the uplift of the coastal zone. It is widely established that uplifted beaches and marine terraces, so characteristic of Svalbard coastal landscapes record uplift from glacial isostatic adjustment caused by the decay of Svalbard-Barents Sea Ice Sheet that covered the archipelago during the Last Glacial Maximum (e.g., Forman et al., 2004; Long et al., 2012; Schomacker et al., 2019; Sessford et al., 2015). However, taking into account that the glacier advance during the Neoglacial cooling and the LIA most probably accumulated the largest ice mass during the Holocene in Svalbard (e.g., Farnsworth et al., 2018; Martín-Moreno et al., 2017; Philipps et al., 2017) the rapid retreat of glaciers observed over the last century may have already overtaken the post-LGM control of solid Earth motion. Indeed, the precise analyses of Global Navigation Satellite System (GNSS) land uplift data are strongly controlled by even annual ice mass variations at nearby glaciers (Kierulf et al., 2022). Most recent uplift rates observed at GNSS stations in Ny Alesund (NW Spitsbergen) and Hornsund (SW Spitsbergen) exceed 9 mm per year suggesting a rapid reduction of sediment accommodation space in the coastal zone. At the same time, such a rapid land uplift may involve longer preservation of glacial landforms exposed by marine-terminating glaciers along new coastlines and exposure of submerged coastal landscapes (e.g., shore platforms). This is already observed for instance along the northern coast of Hornsund (Strzelecki et al., 2017).

Marine-terminating glaciers are also key drivers of Arctic ecosystems, affecting the whole environment in the glacier forefield. Subglacial meltwater often helps to disturb the stable stratification of the water in the coastal zone by enhancing upwelling and thus bringing more nutrients to the surface layer (Willliams et al., 2021). Subglacial drainage, submarine melting and glacier calving not only deliver fresh water to fjord systems but are interconnected paths for the delivery of nutrients as well as mineral and organic matter (Halbach et al., 2019). Indeed, the waters in front of calving terminus of glaciers are often characterised by the highest marine productivity in the entire fjord. The switch from marine-terminating to land-based glaciers can result in substantially lower productivity of the adjacent coastal waters (Meire et al., 2017). The nutrient-rich ecosystem of a marine-terminating glacier also attracts specific species of mammals and birds (e.g., Womble et al., 2021) and constitutes one of the biodiversity hotspots in the Arctic (Lydersen et al., 2014; Urbanski et al., 2017). Comparison of foraminiferal assemblages (i.e., microorganisms quickly reacting to environmental changes) and their development within the last decades in the fjords of Svalbard and Norway revealed that atlantification of Svalbard coastal waters may not affect the local habitats substantially (Kujawa et al., 2021). Hence, the changes in local conditions will be likely the main driving factor for the development of specific Svalbard habitats such as one of the tidewater glacier-dominated fjords.

4 | CONCLUSIONS

Retreating marine-terminating glaciers in Svalbard exposes new shore zones filled with unstable glacial sediments which are available to build up pristine coastal landscapes. We demonstrated that the retreat of Svalbard glaciers in the 1930s–2019 often led to the transition from marine-terminating towards land-based glaciers (60 out of 214 in 1936/1938). This process was accompanied by the origin of over 900 km of new coastline since 1930s (an increase of 16.4% in coastline length) which remain unexplored and for the most part unmapped. This landscape formation process has the potential to change nutrient, organic and mineral supply to coastal waters. Further, it might destabilise not only the local biological production but also influence biogeochemical processes which are responsible for CO_2 cycling (Włodarska-Kowalczuk et al., 2019).

New bays, new straits, new peninsulas and new islands, that have appeared in the last decades of unprecedented warming and associated decay of marine-terminating glaciers in the Arctic are predominantly uncharted and unexplored territories. This foreshadows ice-free Arctic and other cold regions of the warmer future (e.g., Patagonia, Alaska, Antarctica). Gaps in research on recently formed and exposed coasts in rapidly deglaciating Arctic regions are to be addressed urgently, not only to capture the ongoing evolution of new landscapes but also to enhance the coastal zone reconstructions from warmer and less glaciated periods. The importance of multidisciplinary research linking glaciological, geomorphological and ecological studies exploring the new lands and coasts in Arctic archipelagos has never been more important than at present.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the Norwegian Financial Mechanism 2014-2021: SVELTA—Svalbard Delta Systems Under Warming Climate (UMO-2020/37/K/ST10/02852) based at the University of Wroclaw. This work was also supported by the Masaryk University project ARCTOS MU (MUNI/G/1540/2019). MCS research on paraglacial coastal hazards was bolstered up by SONATA BIS (UMO-2020/38/E/ST10/00042) GLAVE project. We acknowledge Professor Antony J. Long for consultation and English proofreading, we thank also Kuba Malecki for explaining to us some of the glaciological intricacies across the archipelago. We thank Anna Irrgang, Mette Bendixen and an anonymous reviewer for their very thoughtful and constructive comments, which significantly improved the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare that they have no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Zenodo at https://zenodo.org/record/7684217#.Y_30nHaZOUI, reference number 10.5281/zenodo.7684217.

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SUPPORTING INFORMATION

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How to cite this article: Kavan, J., & Strzelecki, M. C. (2023). Glacier decay boosts the formation of new Arctic coastal environments—Perspectives from Svalbard. *Land Degradation & Development*, *34*(12), 3467–3474. https://doi.org/10.1002/ldr.4695