Received: 26 July 2022 | Revised: 23 April 2023 | Accepted: 6 May 2023

DOI: 10.1002/ldr.4773

RESEARCH ARTICLE

WILEY

Paraglacial transformation and ice-dammed lake dynamics in a high Arctic glacier foreland, Gåsbreen, Svalbard

Justyna Dudek[1] | Iwo Wieczorek[2] | Mateusz K. Suwiński[3] | Mateusz C. Strzelecki[2]

[1]Department of Environmental Resources and Geohazards, Institute of Geography and Spatial Organization, Polish Academy of Sciences, Toruń, Poland

[2]Alfred Jahn Cold Regions Research Centre, Institute of Geography and Regional Development, University of Wroclaw, Wrocław, Poland

[3]Faculty of Earth Sciences and Spatial Management, Nicolaus Copernicus University, Toruń, Poland

Correspondence
Justyna Dudek, Department of Environmental Resources and Geohazards, Institute of Geography and Spatial Organization Polish Academy of Sciences, Kopernika 19, 87-100 Toruń, Poland.
Email: justyna_dudek@wp.pl

Funding information
Arctic Field Grant, Grant/Award Number: 333199; National Science Centre project 'GLAVE', Grant/Award Number: UMO-2020/38/E/ST10/00042

Abstract

The structural change of the Svalbard landscape from glacially dominated to paraglacial, that has taken place since the termination of the Little Ice Age (ca. 1900) is expressed by the widespread retreat of glaciers and progressive exposure of glacial landforms. This study provides insights into the rate of post-LIA deglaciation and associated paraglacial transformation in the foreland of Gåsbreen, one of the first ever investigated glacier systems in the Arctic. Glacier is situated in Sørkapp Land (Southern Spitsbergen), a region characterized by one of the fastest deglaciation rates in the entire Svalbard Archipelago. During the investigated period, 1938–2020, the Gåsbreen was in a recession that accelerated after 1990, leading to its foreland increasing from 2.2 to 5.8 km^2. The dynamics of landscape change in the glacier foreland, exposed since the end of LIA, manifested in i.e. the formation of ice-dammed lakes, degradation in the surface of ice-cored moraines and the landforms that are underlain by dead-ice. Mass movements and debris flow on ice-cored moraines and fluvioglacial processes had a great influence on this transformation. Enhanced proglacial runoff intensified denudation, transport and accumulation of sediments, which resulted, in: an increase in the extent of sandurs and proglacial riverbeds, an increase in the area of glacial lakes, extending and changing of the course of rivers in the glacier foreland. At the same time, the major lake system in the area—Goësvatnet underwent several cycles of filling and draining, often through glacial outburst flooding events.

KEYWORDS

Arctic, glacial lakes, glacial landforms, glacier retreat, paraglaciation, Svalbard

1 | INTRODUCTION

The last few decades of sustained warming of the Arctic region are predominantly reflected in a strong surface air temperature rise and extensive decline of the sea-ice cover (e.g., Barry, 2017; Sumata et al., 2022; Thoman et al., 2020). Warming of the Arctic climate entailed also changes in terrestrial environments such as an increase of ground temperatures and degradation of permafrost (e.g., Dobiński & Kasprzak, 2022; Karjalainen et al., 2020; Smith et al., 2022), and/or rapid retreat of glaciers (e.g., Cook et al., 2019; Hugonnet et al., 2021; Małecki, 2022; Sasgen et al., 2022). Among subregions of the Arctic, exceptional climate warming was characteristic of the Barents Sea region with Svalbard Archipelago at its heart (Isaksen et al., 2022). Svalbard Archipelago experienced one of the fastest glacier mass loss since the termination of the Little Ice Age (LIA; 1250–1900 CE; Geyman et al., 2022) and serves as a unique area to study the response of cold region landscapes to paraglacial transformation. Paraglaciation is a geomorphological concept describing the evolution of landscape after deglaciation. When glacial sediments and landforms are eroded and transported through a diverse range of sediment cascades to be accumulated or reworked into new, non-glacial landforms and landsystems (e.g., Ballantyne, 2002; Church & Ryder, 1972; Evans, 2005; Mercier, 2008; Strzelecki et al., 2018). In Svalbard paraglacial processes are currently most active on glacier forelands often characterized by ridges of moraines developed by the LIA glacier advance. The most common mechanisms observed along glacier margins are gravitational mass movements, dead ice degradation and associated collapse of landforms, debris slides, erosion, and transport of sediments by meltwater streams (e.g., Evans et al., 2012; Evans et al., 2022; M. W. Ewertowski & Tomczyk, 2020; Lønne & Lyså, 2005; Lukas et al., 2005; Lyså & Lønne, 2001; Schomacker & Kjær, 2008; Tonkin et al., 2016). Another component of paraglacial landscape that started to frequently emerge in front of retreating glaciers are glacial lakes often dammed by moraines or glacier tongues (Urbański, 2022; Wieczorek et al., 2023; Wołoszyn et al., 2022). In sites where marine-terminating glaciers rapidly exposes new bays and fjord shores a diverse of coastal landscapes evolve (Kavan & Strzelecki, 2023; Strzelecki et al., 2020).

Here we present the multidecadal paraglacial transformation of the Gåsbreen proglacial zone, likely the earliest mapped (1899 CE) and investigated glacier in Svalbard (De Geer, 1923). Using this unique study site, we describe and quantify landscape changes controlled by paraglacial processes operating in the glacier foreland with fluctuating glacial lake system, through the outwash plain down to the fjord coast. We define "proglacial zone" as the environment located in front of a glacier including the ice-marginal area and glacier foreland following the definition by Slaymaker (2009).

2 | STUDY AREA

Svalbard Archipelago, situated between the Arctic Ocean, Greenland Sea and Barents Sea, is currently the fastest warming part of the Arctic region (Isaksen et al., 2022). Although the archipelago features an Arctic climate, due to the warm West Spitsbergen Current that passes along the western coast of its major island—Spitsbergen, experiences significantly higher temperatures than other areas at the same latitude (Eckerstorfer & Christiansen, 2011; Gjelten et al., 2016; Hanssen-Bauer et al., 2019). According to Nuth et al., 2013, ca. 57% (i.e., about 34,000 km^2) of Svalbard is covered by glaciers. The rest of the land is controlled by the presence of permafrost, which is present in ice free terrain in a continuous form in deglaciated mountain ranges and valleys (Gilbert et al., 2018; Humlum et al., 2003). The coastal permafrost is strongly controlled by sea water intrusion and exposure to wave impacts disturbing its shape and spatial distribution along the shores (Dobiński & Kasprzak, 2022; Kasprzak, 2020; Kasprzak et al., 2017).

Among other sectors of Svalbard—Sørkapp Land—the southernmost peninsula of Spitsbergen—is characterized by one of the sharpest climatic differentiation linked with influences of cold East Spitsbergen Current that flows along the eastern coast and warm West Spitsbergen Current on the opposite coast (Ziaja & Ostafin, 2014). Currently, the peninsula is connected to the rest of Spitsbergen Island by the ice bridge formed by two marine-terminating glaciers—Hornbreen and Hambergbreen. However, with continuous rates of glacier recession, this ice bridge will fall in the coming decades opening an isthmus between Hambergbukta and Hornsund (Grabiec et al., 2018; Kavan & Strzelecki, 2023; Strzelecki et al., 2020).

For our study we selected the westernmost land-based glacier of Sørkapp Land—Gåsbreen, reaching a length of over 7 km (including the firn field). Surrounded by the high mountain ranges of southern Spitsbergen, it is fed from the northeast by the Bastionbreen and Garwoodbren tributary glaciers resting on the slopes of the Hornsundtind massif (1431 m a.s.l.). Its accumulation zone reaches a height of over 800 m a.s.l. extending partially on the slopes of the Mehesten massif, and glacial snout flows latitudinally from east to west, squeezing between the Silesiafjellet and Nordfallet massifs in the north and Midifjellet in the south (Figure 1).

The bedrock of the area is built of several geological formations. In the eastern and central parts, the metamorphic series of the Heckla Hoek Formation with mica schists, quartzites, limestones, and dolomites of the older Paleozoic dominate. Whereas, in the western part of the area, the finer material of Proterozoic rocks from the Wurmbrandegga and Kovalavskajafjellet mountain ranges (green shales, phyllites, and gray phyllite limestones) prevails (Dallmann, 2014; Szupryczyński, 1963).

3 | MATERIALS AND METHODS

The basis for the spatial analyzes and delimitation of glacial landforms consisted primarily of remote sensing data (aerial photos captured during the photogrammetric overflights commissioned by the Norwegian Polar Institute, Norsk Polarinstitutt, hereinafter referred to as NPI, satellite images, and digital elevation models (DEM) supplemented by topographic maps and pictures from fieldwork campaigns and literature review of archival maps, field reports, and academic papers.

3.1 | Archival data

The first scientific observations of the Gåsbreen glacier and its surroundings were carried out by the Russian expedition wintering on Spitsbergen in 1899/1900. During the expedition, Lake Goësvatnet and the frontal moraines of the Gåsbreen glacier were described and presented on a map at a scale of 1:50,000 (De Geer, 1923). Nearly four decades later, in 1938, during a German expedition operating in

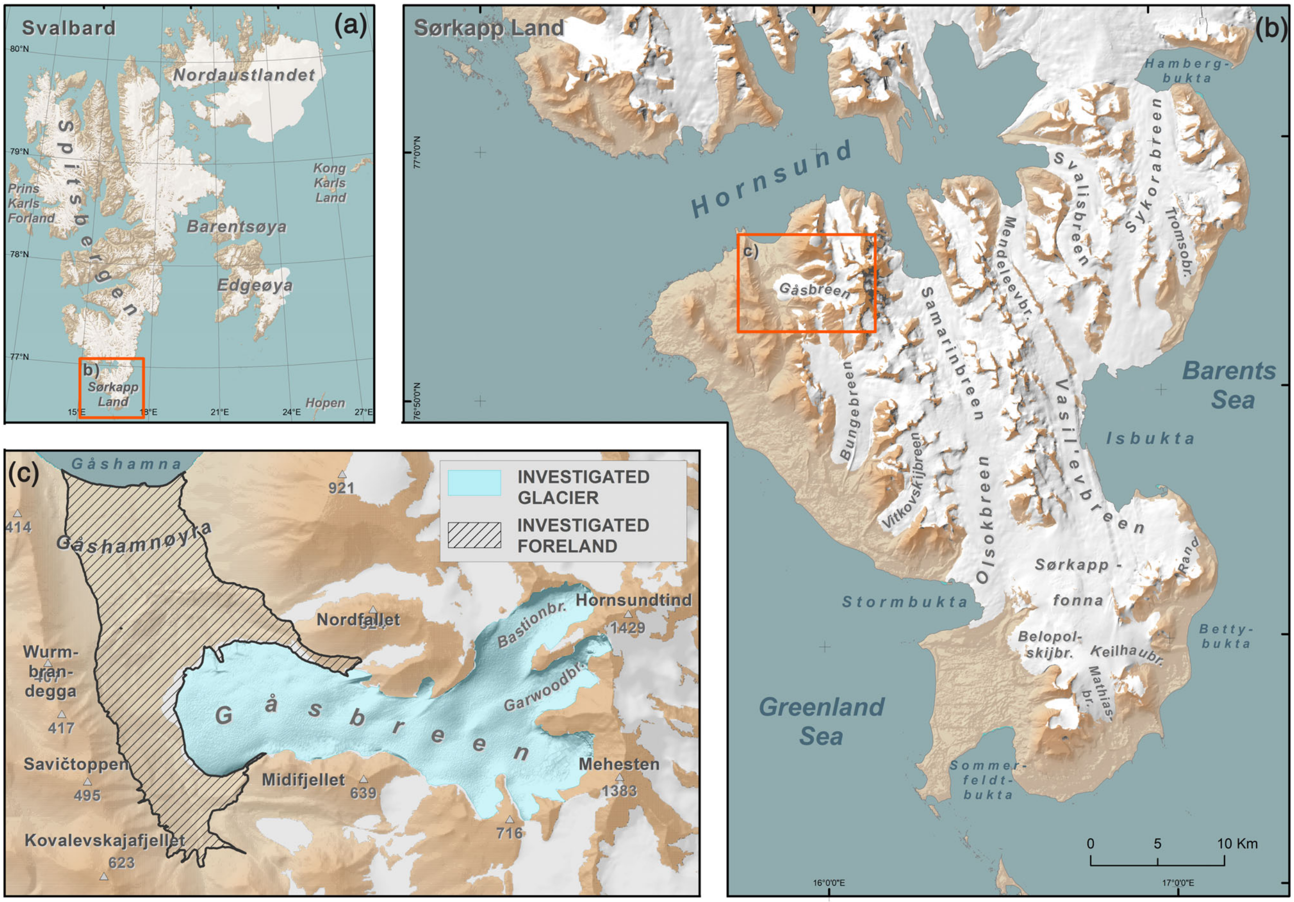

FIGURE 1 Study area location on the background of: (a) the Svalbard archipelago, (b) the Sørkapp Land peninsula, and (c) its vicinity in north-western part of the Sørkapp Land peninsula. [Colour figure can be viewed at wileyonlinelibrary.com]

the same area headed by H. Rieche, another detailed map of the glacier was made at the scale of 1:25,000 (Pillewizer, 1939). One of the aims of the expedition was to investigate the movement of the Gåsbreen glacier, which was measured in several transverse profiles using the method of repeated terrophotogrammetric images (time parallax) (J. Jania, 1988; Pillewizer, 1939). Moreover, the Germans made a bathymetric plan of Lake Goësvatnet, establishing its depth at the glacier cliff at 59 m and stated that it is an ice-dammed lake from which the water outflow periodically onto the outwash plain of the glacier (Rieche, 1970).

Research activities in the foreland of the Gåsbreen continued in 1959 when two members of the Polish Expedition to Spitsbergen conducted research in the western and northern parts of the area. J. Szupryczyński detailed the relief of the Gåsbreen marginal zone, focusing his observations on the forms associated with the direct accumulation of the glacier and its meltwater (Szupryczyński, 1960). In the same season, S. Jewtuchowicz conducted studies of the forms of fluvioglacial accumulation—sanders, kames, and eskers (Jewtuchowicz, 1962; Jewtuchowicz, 1965; Szupryczyński, 1965). After this first season, fruitful for Polish polar explorers, there was a break of several years in research on the peninsula.

The restoration of the Polish Polar Station in 1978, constituting the main scientific base in the south of Spitsbergen, favored the resumption of scientific expeditions to Sørkapp Land, where at the turn of the 1970s and 1980s Polish scientists carried out glaciological observations and photogrammetric measurements. The aftermath of this research is a number of publications concerning Goësvatnet dynamics (Grześ & Banach, 1984), the slope forms and processes of the Gåsdalen area (J. Jania, 1979; J. Jania, 1982; J. A. Jania et al., 1981), the morphology and dynamics of glaciers of western Sørkapp Land, including changes in the extent of the Gåsbreen glacier (J. Jania, 1988; Ziaja, 1999), as well as maps of the surrounding mountain ranges (Kolondra, 1979; Kolondra, 1980). Some of these works were part of a wider research program aimed at the implementation of a synthetic cartographic study of the surroundings of the Hornsund fjord—a geomorphological map (J. A. Jania & Szczypek, 1987) and a topographic map at a scale of 1:25,000—which covered the Gåsbreen glacier along with its foreland (Barna & Warchoł, 1987).

Apart from the research of Polish and German photogrammeters, Austrian scientists conducted photogrammetric measurements in the summer season of 1991 in the foreland of the Gåsbreen glacier. The research goal of the two-person team was to repeat a series of photos taken by W. Pillewizer and on this basis to generate a digital elevation model (DEM) enabling the analysis of glacier geometry changes (M. Schöner & Schöner, 1996; W. Schöner & Schöner, 1997).

The last documented scientific observations in the foreland of the Gåsbreen glacier were conducted by the Jagiellonian University expeditions in the summer seasons of 2000, 2005, and 2008 (Ziaja et al., 2011; Ziaja et al., 2016; Ziaja & Ostafin, 2007; Ziaja & Skiba, 2002).

3.2 | Image data

The image data used in the study show the changes taking place in the glacier foreland since the 1930s. The data for the 1930s constituted oblique photos from the first photogrammetric overflight on Svalbard by the NPI in 1936 (Luncke, 1936) complemented by the photo from the terrestrial photogrammetric campaign carried out in 1938 by the Germans (Pillewizer, 1939). The data for the 1960s and 1990s collected at a scale of 1:50,000 during the photogrammetric overflights commissioned by the NPI included scans of three panchromatic vertical aerial photos, one acquired in the summer of 1960 and two from August 24 and 25 of 1961, together with two scenes acquired on July 31 of 1990 registered on a colored material sensitized to near-infrared. From the last photogrammetric campaign carried out by the NPI in 2010, 7 scenes with a resolution of 0.4 m taken on August 17 with the multispectral digital camera were used.

For observations of Goësvatnet fluctuations, a series of low-resolution (30 m and 60 m) data from Landsat MSS, TM, and ETM+ were implemented. In addition, high-resolution satellite images acquired in summer of the 2013 by WorldView-2 Satellite Sensor and accessed through the software Google Earth Pro were interpreted in the study (Porter et al., 2018). The most recent image data consisted of six multispectral images at a resolution of 3 m acquired in the summer of 2020 by SkySat satellites launched by Planet Labs PBC (2020).

3.3 | Maps

A map for 1938 was produced at a scale of 1:25,000 based on terrestrial photogrammetric measurements carried out by W. Pillewizer during a German summer expedition (Pillewizer, 1939). The map was co-registered using a map grid at a 2 km interval. Subsequently, its coordinates were transformed to ETRS-89 datum in UTM projection (Zone 33X) based on a trigonometric network and the position of the mountain tops (Ziaja et al., 2016). Watercourses, water bodies, glacier boundaries, and contour lines of a 20 m vertical interval were digitized and used throughout the study.

A map representing the years 1960/1961 used in this study consisted of one sheet (08-Gåsbreen) at a scale of 1:25,000 made in a UTM projection based on a European Datum 1950 (ED50) ellipsoid published by the Polish Academy of Sciences (Polska Akademia Nauk, hereinafter referred to as PAS) (Barna & Warchoł, 1987). The processing of the map consisted of several stages. After initial rectification based on the nodes of the cartographic grid, the map coordinate system was converted, adopting the UTM projection (northern hemisphere, zone 33) in the ETRS-89 reference system. Thematic layers of the map—contours, elevation points, rivers, and lakes—were digitized, and subsequently, after finding their shifts in relation to the data from 2010, they were registered based on triangulation and topographic points. This allowed for cartographic compilation and integration of vector layers from the 1960s with data from other years (Dudek & Pętlicki, 2021).

The topographic map at a scale of 1:100,000 for 1990 and 2010 was developed and made available by NPI in the form of vector layers, in the ESRI shapefile format. In the study, we used layers presenting the general image of the area's surface: relief, permanent watercourses, water bodies, and elevation points. Glacier boundary for 1990 was established based on a field campaign and published by M. Schöner and Schöner (1996). The glacier boundary for 2010 was established based on aerial photos and digital elevation models.

3.4 | Digital elevation models

The DEM for the 1960s was constructed from shapefiles derived from the map edited by the PAS (Barna & Warchoł, 1987). Elevation points, streams, and contour lines at a 10 m vertical interval were converted to a 5 m $\times$ 5 m regular grid. Created DEM was validated against the pre-existing 2010 elevation dataset of the NPI which was used as a reference dataset throughout the study (NPI, 2014). The average elevation difference between the 1990 and 1960 DEMs on ice-free areas with slopes inclined less than 20° was 2.28 m with a standard deviation of 3.18 m (Dudek & Pętlicki, 2021).

For the years 1990 and 2010, digital elevation models with a resolution of 20 m and 5 m respectively, made available by the NPI, were used. DEMs were generated using photogrammetric methods based on stereopairs correlation. The vertical accuracy of the DEMs given by the author was 2–5 meters in non-glacial areas and slightly less for glacier surfaces (NPI 2014).

The most recent elevation data used in the study was from July and August of 2020 and consisted of three stripes of ArcticDEM at a resolution of 2 m covering Gåsbreen and its vicinity.

3.5 | Geomorphological mapping

In order to quantify changes in proglacial areas a geomorphological mapping was carried out based on orthoimages, maps, DEMs, and observations from the field following previous mapping campaigns carried out on Svalbard glacier forelands (e. g. Allaart et al., 2018; Allaart et al., 2021; Aradóttir et al., 2019, Eckerstorfer et al., 2015; Evans et al., 2012; M. W. Ewertowski et al., 2016; Farnsworth et al., 2016, 2017; Rubensdotter et al., 2015). The following three groups of depositional and erosional forms with respect to their origin were delimited in the proglacial zone of the glacier:

TABLE 1 Changes in Gåsbreen surface area and length over the period from 1938 to 2020.

Year	1938	1960	1990	2010	2013	2020
Gåsbreen area [km^2]	14.7	13.9	12.6	11.3	11.2	10.9
Gåsbreen length [m]	7645	7615	7300	6565	6490	6340
Research period	**1938–1960**	**1960–1990**	**1990–2010**	**2010–2013**	**2013–2020**	**1938–2020**
Glacier area change [km^2 (%)]	−0.8 (−5.3)	−1.3 (−9.4)	−1.3 (−10.1)	−0.1 (−1.2)	−0.4 (−3.9)	−3.8 (−26.0)
Glacier area change rate per year [km^2 (%)]	−0.04 (−0.2)	−0.04 (−0.3)	−0.06 (−0.5)	−0.05 (−0.4)	−0.06 (−0.6)	−0.05 (−0.3)
Glacier frontal retreat [m, (m/year)]	−30 (−1.4)	−315 (−10.5)	−735 (−37)	−75 (−25)	−150 (−21)	−1305 (−16)

- Forms and sediments of glacial provenience (i.e., terminal moraines frontal and lateral, hummocky moraines, ground moraines, crevasse fillings).
- Forms and sediments of glaciofluvial provenience (i.e., sandurs, eskers, kames, meltwater channels, alluvial fans)
- Slope deposits and forms (i.e., debris flows, proluviums, colluvial fans, gullies).

Geomorphological maps were created for the years 1936, 1961, 1990, 2010, and 2020. This allowed to determine the rates of proglacial and ice-marginal terrain change following deglaciation.

4 | RESULTS

4.1 | Glacier retreat

During the 82 years of the study, Gåsbreen was in recession, as reflected in a decrease in its extent by 27%, from 14.7 km^2 in 1938 to 10.9 km^2 in 2020 (Table 1). In 1938 glacier snout was piling up on the eastern slope of the Wurmbrandegga–Savičtoppen mountain ridge. Glacier was flowing down northwards, reaching below 100 m a.s.l on the Gåshamnøyra lowland. From 1938 to 1990 the area of Gåsbreen decreased by a total of 2.1 km^2, primarily due to the narrowing and thinning of its terminus (Figure 2). During that period, a significant decrease in thickness occurred in the lower parts of the glacier tongue, reaching up to 30–50 m at the glacier's front before 1960, and in the following period, up to 20–85 m, whereas outside the frontal and lateral parts, above 400 m a.s.l., a thickening of the glacier was observed (Figure 3). In the beginning of the study, the mean frontal retreat of the glacier was slow, reaching only 1.4 m per year between 1938 and 1960 and accelerating to 10.5 m per year after 1960. Throughout that first period, the glacier was functioning as the natural dam for the Goësvatnet.

After 1990 recession of Gåsbreen continued to progress, which was accompanied by a significant change in the course of this process, with significant shortening of the glacial tongue and less intense lowering of its surface than in the previous period (Figures 2 and 3). Between 1990 and 2010 frontal retreat rate accelerated almost four times, reaching as much as 37 m per year, while the rate of glacier area reduction almost doubled, amounting to 0.5% per year, compared to an annual retreat rate of 0.2%–0.3% from the previous period. The greatest decrease in glacier thickness, up to 59 m, was at the glacier's front. Significant frontal retreat and thinning of the glacier led to the disappearance of the ice dam which occurred around 2002–2004 (Ziaja et al., 2016). In 2010, there was still a patch of dead ice lying near the glacier front—a remnant of the former ice dam—which melted away in the next decade.

In the following period, 2010–2020, the pace of glacier area loss remained significant, with an annual rate of 0.4%–0.6%. Frontal retreat rate on the other hand slightly slowed down reaching 20–25 m per year (Table 1).

4.2 | Landscape changes

4.2.1 | Proglacial landform changes, 1938–2020

The evolution of Gåsbreen's proglacial zone was determined to some extent by the arrangement of the surrounding mountain ridges. The glacier fills a side valley that descends westwards into much larger Gåsdalen, oriented longitudinally and bordered on the west by the high Wurmbrandegga-Savičtoppen range. The existence of this significant orographic barrier on the path of Gåsbreen transgressing during the Little Ice Age forced a change in the general direction of its flow to the northwest and the build-up of its end moraines on the Gåshamnøyra lowland. At the beginning of the 20th century, the glacier terminus rested on the mountain slopes, and its lower part was spreading sideways in the main valley and constituting a natural ice dam.

The development of marginal zones of Gåsbreen and adjacent smaller glaciers began with their retreat as a result of climate warming in the 20th century. Initially, they consisted of single ice-cored moraines in front of glaciers termini. As the glaciers' fronts retreated, its forelands developed covering an increasingly larger area, and transformed into complexes of various landforms. In the period 1938–2020, the area of Gåsbreen's foreland increased from 2.2 km^2 to 5.8 km^2 (Figure 4). Within its limits, both depositional and erosional landforms were created (Figures 5 and 6).

The formation of depositional landforms is most often associated with the disappearance of the lower parts of the glaciers, which is why they occur mainly at the fronts and around the glaciers' snouts. The most prominent depositional landforms in the foreland of

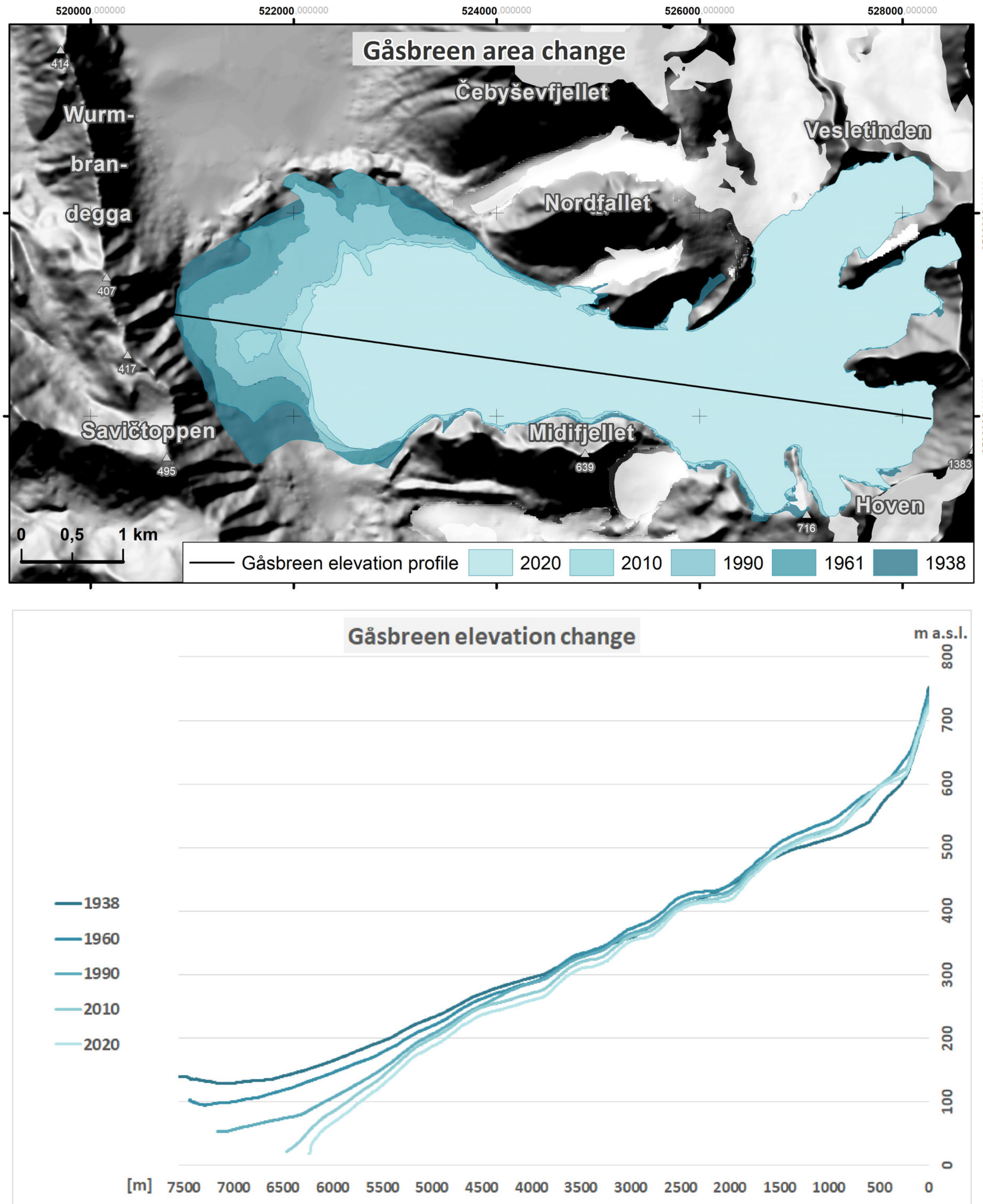

FIGURE 2 Gåsbreen geometry change: glacier area change from 1938 to 2020 (upper part); glacier elevation change along the profile (lower part). [Colour figure can be viewed at wileyonlinelibrary.com]

Gåsbreen are frontal and lateral moraines with an ice core that constitutes up to 90% of their volume (Hagen et al., 2003), and gradually degrades giving a varied morphology to their surface (Figures 5 and 7). The outer edges of end moraines usually mark the maximum extent of glaciers in the Little Ice Age or previous Neoglacial advances (Figure 8a; Farnsworth et al., 2020; Philipps et al., 2017).

At the beginning of the research period, in 1938, Gåsbreen's snout was flattened on the northern side and gently dipping toward the marginal zone framed by arcs of terminal moraines paralleling the glacier front (Figure 5a). Landforms building the outermost ice-cored moraine were arranged in several ridges, with the more prominent size of lateral moraines developed in the eastern part where their

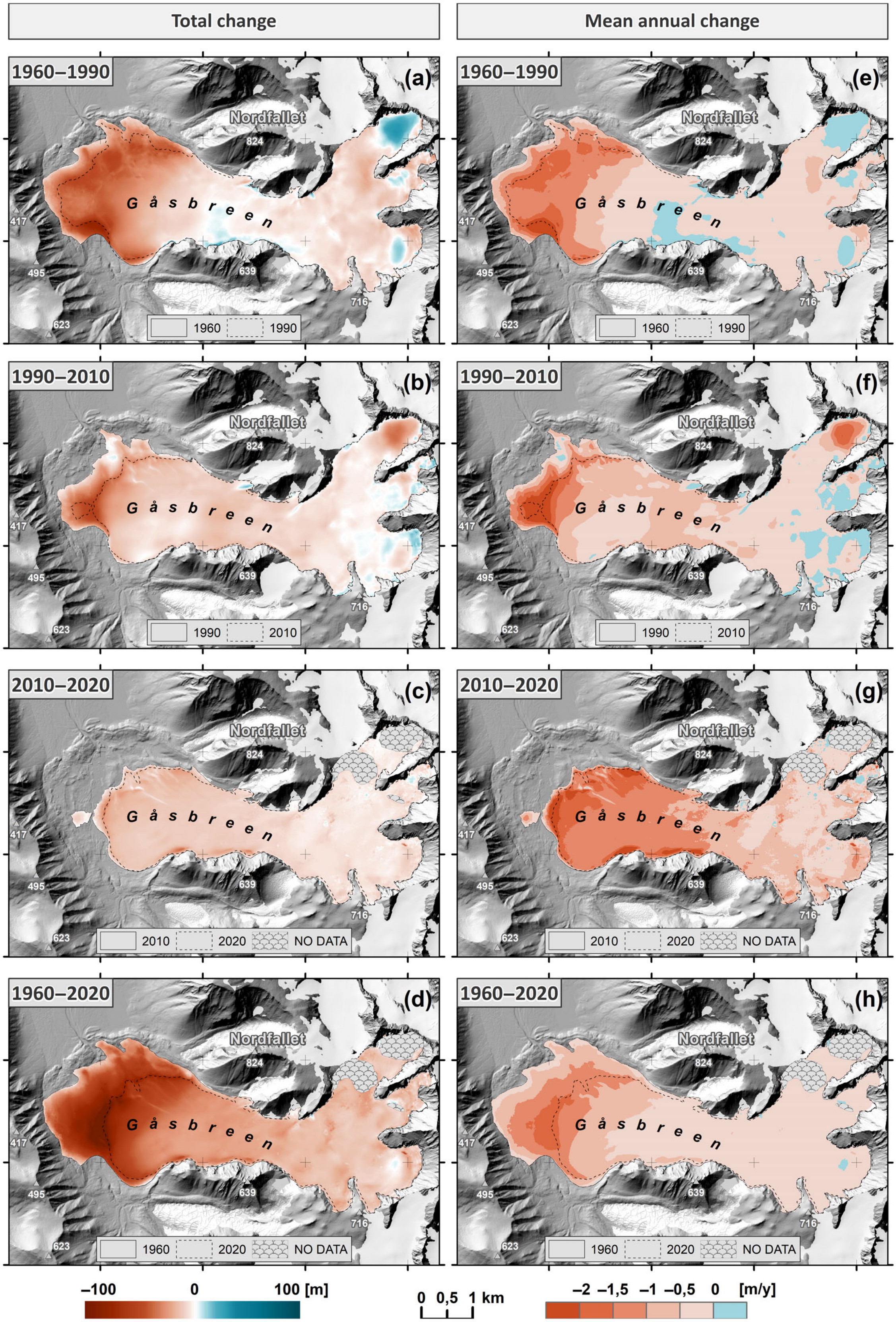

FIGURE 3 Gåsbreen geometry change: Glacier thickness change from 1960 to 2020. [Colour figure can be viewed at wileyonlinelibrary.com]

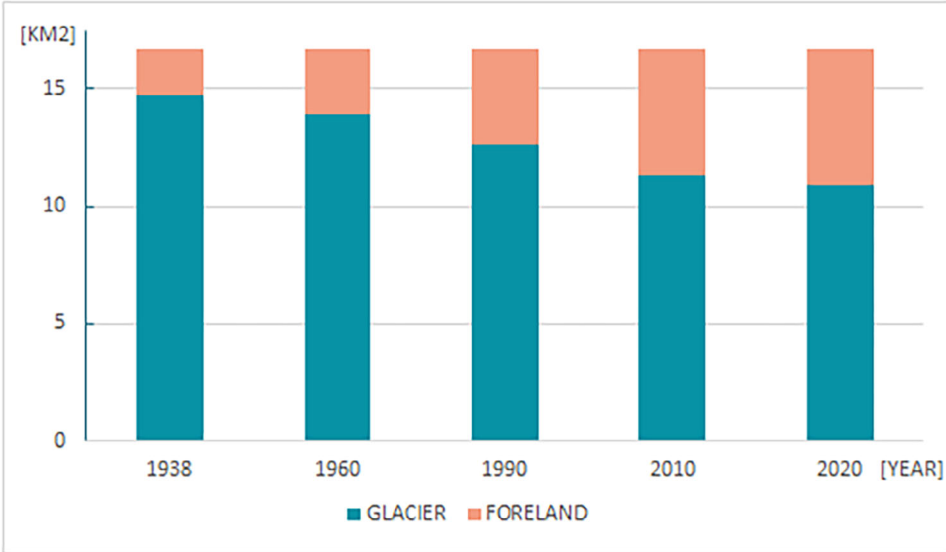

FIGURE 4 Area change of Gåsbreen and its foreland from 1938 to 2020. [Colour figure can be viewed at wileyonlinelibrary.com]

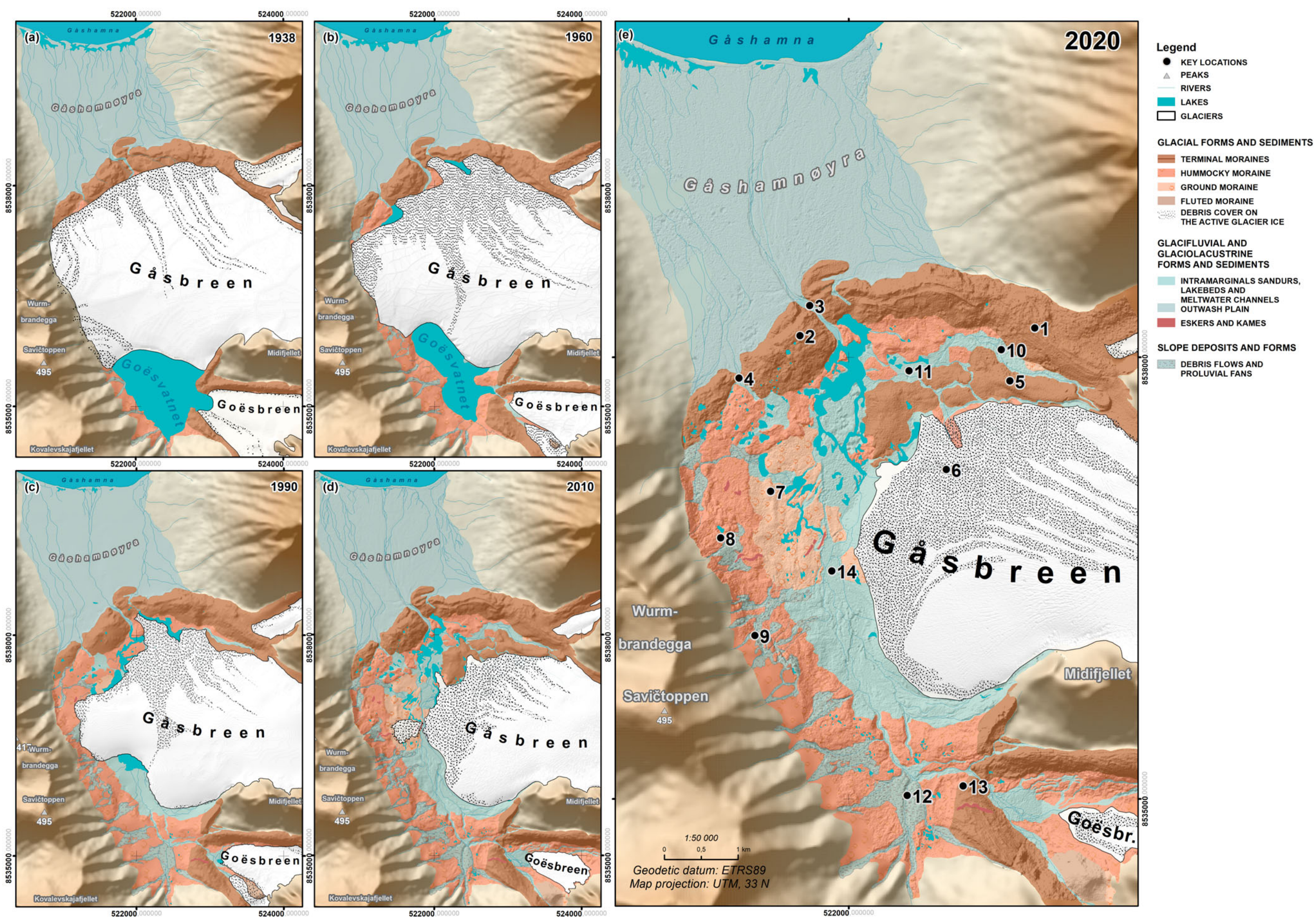

FIGURE 5 Landscape changes in the foreland of Gåsbreen from 1938 to 2020. [Colour figure can be viewed at wileyonlinelibrary.com]

relative height was up to 60 m (Figures 8a and 5e-1). Their surface systematically lowered in the following years, with an annual rate from 0.5 to 0.75 m per year before 2010 to 0.75–1 m per year in the following period (Figure 7). On the west, the relative height of end moraines was 30–40 m. In 1938 the width of the frontal moraine varied, reaching over 400 m in the widest part (Figure 5a,e-2). Central part of the moraine complex was cut by a proglacial river which formed a glaciofluvial fan at the elevation ca. 15 m a.s.l., deposited on

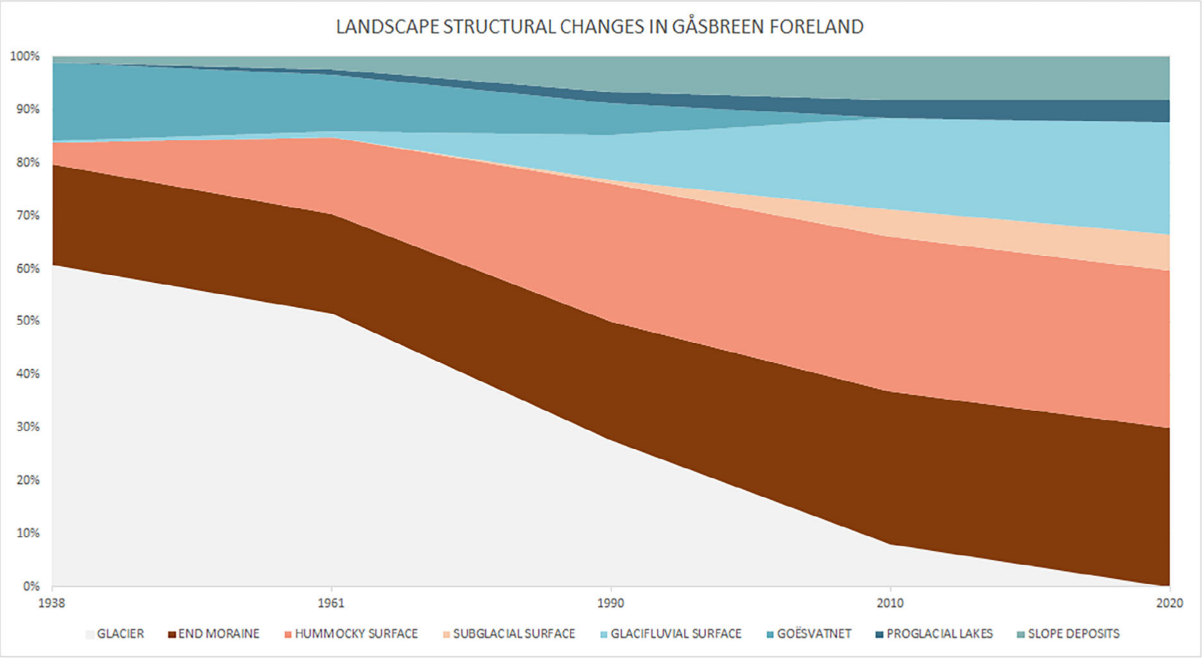

FIGURE 6 Changes of the landforms' area (in % within the boundaries of the foreland in 2020) in the foreland of Gåsbreen from 1938 to 2020. [Colour figure can be viewed at wileyonlinelibrary.com]

the ground with relict ice (Figure 5e-3). The second, 10 m higher sandur level, formed by the river, crossed a terminal moraine in its western part (Figure 5e-4).

In 1960, the Gåsbreen snout area was showing a gradual transition into the proglacial area in the eastern and central parts of the marginal zone. The front of the glacier in this section, resting close to the end moraine complex, was covered with a thick continuous layer of supraglacial debris. In the following years with further Gåsbreen's downwasting a part of the debris-covered snout started to transform into another ice-cored morainic ridge paralleling the glacier front on its northeastern side (Figure 5e-5). By the year 1990 formed ridge with a relative height of 20–25 m had a length of about 950 m and a width of 80–130 (Figure 5c). The deglaciation course in this area was uneven, and after 1990 some parts of the debris-covered glacier snout started to disintegrate into smaller patches of dead ice covered with a thick layer of debris. By 2010, the width of newly forming ice-cored morainic ridges had increased on the east by about 60 m (to 150–190 m). Westwards the width of newly formed ice-cored sediment ridges varied, from 130 m to about 300 m (Figure 5d). On the glacier snout still covered with debris, very distinct folds of the medial moraines and the folded lines of the Gåsbreen foliation are visible in aerial photos from 2010. This might indicate a short episode of accelerated glacier movement after 1990, which, however, did not end with a significant advance of its front (Figures 8b and 5e-6). In following years the width of developing morainic ridges increased by further 20–30 m to a year 2020, when they were finally separated from the glacier front by the glacier river bed.

In the western part of the foreland, between the outermost ridges of the ice-cored moraines and the glacier, a large area consists of hummocky topography or subglacial surfaces often covered with ablation till, forming plains of undulating surface (ground moraine) (Figure 5e-7). Further to the south, at the foot of the Wurmbrandegga range, the down wasting of the glacier and the melting of relict dead ice led to the formation of a very diverse, hummocky terrain after 1960 (Figure 5e-8). Crevasse fillings of supraglacial, englacial, or subglacial origin are characteristic of this area (e.g., Evans et al., 2022). In this section of the proglacial zone glacial landforms and sediments are being slowly replaced by fluvial and slope-waste products (Figure 5e-9). The areas of depositional landforms are often cut by the beds of proglacial rivers and subglacial tunnels. In addition to the meltwater channels, newly formed erosional forms predominate on steep rock slopes and on the sides of the valleys freed from glacier ice. Some of them are partly covered with moraine or fluvioglacial material, especially at the foot of the slopes and in the lower parts of valleys, and usually after exposure they are subject to erosion processes not related to the direct activity of glaciers (Figure 5c–e).

In the eastern part of the foreland, in the period of 1961–1990, the area between the highest end moraine system and the newly emerging morainic ridge was cut and transformed by fluvioglacial waters flowing from the glacier to the system of proglacial lakes, and further through the central gorge, reaching the extra-marginal sandur and the Hornsund fjord (Figure 5c,d,e-10). After 1990, when the largest proglacial lake in this part of the foreland disappeared, the meandering proglacial rivers undercut and partially washed away both ridges of icecored moraines. As a result, the proximal slopes of the highest end moraine were lowered in places by as much as 20 m, and the northernmost part of the newly formed morainic ridges was transformed into an intramarginal sandur cone and proglacial river beds (Figure 5d,e-11).

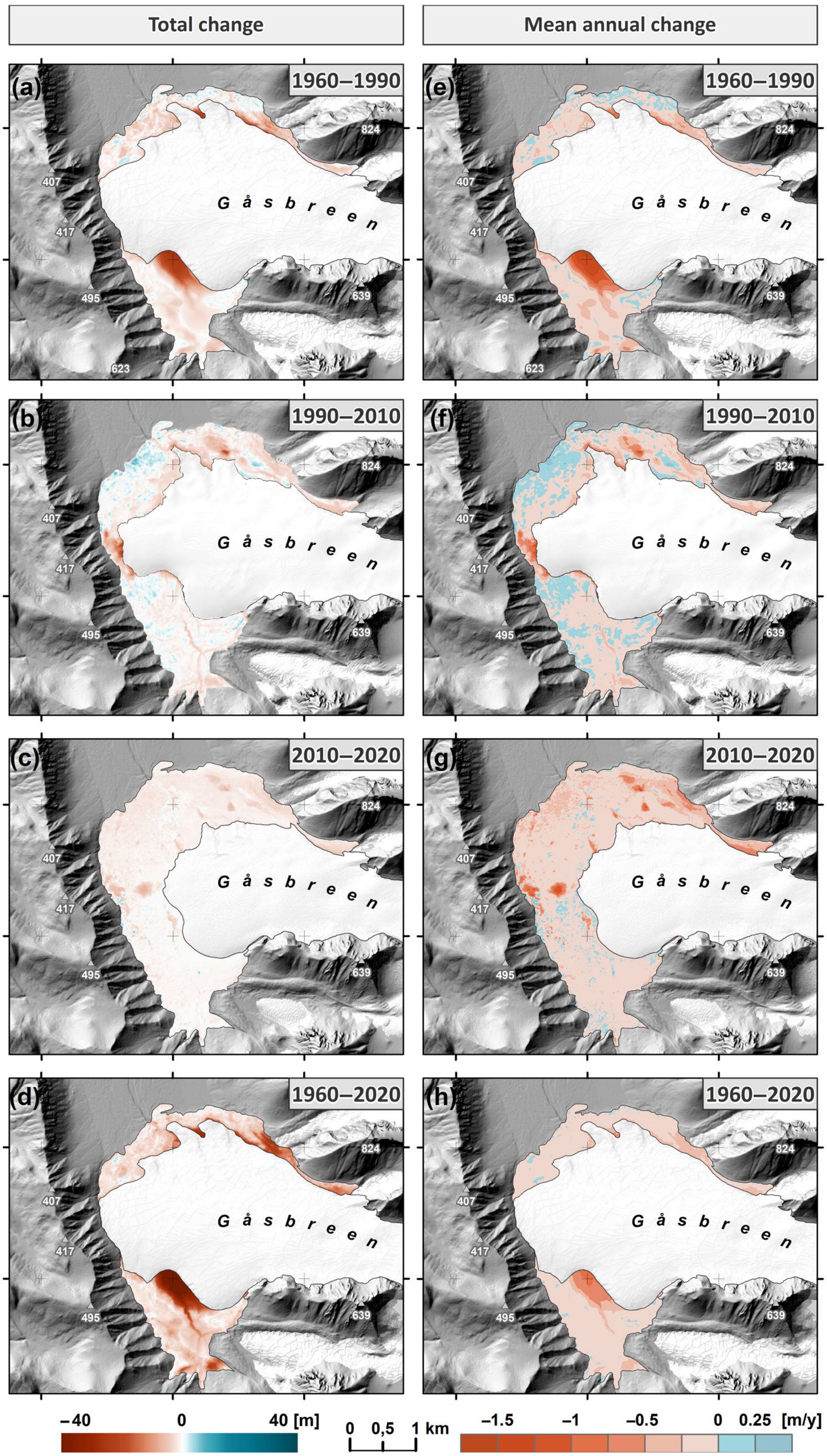

FIGURE 7 Elevation changes in the foreland of Gåsbreen from 1960 to 2020. [Colour figure can be viewed at wileyonlinelibrary.com]

In the southern part of the foreland at the beginning of the research period, Gåsbreen and two adjacent glaciers Goësbreen and Portbreen descended to the Goësvatnet dammed lake with a steep ice cliff (Figure 5a). Since the end of the Little Ice Age, the lake collected the waters of the proglacial rivers of these two glaciers flowing from the east. From the south and west, the lake was periodically fed

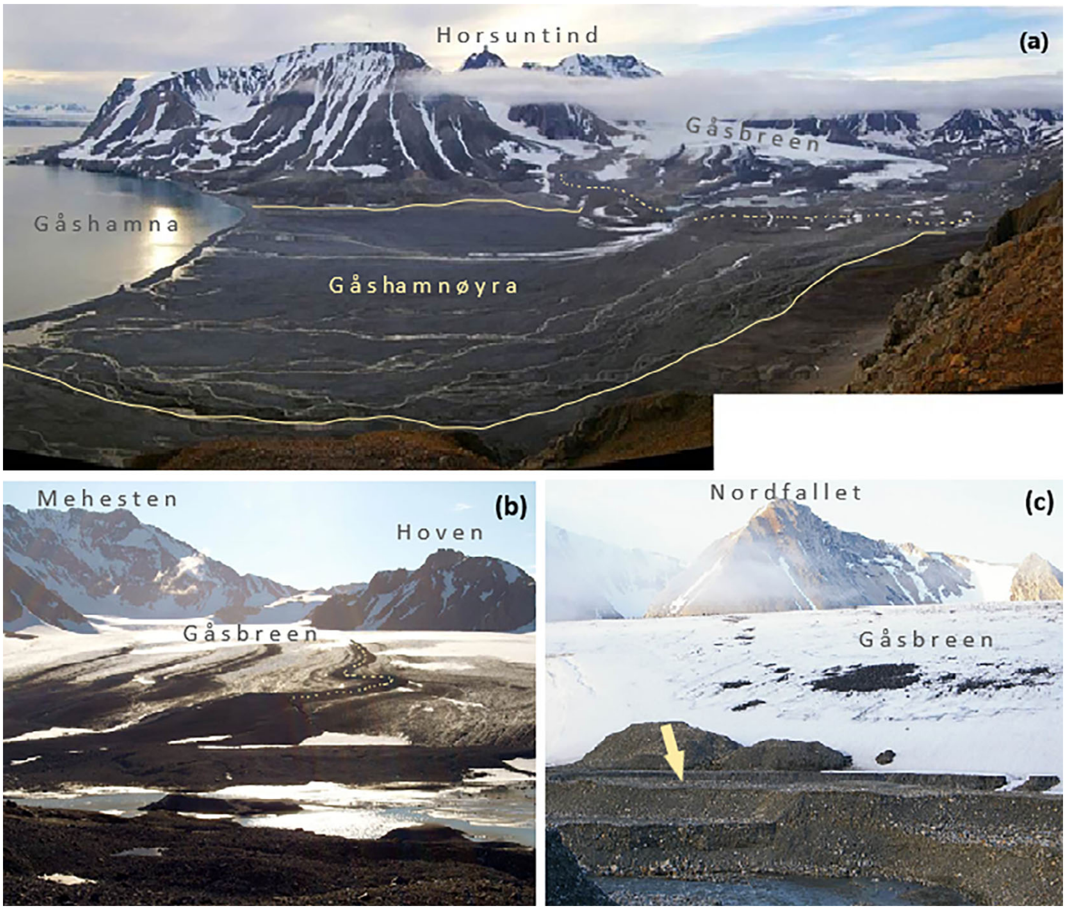

FIGURE 8 (a) Extramarginal outwash plain (in the foreground framed with yellow lines) of Gåsbreen and glaciers' foreland (in the background marked with yellow dotted lines) with ice-cored moraines marking glacier extent at the end of LIA (photo taken in summer season of 2008); (b) Folded medial moraines of Gåsbreen in 2008 (marked with yellow dotted line; photoot. M. Węgrzyn), and (c) A fragment of a terraced river valley in the summer of 2008 formed at the bottom of the Goësvatnet dam lake after its disappearance (indicated by yellow arrow). [Colour figure can be viewed at wileyonlinelibrary.com]

by pronival waters flowing from the slopes of the Kovalevskajafjellet and Savičtoppen massifs. The weathered material carried by these streams was deposited at the foot of the slopes in the form of cones and pronival covers (Figure 5e-12) which lie on tills deposited on the slopes during the Little Ice Age when the extents of Gåsbreen, Goësbreen, and Portbreen were much greater and glaciers joined together (De Geer, 1923; Pillewizer, 1939). In the 1930s lake had a larger area and a different shape than at the end of the 19th century. In the 1960s Goësvatnet was separated from Goësbreen and Portbreen by wide ridges of their frontal and lateral moraines and the area occupied by the lake decreased significantly compared to 1938 (Figure 5e-13).

The decrease in the thickness of the lowest part of Gåsbreen (which was the natural Goësvatnet dam) in the following years influenced the lowering of the lake's water table and its shift toward the north. In the years 1979–1980, the maximum water level in the lake reached 87 m above sea level (Grześ & Banach, 1984). Lake Goësvatnet was observed in the field for the last time in the summer of 2000. By 2005, the subglacial tunnel had been destroyed and then transformed into a narrow valley, cut in the glacier ice, separating the glacier front from the dead ice patch in its foreland (Figure 5d,e-14; Ziaja & Ostafin, 2007). In the following years the valley was transformed and modeled by fluvial processes (Figure 8c).

Higher volume of glacio-fluvial waters has intensified transport and accumulation of sediments in proglacial zone, leading to an increase in the surface area of outwash plain and changes of the coastline. Image data for the years 1990–1961 and 2020 shows in places a change of the position of the coastline up to 20 m toward the fjord.

4.2.2 | Evolution of the drainage network and proglacial lakes, 1938–2020

Since 1899, when a relatively systematic study of the Gåsbreen proglacial area started, more than a dozen glacier lake outburst floods have been documented for Goësvatnet, which, until 1938, was the only lake in the foreland of Gåsbreen (Grześ & Banach, 1984; W. Schöner & Schöner, 1997). The occurrence of the lake and its outburst floods was directly related to changes in the area and extent of Gåsbreen, Goësbreen and Portbreen. The first of these glaciers, and

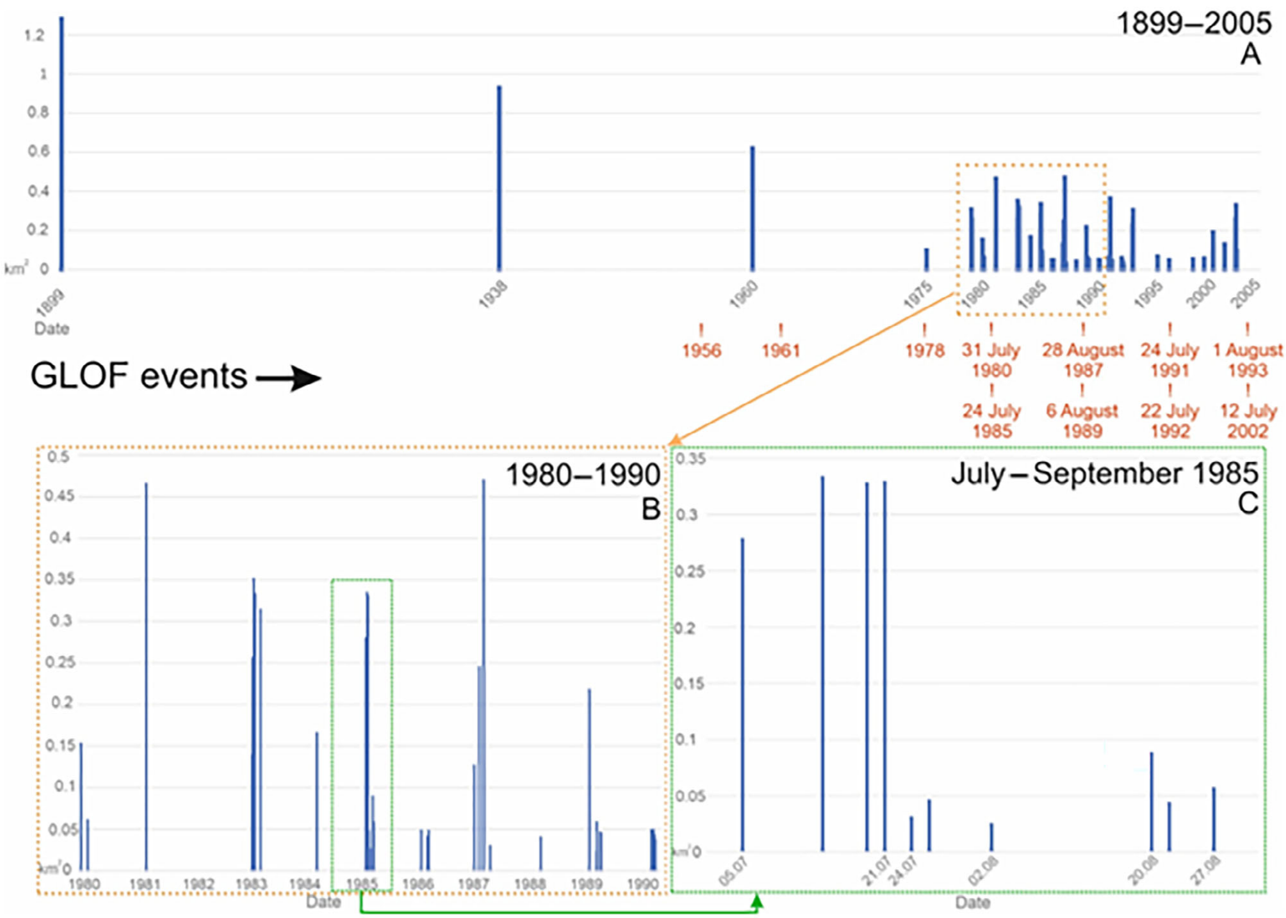

FIGURE 9 Recorded GLOF events of Goësvatnet since the beginning of 20th Century. [Colour figure can be viewed at wileyonlinelibrary.com]

the largest, was the main dam for the described lake, at the same time classifying it as an ice-blocked lake, and successively (subclass) as an advancing glacier blocked lake (Yao et al., 2018). The next two glaciers as mentioned before were the main source of water for Goësvatnet.

Based on our analysis based on de Geer's (1923) map of the Gåsbreen proglacial zone, the largest documented extent, Goësvatnet was 1.2 km^2 in 1899 (W. Schöner & Schöner, 1997). Since then (as systematically depicted in Figure 5), the lake has decreased in area, evolving with the retreating Gåsbreen, so that it did not refill its lake basin in 2004 due to a destroyed subglacial channel.

By analyzing the lake's extent on specific dates, it was possible to follow the trends associated with the evolution of Goësvatnet, which was characterized by a dynamic, seasonal variation in area. At the beginning of the summer season (i.e., June), the lake basin was freed from under the ice and gradually accumulated water from melting glaciers as well as from the surrounding peaks. It reached its maximum extent in a given year systematically at the turn of July and August (Figures 9 and 10). The years, for which we obtained a systematic range of data showing landscape changes over the whole summer season (with intervals of several days or more), indicate annual drainages of the lake just after reaching its maximum for a given season. These runoffs, due to the amount of accumulated water and their duration, had the character of glacial lake outburst flooding (GLOF). After each runoff, the lake did not refill again for the season.

The first and biggest documented runoff occurred between 1938 and 1956 and reduced the lake by 0.93 km^2, 0.35 km^3 (Table 2). Further runoff occurred in 1961 and 1978. Since the 1970s, the accuracy of the analysis of glacial lake changes has been narrowed to specific days through the use of satellite data. Thus, it has been possible to document eight GLOFs consecutively (Figure 9). While the drainage of the lake in the 20th century was by means of a subglacial tunnel, under Gåsbreen, in the 21st century the tunnel was destroyed and the last drainage of the lake took place through a channel separating the Gåsbreen tongue from the dead ice, leading to the eventual disappearance of Goësvatnet (Ziaja & Ostafin, 2007).

The Goësvatnet runoff contributed to the modeling of the proglacial zone by creating new depressions, later used by the end-moraine dammed lakes, as well as shifting the course of the proglacial river channel, which, as a result of these sudden runoffs, had the character of an anastomosing river (Rosgen, 1994).

In 1938 surface area of Goësvatnet was approximately 0.93 km^2 (Figures 5 and 11). In the 1960s, with the recession of Gåsbreen, end-moraine dammed lakes were created with a total area of 0.06 km^2, which together with the developed Goësvatnet (0.62 km^2) totaled

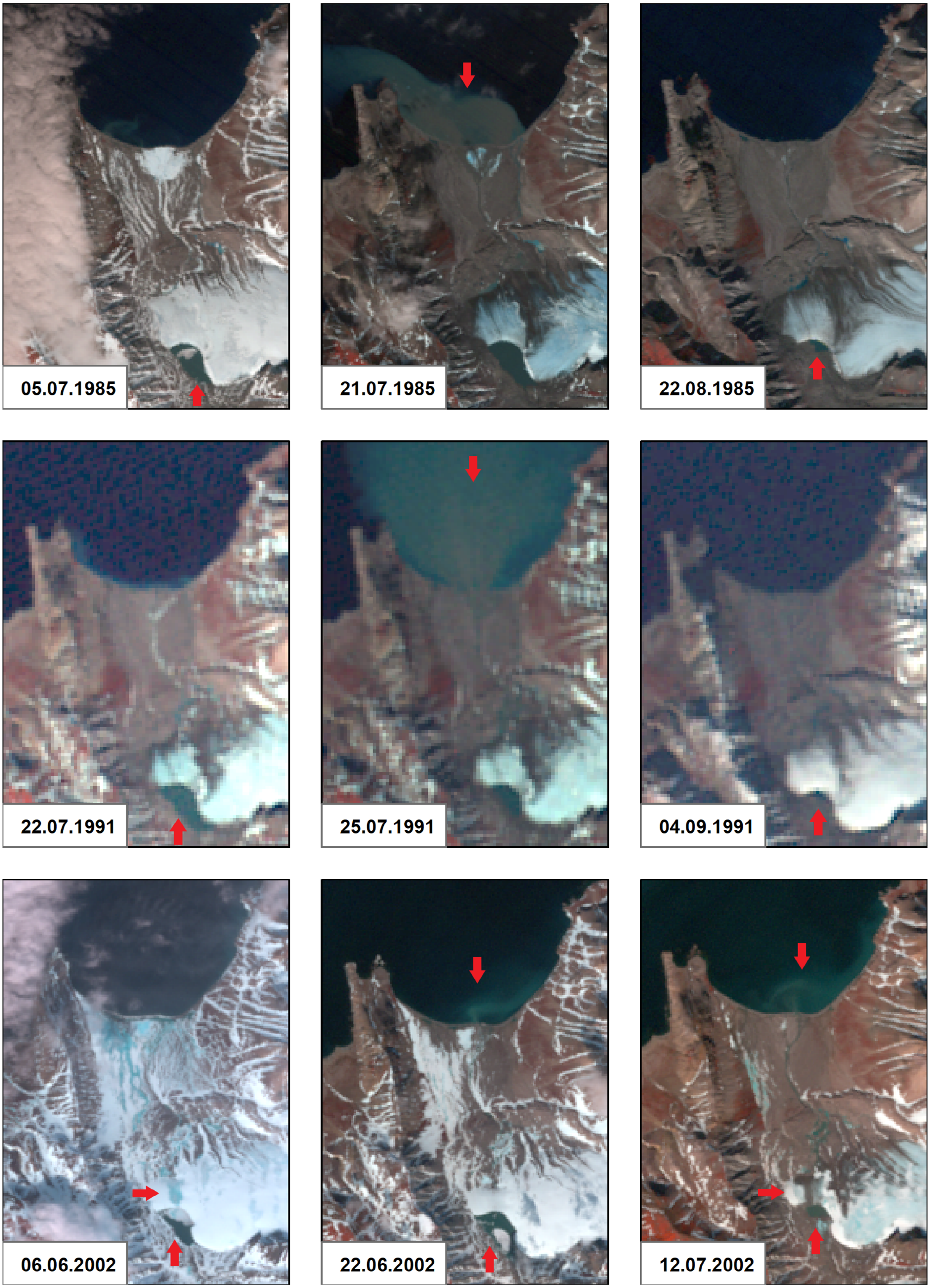

FIGURE 10 Seasonal variation in area of Goësvatnet. On the left images show the state of the lake before runoff (in the bottom left image red arrow indicates a subglacial tunnel in the last summer when the lake was observed), and in the middle column a lake discharge and turbidity plum in the fjord can be observed, on the right images present the state of the lake and the fjord after runoff. [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Changes of Goësvatnet 1938–2002.

Year	1938	1961	1990 (before GLOF)	1990 (after GLOF)	2002
Goësvatnet area [km^2]	0.93	0.62	0.37	0.05	0.36
Goësvatnet estimated water volume [m^3]	35,633,935	12,059,328	7,888,621	497,229	7,129,815
Goësvatnet water volume as Olympic swimming pools	10.18	3.45	2.25	0.14	2.04

about 0.7 km^2 of water bodies, an increase of more than 0.3 km^2 compared to the 1930s (Figure 5). In the 1990s, the impact of the GLOF phenomenon is noticeable, which caused the total area of lakes to decrease to 0.2 km^2, this runoff simultaneously initiated the formation of lakes in the proglacial zone of Gåsbreen, causing the proglacial zone to hold the most water bodies from then on (Figure 5). Another noticeable increase in lakes can be observed in 2013, when the end-moraine dammed lake more than doubled compared to 2010 (from 0.1 to 0.2 km^2), only to drain by more than 100% of its area (0.09 km^2) in the following years (Figure 5). Taking into account all the lakes in the proglacial zone of the analyzed glacier, between 1899 and 2020 we can indicate a recession of the total area from 1.24 to 0.17 km^2 (Figure 5). However, when excluding Lake Goës from this analysis, there is a gradual increase in lake area, which amounts to 0.17 km^2 and began in the 1960s (Figure 5).

Changes in the river network in the Gåsbreen foreland are directly related to changes in lakes and the extent of glaciers. A comparative analysis showed that the Gåsbreen foreland and outwash plain had a total length of rivers 23.6 km in 1938, 23.7 km in 1961, 23.4 km in 1990, 46.1 km in 2010, 52.9 km in 2013, and 42.7 in 2020 (Figure 11). This shows that over the five decades the river network in the Gåsbreen foreland has increased by about 19 km. However, it should be noted that for the year 2020 we do not have as high-resolution data as for previous periods, which makes this result subject to a certain margin of error. So, if we assume that 2013 is the year with better resolution scenes, and is more authoritative in terms of river network changes since the 1930s, the increase is ca. 29 km.

Since the 1930s, the density of watercourses in the study area has also changed (Figure 11). In 1938 and 1961, the highest concentration of rivers was at the mouth of the bay and between the head of Gåsbreen and the moraine dike (Figure 5a). In 1990, the density of watercourses changed markedly—with a significant reduction in the area of Goësvatnet—with most watercourses located in the proglacial zone and in the area that was once occupied by the aforementioned lake (Figure 5b). In 2010, where Gåsbreen is significantly regressing from previous decades, the highest density of watercourses is in front of the moraine in the area where the former subglacial tunnel that drained Goësvatnet had its outlet and in the area that was once occupied by the lake (Figure 5c). A similar trend (up to 2010) of river course densities continued until 2020 (Figure 11).

5 | DISCUSSION

The warming of the Arctic climate entails changes in the glacial systems which are being translated into the dynamics of the entire polar environment. The course of the Gåsbreen recession was different than other land terminating glaciers of western Spitsbergen. Due to its specific terrain settings and the existence of a mountain barrier limiting the advance of the glacier and causing its pilling up on the slopes, Gåsbreen's frontal retreat rate before the 1990s, was relatively small in comparison with glaciers situated on the Wedel-Jarlsberg Land (Janina et al., 1984; Reder, 1996; Rodzik et al., 2013), in the central part of Spitsbergen (M. W. Ewertowski et al., 2019; Holmlund, 2021; Kavan, 2020; Małecki, 2016; Rachlewicz et al., 2007), in Kaffiøyra (Sobota & Lankauf, 2010) or further north in the vicinity of Ny-Ålesund (Nuth et al., 2007). Following climate trends as recorded in meteorological stations across Spitsbergen an acceleration in the retreat rate of Gåsbreen was measured since the 1990s, which is consistent with similar recession styles observed for other land terminating glaciers in the region of western Sørkapp Land as well as further north of Spitsbergen (Dudek & Pętlicki, 2021; Kohler et al., 2007).

Retreat of glaciers in Spitsbergen since the end of LIA left widespread areas of diversified terrain with freshly deposited glacial sediments. Paraglacial processes operating on these areas plays a major role in controlling landscape change. One of the manifestations of the dynamic landscape transformation in glacier proglacial zones is the decrease in the height of terminal moraines and other forms underlain by the dead ice. The process of transformation of end moraines in the Gåsbreen proglacial zone has varied in the course and pace since the 1960s, with the greatest dimensions (maximum reduction even by about 20 m of height) being reached on the end moraine's proximal slopes washed away by proglacial waters.

Previous studies of the degradation of end moraines in Svalbard were rather sparse, which limits the possibility of comparing the size of this process within the archipelago (Bennett et al., 2000; Lukas et al., 2005; Ziaja & Pipała, 2007). Only a few areas in the north and north-west of Spitsbergen (Midgley et al., 2018; Schomacker, 2007; Schomacker & Kjær, 2008; Tonkin et al., 2016) and in its central part (M. Ewertowski, 2014) were measured for at least one decade.

The results from the proglacial zones of the glaciers in the northern Spitsbergen—Holmströmbreen (Schomacker & Kjær, 2008) and Austre Lovénbreen (Tonkin et al., 2016)—mostly corresponded to the obtained results of the degradation rate of terminal moraines on the Sørkapp Land peninsula. On the other hand, in the foreland of the Ragnarbreen glaciers (M. Ewertowski, 2014) and Midtre Lovénbreen (Midgley et al., 2018), in recent decades the average dynamics of elevation changes was much lower than on Sørkapp Land. This proves that non-climatic factors, such as topography conditioning mass movements and debris flows, exposing relict ice to solar radiation, as well as fluvial erosion, may be of great importance for the transformation of end-moraines (Lukas et al., 2005; Schomacker, 2008).

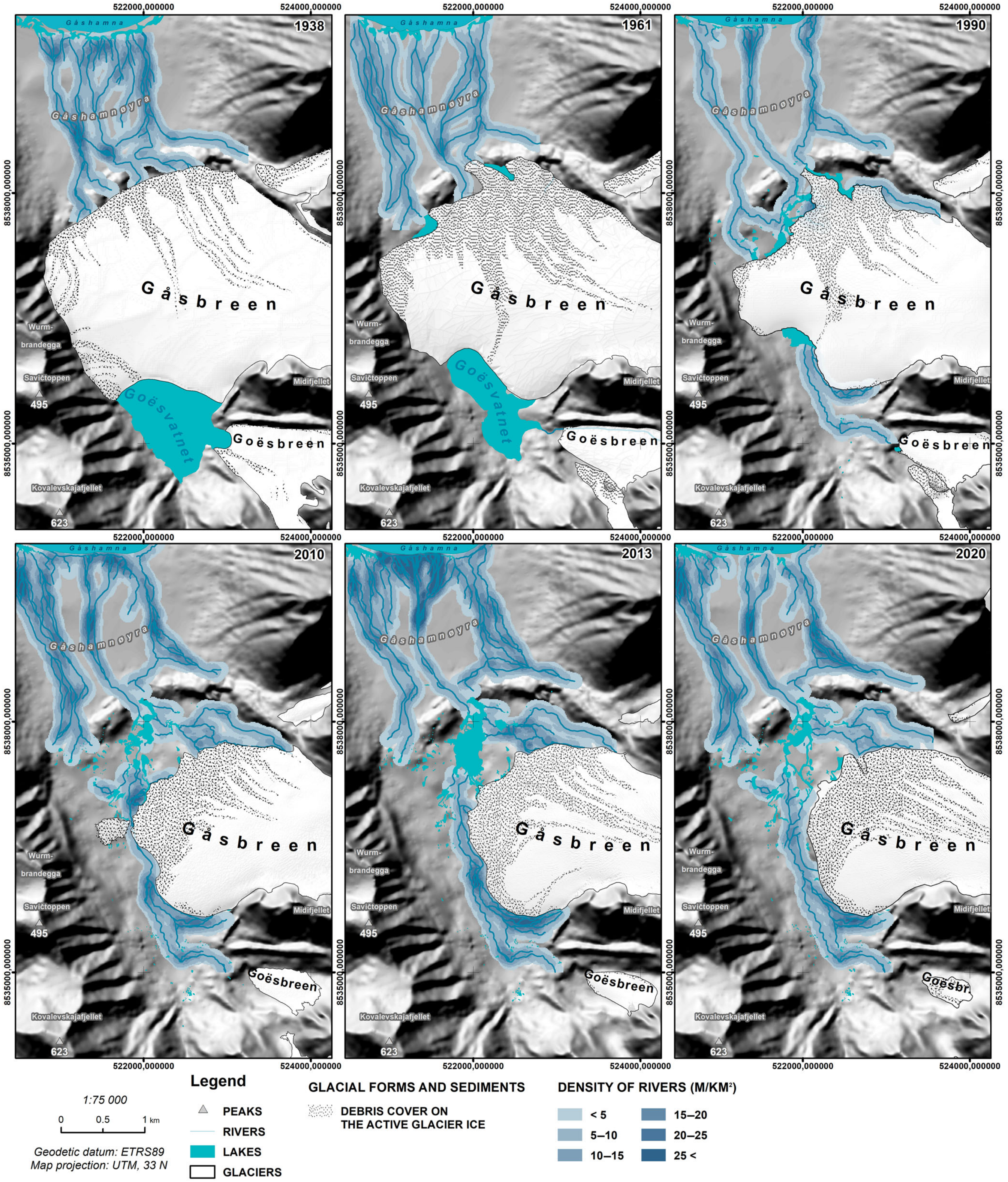

FIGURE 11 Changes in river network in Gåsbreen foreland over the period 1938–2020. *Source*: Image © 2020 Planet Labs PBC. [Colour figure can be viewed at wileyonlinelibrary.com]

The results of recent short-term (2-year) studies conducted in the foregrounds of several glaciers of central Spitsbergen (M. W. Ewertowski & Tomczyk, 2015; Irvine-Flynn et al., 2011) seem to confirm these conclusions. They indicate a relatively low rate of degradation of end moraines as a result of melting their ice nuclei only, and its significant acceleration under the influence of mass movements and washing away by proglacial waters, leading for example, to redistribution of moraine material (M. W. Ewertowski & Tomczyk, 2015; M. W. Ewertowski & Tomczyk, 2020).

The progressive glacier recession leads to the exposure of the surface of subglacial forms and sediments or mutonised rocks of the substrate. In most of the Gåsbreen proglacial zone, there is still dead ice under the glacier deposits. Its slow melting is the cause of the continuous transformation of the relief and lowering its absolute and relative altitude (Ziaja et al., 2011). Where the ice has melted, the rate of evolution of landforms clearly slows down, which leads—at least in some places—to their stabilization and consolidation. The melting of dead ice was fostered by the impact of flowing and stagnant meltwater, which led to the formation of kettle holes and debris flows (Ziaja et al., 2011).

One of the elements of paraglacial landscape developing in front of retreating Gåsbreen is the network of seasonally disappearing glacial lakes. The lakes in the foreland of Gåsbreen are an example of glacial lake evolution, which additionally has numerous GLOF events in its history. The evolution of Goësvatnet, the major glacial lake formed in the area, shows how the development of ice-dammed lakes can proceed, which through its seasonal fluctuations has led to the formation of numerous end-dammed moraine lakes (Shukla et al., 2018). Due to its location, away from human settlements, Goësvatnet has never posed a real threat to humans. Ice-dammed lakes are among the most dynamic glacial lakes in the world, which also pose the greatest threat of glacial flooding (Bhambri et al., 2020; Prakash & Nagarajan, 2018; Shugar et al., 2020). Goësvatnet is not only indeed characterized by seasonal changes, which have been elaborated thanks to the availability of satellite images, but additionally, it inscribes a trend related to reaching the maximum of its extent in July/August and then creating a sudden drainage in the form of GLOF. Glacial flooding was observed at this location prior to the era of satellite imagery and it is evidenced by the numerous works of polar explorers who spends the summer season on the foreland of Gåsbreen, documented sudden, often single-day runoffs (Grześ & Banach, 1984; W. Schöner & Schöner, 1997; Ziaja et al., 2016). The mechanism of lake drainage itself was not fully understood from the outset. Seasonal runoff was accompanied by theories related to ice uplift due to the attainment of a sufficient height of the dammed lake surface (taking into account the buoyancy force) and the one that proved to be the final explanation—the formation of a subglacial channel due to summer ablation of the glacier and its refreezing in the winter season (Grześ & Banach, 1984). The number of papers describing the fluctuations of Goësvatnet may indicate that it is the best documented glacial lake in the entire Arctic, dating back to 1899 (Ziaja et al., 2016). With the data from the DEMs used, we were able to estimate the volume of water present in the lake before the individual GLOF events. We related these results directly to those presented by M. Schöner and Schöner (1996). It turned out that our estimated values were different from those presented in the indicated publication. This is clearly affected by the measurement error at the level of the DEM used (10 m resolution). Nevertheless, it indicates how large the scale of the GLOF events we have listed was. It is also important that we have added information to the current state of knowledge about the difference in the volume of the glacial lake from 1990 before and after the glacial flood, as well as from 2002 when it was last observed. Lakes formed after the final disappearance of Goësvatnet in the Gåsbreen foreland undoubtedly also arose from Goësvatnet runoff, especially the importance of the end-moraine dammed lakes, which today constitute the largest water bodies in the Gåsbreen foreland, must be emphasized here. Moraine-dammed lakes constitute the vast majority throughout Svalbard, which is related to the geological structure of western Spitsbergen (sedimentary rocks) and geomorphological conditions resulting from glacial activity (Małecki, 2016; Sobota et al., 2016). Due to the fact that moraine dams are made of unconsolidated material and also have dead ice inside, they are also characterized by low stability and sometimes seasonal changes in extent, as is the case with lakes in the analyzed area (Baťka et al., 2020; M. W. Ewertowski & Tomczyk, 2020; Shijin et al., 2015). Forms indicative of the presence of dead ice in the substrate are the numerous Kettle lakes, which constitute the most numerous group of glacial lakes in the Gåsbreen foreland. The seasonal run-off of the Goësvatnet lake and later the end-moraine dammed lakes causes a sudden outflow of a considerable amount of sediment into Gåshamna, which can be seen on satellite images. The ability to compare aerial photographs showing the actual extent of sediment in the bay in 1960 and 1961 has made it possible to indicate the occurrence of GLOF in these years (Kavan et al., 2022). Numerous glacial lake runoffs have also led to a strong remodeling of the Gåsbreen proglacial zone, as indicated by numerous (often only periodically water-filled) river channels. The layout of these riverbeds indicates a model example of an anastomosing river (Rosgen, 1994), which, however, due to the length of runoff, is unable to develop the large forms associated with this river type. The aforementioned river type is indicative of the large amount of sediment that is carried by it and with a periodically flooded runoff zone (Teisseyre, 1984; Teisseyre, 1991).

6 | CONCLUSIONS

1. Over a century since the termination of the Little Ice Age Gåsbreen experienced constant recession and decrease in thickness, which significantly increased after 1990. The pace of rapid retreat was maintained in the 21st century and to a large degree modified by local topographic conditions.
2. The area of the Gåsbreens' foreland doubled in size due to glacier recession and is characterized by a highly dynamic landscape transformation. The key process observed in those freshly developing paraglacial areas is the degradation and lowering of frontal moraine ridges and other dead-ice landforms through mass movements and glaciofluvial action.
3. Decay of Gåsbreen exposed not only numerous glacial landforms but also created space for the formation of glacial lakes. The role of the glacial lake system in storing and redistributing glacial sediments in paraglacial sediment cascade is unknown and requires further study. With the increasing likelihood of GLOF events in the warming Arctic systems like Goësvatnet are of crucial importance for a proper understanding of paraglacial landscape transformation by extreme processes resulting from glacier degradation.

4. Ablation-driven glaciofluvial activity has intensified, resulting in enhanced landform denudation as well as the transport and accumulation of sediments across the foreland. These effects are visible in the surface area expansion of the Gåsbreen outwash plain, Goësvatnet lake basin, and proglacial river systems.
5. Under the predicted accelerated warming scenario, Gåsbreen recession and the dynamics of glacier foreland processes will most probably intensify. This will open up new avenues for research into the course of Svalbard paraglacial landscape change in the area particularly in landscape reconstruction studies of ice-free conditions that prevailed in the majority of valleys in warmer phases of the Holocene.

AUTHOR CONTRIBUTIONS

Conceptual framework of the research was designed by Justyna Dudek who also collected data in the field and carried out remote sensing, GIS and cartographic analyses with support from Mateusz K. Suwiński. Iwo Wieczorek analyzed and described changes of Goësvatnet lake system and transformation of river drainage network. Manuscript was written by Justyna Dudek, Iwo Wieczorek and Mateusz C. Strzelecki. Justyna Dudek and Iwo Wieczorek prepared figures.

ACKNOWLEDGMENTS

This study is the contribution to the National Science Centre project "GLAVE" (Award No. UMO-2020/38/E/ST10/00042) awarded to MCS. IW work on glacial lakes contributes to the Arctic Field Grant project no. 333199 (RIS ID: 11620). Publication of this article was financially supported by the Excellence Initiative – Research University program for the University of Wrocław (Project IDUB no. 320/2020/20). Michał Węgrzyn is thanked for providing unique field images of Gåsbreen foreland. Wiesław Ziaja is acknowledged for introduction to the field site and inspiring expeditions to Sørkapp Land over the years.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Justyna Dudek https://orcid.org/0000-0001-6233-5381
Mateusz C. Strzelecki https://orcid.org/0000-0003-0479-3565

REFERENCES

Allaart, L., Friis, N., Ingólfsson, Ó., Håkansson, L., Noormets, R., Farnsworth, W. R., Mertes, J., & Schomacker, A. (2018). Drumlins in the Nordenskiöldbreen forefield, Svalbard. *Gff*, *140*(2), 170–188. https://doi.org/10.1080/11035897.2018.1466832

Allaart, L., Schomacker, A., Håkansson, L. M., Farnsworth, W. R., Brynjólfsson, S., Grumstad, A., & Kjellman, S. E. (2021). Geomorphology and surficial geology of the Femmilsjøen area, northern Spitsbergen. *Geomorphology*, *382*, 107693. https://doi.org/10.1016/j.geomorph.2021.107693

Aradóttir, N., Ingólfsson, Ó., Noormets, R., Benediktsson, Í. Ö., Ben-Yehoshua, D., Håkansson, L., & Schomacker, A. (2019). Glacial geomorphology of Trygghamna, western Svalbard-integrating terrestrial and submarine archives for a better understanding of past glacial dynamics. *Geomorphology*, *344*, 75–89. https://doi.org/10.1016/j.geomorph.2019.07.007

Ballantyne, C. K. (2002). Paraglacial geomorphology. *Quaternary Science Reviews*, *21*(18–19), 1935–2017. https://doi.org/10.1016/S0277-3791(02)00005-7

Barna, S., & Warchoł, Z. (1987). *Spitsbergen, 1:25 000–10 sheets*. Institute of Geophysics of the Polish Academy of Sciences, Topographic Service of the Polish Army, Institute of Geodesy and Cartography.

Barry, R. G. (2017). The Arctic cryosphere in the twenty-first century. *Geographical Review*, *107*(1), 69–88. https://doi.org/10.1111/gere.12227

Baťka, J., Vilímek, V., Štefanová, E., Cook, S. J., & Emmer, A. (2020). Glacial lake outburst floods (GLOFs) in the cordillera Huayhuash, Peru: Historic events and current susceptibility. *Water*, *12*(10), 2664. https://doi.org/10.3390/w12102664

Bennett, M. R., Huddart, D., Glasser, N. F., & Hambrey, M. J. (2000). Resedimentation of debris on an ice-cored lateral moraine in the high-Arctic (Kongsvegen, Svalbard). *Geomorphology*, *35*(1–2), 21–40. https://doi.org/10.1016/S0169-555X(00)00017-9

Bhambri, R., Watson, C. S., Hewitt, K., Haritashya, U. K., Kargel, J. S., Shahi, A. P., Chand, P., Kumar, A., Verma, A., & Govil, H. (2020). The hazardous 2017–2019 surge and river damming by Shispare glacier, Karakoram. *Scientific Reports*, *10*(1), 4685. https://doi.org/10.1038/s41598-020-61277-8

Church, M., & Ryder, J. M. (1972). Paraglacial sedimentation: A consideration of fluvial processes conditioned by glaciation. *Geological Society of America Bulletin*, *83*(10), 3059–3072. https://doi.org/10.1130/0016-7606(1972)83[3059:PSACOF]2.0.CO;2

Cook, A. J., Copland, L., Noël, B. P., Stokes, C. R., Bentley, M. J., Sharp, M. J., Bingham, R. G., & van den Broeke, M. R. (2019). Atmospheric forcing of rapid marine-terminating glacier retreat in the Canadian Arctic archipelago. *Science Advances*, *5*(3), 1–10. https://doi.org/10.1126/sciadv.aau8507

Dallmann, W. K. (2014). *Geological map of Svalbard, 1:750000*. Norwegian Polar Institute.

De Geer, G. (1923). *Plan of the Swedish-Russian degree measurement network on Spitsbergen after the latest compiled May 1900 1:1000000 in: Measurement of a Meridian Arc in Spitsbergen, Entr. in 1899–1902, Topographical Description of the Explored Region. Geology*. Aktiebolaget Centraltryckeriet (in French).

Dobiński, W., & Kasprzak, M. (2022). Permafrost base degradation: Characteristics and unknown thread with specific example from Hornsund, Svalbard. *Frontiers in Earth Science*, *10*, 65. https://doi.org/10.3389/feart.2022.802157

Dudek, J., & Pętlicki, M. (2021). *Topography of the western Sørkapp land (Svalbard) in the year 1961 (version 2)* [Data set]. Zenodo. https://doi.org/10.5281/zenodo.4573130

Eckerstorfer, M., & Christiansen, H. H. (2011). The "high Arctic maritime snow climate" in Central Svalbard. *Arctic, Antarctic, and Alpine Research*, *43*, 11–21. https://doi.org/10.1657/1938-4246-43.1.11

Eckerstorfer, M., Rubensdotter, L., Stalsberg, K., Christiansen, H., & Trøyen, P. (2015). *Landforms and sediments in Todalen and upper Gangdalen and Bødalen, Svalbard, Scale 1:25 000*. Geological Survey of Norway (NGU).

Evans, D. J., Ewertowski, M., Roberts, D. H., & Tomczyk, A. M. (2022). The historical emergence of a geometric and sinuous ridge network at the Hørbyebreen polythermal glacier snout, Svalbard and its use in the interpretation of ancient glacial landforms. *Geomorphology*, *406*, 108213. https://doi.org/10.1016/j.geomorph.2022.108213

Evans, D. J., Strzelecki, M., Milledge, D. G., & Orton, C. (2012). Hørbyebreen polythermal glacial landsystem, Svalbard. *Journal of*

Maps, *8*(2), 146–156. https://doi.org/10.1080/17445647.2012.680776

Evans, D. J. A. (2005). *Glacial landsystems* (p. 544). Hodder Arnold.

Ewertowski, M. W. (2014). Recent transformations in the high-Arctic glacier landsystem, Ragnarbreen, Svalbard. *Geografiska Annaler: Series A, Physical Geography*, *96*(3), 265–285. https://doi.org/10.1111/geoa.12049

Ewertowski, M. W., Evans, D. J., Roberts, D. H., & Tomczyk, A. M. (2016). Glacial geomorphology of the terrestrial margins of the tidewater glacier, Nordenskiöldbreen, Svalbard. *Journal of Maps*, *12*(Suppl 1), 476–487. https://doi.org/10.1080/17445647.2016.1192329

Ewertowski, M. W., Evans, D. J., Roberts, D. H., Tomczyk, A. M., Ewertowski, W., & Pleksot, K. (2019). Quantification of historical landscape change on the foreland of a receding polythermal glacier, Hørbyebreen, Svalbard. *Geomorphology*, *325*, 40–54. https://doi.org/10.1016/j.geomorph.2018.09.027

Ewertowski, M. W., & Tomczyk, A. M. (2015). Quantification of the ice-cored moraines' short-term dynamics in the high-Arctic glaciers Ebbabreen and Ragnarbreen, Petuniabukta, Svalbard. *Geomorphology*, *234*, 211–227. https://doi.org/10.1016/j.geomorph.2015.01.023

Ewertowski, M. W., & Tomczyk, A. M. (2020). Reactivation of temporarily stabilized ice-cored moraines in front of polythermal glaciers: Gravitational mass movements as the most important geomorphological agents for the redistribution of sediments (a case study from Ebbabreen and Ragnarbreen, Svalbard). *Geomorphology*, *350*, 106952. https://doi.org/10.1016/j.geomorph.2019.106952

Farnsworth, W. R., Allaart, L., Ingólfsson, Ó., Alexanderson, H., Forwick, M., Noormets, R., Michelle, R., & Schomacker, A. (2020). Holocene glacial history of Svalbard: Status, perspectives and challenges. *Earth-Science Reviews*, *208*, 103249. https://doi.org/10.1016/j.earscirev.2020.103249

Farnsworth, W. R., Ingólfsson, Ó., Noormets, R., Allaart, L., Alexanderson, H., Henriksen, M., & Schomacker, A. (2017). Dynamic Holocene glacial history of st. Jonsfjorden, Svalbard. *Boreas*, *46*(3), 585–603. https://doi.org/10.1111/bor.12269

Farnsworth, W. R., Ingólfsson, Ó., Retelle, M., & Schomacker, A. (2016). Over 400 previously undocumented Svalbard surge-type glaciers identified. *Geomorphology*, *264*, 52–60. https://doi.org/10.1016/j.geomorph.2016.03.025

Geyman, E. C., van Pelt, W., Maloof, A. C., Aas, H. F., & Kohler, J. (2022). Historical glacier change on Svalbard predicts doubling of mass loss by 2100. *Nature*, *601*(7893), 374–379. https://doi.org/10.1038/s41586-021-04314-4

Gilbert, G. L., O'Neill, H. B., Nemec, W., Thiel, C., Christiansen, H. H., & Buylaert, J. P. (2018). Late quaternary sedimentation and permafrost development in a Svalbard fjord-valley, Norwegian high Arctic. *Sedimentology*, *65*(7), 2531–2558. https://doi.org/10.1111/sed.12476

Gjelten, H. M., Nordli, Ø., Isaksen, K., Førland, E. J., Sviashchennikov, P. N., Wyszynski, P., Prokhorova, U. V., Przybylak, R., Ivanov, B. V., & Urazgildeeva, A. V. (2016). Air temperature variations and gradients along the coast and fjords of western Spitsbergen. *Polar Research*, *35*(1), 29878. https://doi.org/10.3402/polar.v35.29878

Grabiec, M., Ignatiuk, D., Jania, J. A., Moskalik, M., Głowacki, P., Błaszczyk, M., Budzik, T., & Walczowski, W. (2018). Coast formation in an Arctic area due to glacier surge and retreat: The Hornbreen–Hambergbreen case from Spistbergen. *Earth Surface Processes and Landforms*, *43*(2), 387–400. https://doi.org/10.1002/esp.4251

Grześ, M., & Banach, M. (1984). The origin and evolution of the goes Lake in Sørkapp land, Spitsbergen. *Polish Polar Research*, *5*(3–4), 241–253. https://journals.pan.pl/dlibra/publication/127795/edition/111508/content

Hagen, J. O., Kohler, J., Melvold, K., & Winther, J. G. (2003). Glaciers in Svalbard: Mass balance, runoff and freshwater flux. *Polar Research*, *22*(2), 145–159. https://doi.org/10.3402/polar.v22is.6452

Hanssen-Bauer, I., Førland, E. J., Hisdal, H., Mayer, S., Sandø, A. B., & Sorteberg, A. (2019). *Climate in Svalbard 2100—A knowledge base for climate adaptation* (NCCS Report no. 1/2019). www.klimaservicesenter.no

Holmlund, E. S. (2021). Aldegondabreen glacier change since 1910 from structure-from-motion photogrammetry of archived terrestrial and aerial photographs: Utility of a historic archive to obtain century-scale Svalbard glacier mass losses. *Journal of Glaciology*, *67*, 107–116. https://doi.org/10.1017/jog.2020.89

Hugonnet, R., McNabb, R., Berthier, E., Menounos, B., Nuth, C., Girod, L., Farinotti, D., Huss, M., Dussaillant, I., Brun, F., & Kääb, A. (2021). Accelerated global glacier mass loss in the early twenty-first century. *Nature*, *592*(7856), 726–731. https://doi.org/10.1038/s41586-021-03436-z

Humlum, O., Instanes, A., & Sollid, J. L. (2003). Permafrost in Svalbard: A review of research history, climatic background and engineering challenges. *Polar Research*, *22*(2), 191–215. https://doi.org/10.3402/polar.v22i2.6455

Irvine–Fynn, T. D. L., Barrand, N. E., Porter, P. R., Hodson, A. J., & Murray, T. (2011). Recent High–Arctic glacial sediment redistribution: A process perspective using airborne lidar. *Geomorphology*, *125*(1), 27–39. https://doi.org/10.1016/j.geomorph.2010.08.012

Isaksen, K., Nordli, Ø., Ivanov, B., Køltzow, M. A. Ø., Aaboe, S., Gjelten, H. M., Mezghani, A., Eastwood, S., Førland, E., Benestad, R. E., Hanssen-Bauer, I., Brækkan, R., Sviashchennikov, P., Demin, V., Revina, A., & Karandasheva, T. (2022). Exceptional warming over the Barents area. *Scientific Reports*, *12*, 9371. https://doi.org/10.1038/s41598-022-13568-5

Jania, J. A. (1982). Debris forms and processes in Gåsdalen region in photogrammetric investigations and repeated terrestrial photograms. Results of investigations of the Polish scientific Spitsbergen expeditions. *Acta Universitatis Wratislaviensis*, *525*(4), 93–114.

Jania, J. A. (1988). Dynamic glacial processes in South Spitsbergen. In the light of photointerpretation and photogrammetric research. *Prace Naukowe Uniwersytetu Śląskiego w Katowicach*, *258* (in Polish), 423–429. https://doi.org/10.2343/geochemj.1.0141

Jania, J. A. (1979). *Contemporary slope processes on the Sörkappland (Spitsbergen) in the light of photointerpretation studies. IX Ogólnopolska Konferencja Fotointerpretacji* (in Polish) (pp. 33–34). Uniwersytet Śląski.

Jania, J. A., Lentowicz, Z., Szczypek, T., & Wach, J. (1981). *Geomorphological sketch of the Gåsdalen area (southern Spitsbergen). VIII Sympozjum Polarne, Instytut Geografii UŚ* (pp. 120–129). Klub Polarny PTG (in Polish).

Jania, J. A., & Szczypek, T. (1987). Geomorphological mapping of the surroundings of the Hornsund Fjord based on the interpretation of aerial photographs. *Fotointerpretacja w Geografii*, *9*(19), 108–128 (in Polish). http://geoinformatics.uw.edu.pl/wp-content/uploads/sites/26/2014/03/TS_v19_108_Jania_2MB.pdf

Janina, J., Lipert, C., & Mechliński, Z. (1984). The ice mass loss in the front zone of the Werenskiold glacier from 1957 to 1978 determined using terrestrial photogrammetry. *Polish Polar Research*, *5*(3–4), 207–216. https://journals.pan.pl/publication/127793/edition/111506/polish-polar-research-1984-vol-5-no-3-4-the-ice-mass-loss-in-the-front-zone-of-the-werenskiold-glacier-from-1957-to-1978-determined-using-terrestrial-photogrammetry-janina-jacek-lipert-cezary-mechlinski-zbigniew?language=en

Jewtuchowicz, S. (1962). Studies in the glacial geomorphology of the northern part of Sörkapp. *Acta Geographica Lodzensia*, *11*, 5–79 (in Polish).

Jewtuchowicz, S. (1965). Description of eskers and kames in Gåshamnöyra and on Bungebreen, south of Hornsund, Vestspitsbergen. *Journal of Glaciology*, *5*(41), 719–725. https://doi.org/10.3189/S0022143000018712

Karjalainen, O., Luoto, M., Aalto, J., Etzelmüller, B., Grosse, G., Jones, B. M., Lilleøren, K. S., & Hjort, J. (2020). High potential for loss of permafrost landforms in a changing climate. *Environmental Research Letters*, *15*, 104065. https://doi.org/10.1088/1748-9326/abafd5

Kasprzak, M. (2020). Seawater intrusion on the Arctic coast (Svalbard): The concept of onshore-permafrost wedge. *Geosciences*, *10*(9), 349. https://doi.org/10.3390/geosciences10090349

Kasprzak, M., Strzelecki, M. C., Traczyk, A., Kondracka, M., Lim, M., & Migała, K. (2017). On the potential for a bottom active layer below coastal permafrost: The impact of seawater on permafrost degradation imaged by electrical resistivity tomography (Hornsund, SW Spitsbergen). *Geomorphology*, *293*, 347–359. https://doi.org/10.1016/j.geomorph.2016.06.013

Kavan, J. (2020). Early twentieth century evolution of Ferdinand glacier, Svalbard, based on historic photographs and structure-from-motion technique. *Geografiska Annaler: Series A*, *102*, 57–67. https://doi.org/10.1080/04353676.2020.1715124

Kavan, J., & Strzelecki, M. C. (2023). Glacier decay boosts formation of new Arctic coastal environments—Perspectives from Svalbard. *Land Degradation and Development*. *2023*, 1–8. https://doi.org/10.1002/ldr.4695

Kavan, J., Wieczorek, I., Tallentire, G. D., Demidionov, M., Uher, J., & Strzelecki, M. C. (2022). Estimating suspended sediment fluxes from the largest glacial Lake in Svalbard to fjord system using Sentinel-2 data: Trebrevatnet case study. *Water*, *14*(12), 1840. https://doi.org/10.3390/w14121840

Kohler, J., James, T. D., Murray, T., Nuth, C., Brandt, O., Barrand, N. E., Aas, H. F., & Luckman, A. (2007). Acceleration in thinning rate on western Svalbard glaciers. *Geophysical Research Letters*, *34*(18), L18502. https://doi.org/10.1029/2007GL030681

Kolondra, L. (1979). *Mapa 1:5000, Wurmbrandegga—fragment wsch. stoku pasma*. Okręgowe Przedsiębiorstwo Geodezyjno-Kartograficzne A-1.14.

Kolondra, L. (1980). *Mapa 1:5000, Tsjebysjovfiellet—fragment zach. stoku pasma*. *Okręgowe Przedsiębiorstwo Geodezyjno-Kartograficzne* A-1.

Lønne, I., & Lyså, A. (2005). Deglaciation dynamics following the Little Ice Age on Svalbard: Implications for shaping of landscapes at high latitudes. *Geomorphology*, *72*(1–4), 300–319. https://doi.org/10.1016/j.geomorph.2005.06.003

Lukas, S., Nicholson, L. I., Ross, F. H., & Humlum, O. (2005). Formation, meltout processes and landscape alteration of high-Arctic ice-cored moraines—Examples from Nordenskiold land, Central Spitsbergen. *Polar Geography*, *29*(3), 157–187. https://doi.org/10.1080/789610198

Luncke, B. (1936). *Luftkartlegningen på Svalbard 1936*. https://doi.org/10.1080/00291953608551534

Lyså, A., & Lønne, I. (2001). Moraine development at a small high-Arctic valley glacier: Rieperbreen, Svalbard. *Journal of Quaternary Science*, *16*(6), 519–529. https://doi.org/10.1002/jqs.613

Małecki, J. (2016). Accelerating retreat and high-elevation thinning of glaciers in central Spitsbergen. *The Cryosphere*, *10*(3), 1317–1329. https://doi.org/10.5194/tc-10-1317-2016

Małecki, J. (2022). Recent contrasting behaviour of mountain glaciers across the European high Arctic revealed by ArcticDEM data. *The Cryosphere*, *16*(5), 2067–2082. https://doi.org/10.5194/tc-16-2067-2022

Mercier, D. (2008). Paraglacial and paraperiglacial landsystems: Concepts, temporal scales and spatial distribution. *Géomorphologie: Relief, Processus, Environnement*, *14*(4), 223–233. https://doi.org/10.4000/geomorphologie.7396

Midgley, N. G., Tonkin, T. N., Graham, D. J., & Cook, S. J. (2018). Evolution of high-Arctic glacial landforms during deglaciation. *Geomorphology*, *311*, 63–75. https://doi.org/10.1016/j.geomorph.2018.03.027

Norwegian Polar Institute. (2014). *Terrengmodell Svalbard* (*S0 Terrengmodell*) [Data set]. https://doi.org/10.21334/npolar.2014.dce53a47

Nuth, C., Kohler, J., Aas, H. F., Brandt, O., & Hagen, J. O. (2007). Glacier geometry and elevation changes on Svalbard (1936–90): A baseline dataset. *Annals of Glaciology*, *46*, 106–116. https://doi.org/10.3189/172756407782871440

Nuth, C., Kohler, J., König, M., von Deschwanden, A., Hagen, J. O., Kääb, A., Moholdt, G., & Pettersson, R. (2013). Decadal changes from a multi-temporal glacier inventory of Svalbard. *The Cryosphere*, *7*(5), 1603–1621. https://doi.org/10.5194/tc–7–1603–2013

Philipps, W., Briner, J. P., Gislefoss, L., Linge, H., Koffman, T., Fabel, D., Xu, S., & Hormes, A. (2017). Late Holocene glacier activity at inner Hornsund and Scottbreen, southern Svalbard. *Journal of Quaternary Science*, *32*(4), 501–515. Portico. https://doi.org/10.1002/jqs.2944

Pillewizer, W. (1939). *The cartographic and glaciological results of the German Spitsbergen Expedition 1938* (p. 238). Petermanss Geographische Mitteilungen Erganzh (in German).

Planet Labs PBC. (2020). Planet Imagery, Education and Research Program, Inc.: 2020.

Porter, C., Morin, P., Howat, I., Noh, M. J., Bates, B., Peterman, K., Keesey, S., Schlenk, M., Gardiner, J., Tomko, K., Willis, M., Kelleher, C., Cloutier, M., Husby, E., Foga, S., Nakamura, H., Platson, M., Wethington, M. J., Williamson, C., … Bojesen, M. (2018). *Arctic DEM*. Harvard Dataverse. https://doi.org/10.7910/DVN/OHHUKH

Prakash, C., & Nagarajan, R. (2018). Glacial lake changes and outburst flood hazard in Chandra basin, North-Western Indian Himalaya. *Geomatics, Natural Hazards and Risk*, *9*(1), 337–355. https://doi.org/10.1080/19475705.2018.1445663

Rachlewicz, G., Szczuciński, W., & Ewertowski, M. (2007). Post-"Little Ice Age" retreat rates of glaciers around Billefjorden in central Spitsbergen, Svalbard. *Polish Polar Research*, *3*, 159–186. https://journals.pan.pl/Content/110598/PDF/PPR28–159.pdf

Reder, J. (1996). Evolution of marginal zones during continued glacial retreat in northwestern Wedel Jarlsberg land, Spitsbergen. *Polish Polar Research*, *17*(1–2), 61–84.

Rieche, H. (1970). *The Hornsund. History and nature of the southernmost fjord Spitsbergen*. Ulm (in German).

Rodzik, J., Gajek, G., Reder, J., & Zagórski, P. (2013). Glacial geomorphology. In P. Zagórski, M. Harasimiuk, & J. Rodzik (Eds.), *The geographical environment of NW part of Wedel Jarlsberg land (Spitsbergen, Svalbard)*. Faculty of Earth Sciences and Spatial Management Maria Curie-Skłodowska University.

Rosgen, D. L. (1994). A classification of natural rivers. *Catena*, *22*(3), 169–199. https://doi.org/10.1016/0341-8162(94)90001-9

Rubensdotter, L., Romundset, A., Farnsworth, F., & Christiansen, H. (2015). *Landforms and 821 sediments in Bjørndalen—Vestpynten, Svalbard. Quaternary Geological Map 1:10 000*. Geological Survey of Norway (NGU).

Sasgen, I., Salles, A., Wegmann, M., Wouters, B., Fettweis, X., Noël, B. P. Y., & Beck, C. (2022). Arctic glaciers record wavier circumpolar winds. *Nature Climate Change*, *12*, 249–255. https://doi.org/10.1038/s41558-021-01275-4

Schomacker, A. (2007). *Dead-ice under different climate conditions: Processes, landforms, sediments and melt rates in Iceland and Svalbard*. Doctoral Thesis (compilation), Quaternary Sciences, Department of Geology, Lund University.

Schomacker, A. (2008). What controls dead-ice melting under different climate conditions? A discussion. *Earth-Science Reviews*, *90*(3–4), 103–113. https://doi.org/10.1016/j.earscirev.2008.08.003

Schomacker, A., & Kjær, K. H. (2008). Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier Holmströmbreen, Svalbard. *Boreas*, *37*(2), 211–225. https://doi.org/10.1111/j.1502-3885.2007.00014.x

Schöner, M., & Schöner, W. (1996). *Photogrammetric and glaciological investigations at Gåsbre* (*results of the Spitsbergen expedition 1991*). *Geowissenschaftliche Mitteilungen, Schriftenreihe der Studienrichtung Vermessungswesen der Technischen Universität Wien*, *42*, 120 + 2 maps (in German). Geophysical studies of the University in Wienna.

Schöner, W., & Schöner, M. (1997). Effects of glacier retreat on the outbursts of Goësvatnet, Southwest Spitsbergen, Svalbard. *Journal of Glaciology*, *43*(144), 276–282. https://doi.org/10.3189/S0022143000003221

Shijin, W., Dahe, Q., & Cunde, X. (2015). Moraine-dammed Lake distribution and outburst flood risk in the Chinese Himalaya. *Journal of Glaciology*, *61*(225), 115–126. https://doi.org/10.3189/2015JoG14J097

Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., Bevington, A. R., Betts, R. A., Harrison, S., &

Strattman, K. (2020). Rapid worldwide growth of glacial lakes since 1990. *Nature Climate Change*, *10*(10), 939–945. https://doi.org/10.1038/s41558-020-0855-4
Shukla, A., Garg, P. K., & Srivastava, S. (2018). Evolution of glacial and high-altitude lakes in the Sikkim, eastern Himalaya over the past four decades (1975–2017). *Frontiers in Environmental Science*, *6*, 81. https://doi.org/10.3389/fenvs.2018.00081
Slaymaker, O. (2009). Proglacial, periglacial or paraglacial? In J. Knight & S. Harrison (Eds.), *Periglacial and paraglacial processes and environments* (Vol. 320, pp. 71–84). The Geological Society, London, Special Publications. https://doi.org/10.1144/SP320.6
Smith, D. M., Gillett, N. P., Simpson, I. R., Athanasiadis, P. J., Baehr, J., Bethke, I., Bilge, T. A., Bonnet, R., Boucher, O., Findell, K. L., Gastineau, G., Gualdi, S., Hermanson, L., Leung, L. R., Mignot, J., Müller, W. A., Osprey, S., Otterå, O. H., Persad, G. G., … Ziehn, T. (2022). Attribution of multi-annual to decadal changes in the climate system: The Large Ensemble Single Forcing Model Intercomparison project (LESFMIP). *Frontiers in Climate*, *4*, 955414. https://doi.org/10.3389/fclim.2022.955414
Sobota, I., & Lankauf, K. R. (2010). Recession of Kaffiøyra region glaciers, Oscar II land, Svalbard. *Bulletin of Geography. Physical Geography Series*, *3*, 27–45. https://doi.org/10.2478/2327
Sobota, I., Nowak, M., & Weckwerth, P. (2016). Long-term changes of glaciers in North-Western Spitsbergen. *Global and Planetary Change*, *144*, 182–197. https://doi.org/10.1016/j.gloplacha.2016.07.006
Strzelecki, M. C., Long, A. J., Lloyd, J. M., Małecki, J., Zagórski, P., Pawłowski, Ł., & Jaskólski, M. W. (2018). The role of rapid glacier retreat and landscape transformation in controlling the post-Little Ice Age evolution of paraglacial coasts in central Spitsbergen (Billefjorden, Svalbard). *Land Degradation & Development*, *29*(6), 1962–1978. https://doi.org/10.1002/ldr.2923
Strzelecki, M. C., Szczuciński, W., Dominiczak, A., Zagórski, P., Dudek, J., & Knight, J. (2020). New fjords, new coasts, new landscapes: The geomorphology of paraglacial coasts formed after recent glacier retreat in Brepollen (Hornsund, southern Svalbard). *Earth Surface Processes and Landforms*, *45*, 1325–1334. https://doi.org/10.1002/esp.4819
Sumata, H., de Steur, L., Gerland, S., Divine, D. V., & Pavlova, O. (2022). Unprecedented decline of Arctic Sea ice outflow in 2018. *Nature Communications*, *13*(1), 1747. https://doi.org/10.1038/s41467-022-29470-7
Szupryczyński, J. (1960). The marginal zone of the Gås glacier (Sörkappland, southern Spitsbergen). *Bulletin de l'Académie Polonaise des Sciences, Série des Sciences Géologiques et Géographiques*, *8*, 313–319.
Szupryczyński, J. (1963). *Rzeźba strefy marginalnej i typy deglacjacji lodowców południowego Spitsbergenu*. Prace Geograficzne, Instutut Geografii Polskiej Akademii Nauk, 39. Institute of Geography of Polish Academy of Sciences. http://rcin.org.pl/igipz/Content/16863/PDF/WA51_21998_r1963_nr39_Prace-Geogr.pdf
Szupryczyński, J. (1965). Eskers and kames in the Spitsbergen area. *Geographia Polonica*, *6*, 127–140.
Teisseyre, A. K. (1984). Procesy fluwialne i rozwój koryta górnego Bobru na odcinku badawczym w Błażkowej (1967-1982). *Geologia Sudetica*, *19*(1), 7–74.
Teisseyre, A. K. (1991). Klasyfikacja rzek w swietle analizy systemu fluwialnego i geometrii hydraulicznej. *Prace Geologiczno-Mineralogiczne Uniwersytetu Wrocławskiego* [studies of the University of Wrocław], *22*, 1–210.
Thoman, R. L., Richter-Menge, J., & Druckenmiller, M. L. (2020). *Arctic report card 2020* (p. 10). NOAA. https://doi.org/10.25923/5S0F-5163
Tonkin, T. N., Midgley, N. G., Cook, S. J., & Graham, D. J. (2016). Ice-cored moraine degradation mapped and quantified using an unmanned aerial vehicle: A case study from a polythermal glacier in Svalbard. *Geomorphology*, *258*, 1–10. https://doi.org/10.1016/j.geomorph.2015.12.019
Urbański, J. A. (2022). Monitoring and classification of high Arctic lakes in the Svalbard Islands using remote sensing. *International Journal of Applied Earth Observation and Geoinformation*, *112*, 102911. https://doi.org/10.1016/j.jag.2022.102911
Wieczorek, I. W., Strzelecki, M. C., Stachnik, L., Yde, J. C., & Małecki, J. (2023). Post-Little Ice Age glacial lake evolution in Svalbard: Inventory of lake changes and lake types. *Journal of Glaciology*, 1–18. https://doi.org/10.1017/jog.2023.34
Wołoszyn, A., Owczarek, Z., Wieczorek, I., Kasprzak, M., & Strzelecki, M. C. (2022). Glacial outburst floods responsible for major environmental shift in Arctic coastal catchment, Rekvedbukta, Albert I land, Svalbard. *Remote Sensing*, *14*, 6325. https://doi.org/10.3390/rs14246325
Yao, X., Liu, S., Han, L., Sun, M., & Zhao, L. (2018). Definition and classification system of glacial lake for inventory and hazards study. *Journal of Geographical Sciences*, *28*, 193–205. https://doi.org/10.1007/s11442-018-1467-z
Ziaja, W. (1999). *Geosystem development of Sørkappland Svalbard*. Habilitation Dissertations of the Jagiellonian University, Jagiellonian University Press, *343*, 105 (in Polish).
Ziaja, W., Dudek, J., Lisowska, M., Olech, M., Ostafin, K., Osyczka, P., & Węgrzyn, M. (2011). *Transformation of the natural environment in Western Sørkapp land (Spitsbergen) since the 1980s*. Jagiellonian University Press.
Ziaja, W., Dudek, J., & Ostafin, K. (2016). Landscape transformation under the Gåsbreen glacier recession since 1899, southwestern Spitsbergen. *Polish Polar Research*, *37*, 155–172. https://doi.org/10.1515/popore-2016-0010
Ziaja, W., & Ostafin, K. (2007). A contemporary transformation of the Gås glacier landscape and its surroundings. In R. Przybylak, M. Kejna, A. Araźny, & P. Głowacki (Eds.), *Abiotic environment of Spitsbergen in 2005–2006 in conditions of global warming. Nicolai Copernicus University, Institute of Geophysics of the Polish Academy of Sciences* (in Polish) (pp. 235–246). Nicolai Copernicus University, Institute of Geophysics of the Polish Academy of Sciences.
Ziaja, W., & Ostafin, K. (2014). Landscape-seascape dynamics in the isthmus between Sørkapp land and the rest of Spitsbergen: Will a new big Arctic island form? *Ambio*, *44*, 332–342. https://doi.org/10.1007/s13280-014-0572-1
Ziaja, W., & Pipała, R. (2007). Glacial recession 2001–2006 and its landscape effects in the Lindströmfjellet-Hĺbergnuten mountain ridge, Nordenskiöld land, Spitsbergen. *Polish Polar Research*, *28*(4), 237–247. https://journals.pan.pl/publication/126741/edition/110601/polish–polar–research–2007–no–4–glacial–recession–2001–2006–and–its–landscape–effects–in–the–lindstromfjellet–hlbergnuten–mountain–ridge–nordenskiold–land–spitsbergen–ziaja–wieslaw–pipala–robert?language=en
Ziaja, W., & Skiba, S. (2002). *Sørkappland landscape structure and functioning*. Spitsbergen.

How to cite this article: Dudek, J., Wieczorek, I., Suwiński, M. K., & Strzelecki, M. C. (2023). Paraglacial transformation and ice-dammed lake dynamics in a high Arctic glacier foreland, Gåsbreen, Svalbard. *Land Degradation & Development*, *34*(14), 4252–4271. https://doi.org/10.1002/ldr.4773