Journal of Glaciology

Article

Cite this article: Kavan J, Luláková P, Małecki J, Strzelecki MC (2023). Capturing the transition from marine to land-terminating glacier from the 126-year retreat history of Nordenskiöldbreen, Svalbard. *Journal of Glaciology* 1–11. https://doi.org/10.1017/jog.2023.92

Received: 1 February 2023
Revised: 16 October 2023
Accepted: 17 October 2023

Keywords:
climate warming; coastal zone development; glacier retreat; marine-terminating glacier; Svalbard

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cambridge.org/jog

Capturing the transition from marine to land-terminating glacier from the 126-year retreat history of Nordenskiöldbreen, Svalbard

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Abstract

Svalbard has experienced a dramatic increase in air temperature and glacier retreat since the end of the Little Ice Age. In many cases, this retreat has resulted in glaciers transitioning from being marine-terminating to land-terminating. Nordenskiöldbreen is an excellent contemporary example of this transition. A set of historical observations of glacier front positions was used to assess Nordenskiöldbreen's retreat rate and we found that the southern portion of the glacier front retreated by ~3500 m, since records began in 1896. The general retreat rate corresponds well with the air temperature trend during most of the 20th century. However, the average retreat rate has slowed since the 1990s despite increasing air temperatures. We show that this discrepancy between air temperature and retreat rate marks the transition from marine-terminating towards a land-terminating glacier, as the glacier's bedrock topography started to play an essential role in the glacier margin geometry, ice flow and retreat dynamics.

Introduction

The Arctic has experienced rapid rates of warming that are above the global average, due to the effect of polar amplification; a series of positive feedbacks related to the extent of glaciers, snow cover, sea ice, permafrost and the biosphere (Callaghan and others, 2011; Comiso and Hall, 2014). Warming of the Arctic region started after the end of the Little Ice Age (LIA) in the 1900s (Bengtsson and others, 2004) and has been particularly marked in Svalbard (Nordli and others, 2020). The meteorological station at Svalbard Airport (Longyearbyen) has recorded an increase in annual mean air temperature of 3.7°C since 1898 (Bengtsson and others, 2004), and a particularly rapid temperature increase from 1991 to present (Hanssen-Bauer and others, 2019). During the last 30 years, the warming rate in the Barents Sea region is estimated to be twice the Arctic average and seven times the global average; this is among the greatest rate of modern warming recorded on Earth (Isaksen and others, 2016; Nordli and others, 2020). The temperature increase, which is most apparent during the coldest months (Bengtsson and others, 2004), impacts the form of precipitation in winter, and an increasing number of rain on snow events affects snow and firn characteristics and snow accumulation with further impact on the whole ecosystem (Peeters and others, 2019).

The final glacier advance of the Late Weichselian took place in Svalbard between 12.5 and 10 ky BP (Mangerud and others, 1992). Ice masses in Svalbard were in overall retreat during the Holocene but advances have been detected across the entire archipelago during the Neoglacial (onset c. 3.0 ky ago), in the latter half of the Holocene (Farnsworth and others, 2020; Osika and others, 2022). The most recent glacier advances took place during the LIA, which ended in 1900 in Svalbard (Martín-Moreno and others, 2017). The position of the LIA glacier extent is typically marked by prominent frontal and lateral moraines (e.g. Werner and others, 1993; Lønne and Lyså, 2005 or specifically for the study area in Rachlewicz and others, 2007). Marine-terminating glaciers have similar subaqueous counterparts (Bennett, 2001). These submarine landforms are studied widely in Svalbard (e.g. Baeten and others, 2010; Flink and others, 2015; Farnsworth and others, 2017; Streuff and others, 2017; Noormets and others, 2021) and globally (Streuff and others, 2022). Apart from these landforms, the positions of glacier fronts and glacier margins were repeatedly marked on topographic maps and sea charts throughout the 20th century. Such mapping has been conducted at Nordenskiöldbreen (Allaart and others, 2018 and references therein), which offers a unique chance to study the retreat dynamics in relatively high temporal resolution.

A substantial proportion of Svalbard glaciers are surge-type; with different frequencies of activity (Hagen and others, 1993; Jiskoot and others, 2000; Farnsworth and others, 2016). Glacier surges are dynamic instabilities which lead to rapid transfer of ice mass from higher to lower elevations of glaciers during the active phase of a surge (Benn and others, 2019). Therefore, actively surging glaciers commonly display frontal advances, up to kilometre-scale, even despite climate warming trends, and anomalous surface elevation changes, i.e. thinning in upper parts and thickening in lower parts (e.g. Murray and others, 2012; Sund and others, 2014; Benn and others, 2023). Surge cycles can therefore complicate the study of climatic drivers of glacier behaviour (Blaszczyk and others, 2013). Thus, records from glaciers not affected by surge cycles are of great value for studying the interconnections of glacier retreat and climate. Surges were probably more common during LIA than at present (Dowdeswell and others, 1995; Sevestre and others, 2015; Farnsworth and others, 2016). Nordenskiöldbreen has no documented surge activity, including no clear evidence from its geomorphological assemblage (Ewertowski and others, 2016), which provides a good opportunity to study the interconnections between climate, fjord bathymetry and front retreat.

Marine-terminating glaciers are characterized by a steep ice cliff ending in the fjord and they primarily lose mass by frontal ablation (Cogley and others, 2011; Kochtitzky and others, 2022). Frontal ablation represents a large proportion of the total glacier mass loss in Svalbard, estimated to be up to 32% by Błaszczyk and others (2009). Another specific feature of the marine-terminating glaciers is the subglacial drainage of meltwater in the calving front, which alters the circulation in the fjord and enhances the upwelling of mineral-rich water (Kanna and others, 2018). Similarly, a high flux of minerals and nutrients enters the fjord directly from the glacier (Fransson and others, 2015; Meire and others, 2016, 2023). Margins of marine-terminating glaciers in the high Arctic are biodiversity hotspots (Lydersen and others, 2014; Urbanski and others, 2017; Womble and others, 2021).

The presence of seawater at the glacier terminus typically increases ice velocities when compared with land-terminating glaciers (e.g. Sakakibara and Sugiyama, 2014; Baurley and others, 2020). At water depths of tens or hundreds of metres, the behaviour of the ice margin is influenced by large-scale topographic features on the seafloor. For example, the spatial variability of the fjord width, pinning points, prograde or retrograde slopes affect the stability of glacier grounding lines (e.g. Katz and Grae Worster, 2010; Carr and others, 2017; Catania and others, 2018; Frank and others, 2022). In contrast, in very shallow water glacier environments (depths of metres), even small-scale bed undulations along the glacier front can significantly modify local frontal ablation (Enderlin and others, 2013). A shallow bed and/or a multitude of bedrock outcrops extending above the waterline often helps to form an irregular line of the glacier margin with spatially variable rates of margin fluctuations (Vieli and others, 2002; Błaszczyk and others, 2013).

The retreat dynamics of marine-terminating glaciers have been studied at numerous sites around Svalbard (e.g. Blaszczyk and others, 2009). However, these studies typically have a low temporal resolution, with the LIA maximum extent identified by the position of the terminal moraine and ratified with use of the 1936/1938 aerial photography campaign (e.g. Rachlewicz and others, 2007; Martín-Moreno and others, 2017; Kavan, 2020a). Often, few additional glacier front positions have been available for comparison (Holmlund, 2021; Kavan and others, 2022). Such glacier retreat results in the development of a new coastline, which is then exposed to active coastal processes. These processes remodel the unconsolidated glacial sediments and landforms left behind by retreating glaciers (e.g. Strzelecki and others, 2020). More than 900 km of new coastline has appeared in Svalbard as a result of marine-terminating glacier retreat since 1936 (Kavan and Strzelecki, 2023). During the last two decades, the retreating marine-terminating glaciers trend has been common in Svalbard and across the Arctic as a whole (Kochtitzky and Copland, 2022).

The aim of this paper is to describe the retreat dynamics of Nordenskiöldbreen since the LIA. The retreat of the front of this marine-terminating glacier has been observed using a set of historic maps, aerial images and satellite images. Nordenskiöldbreen was chosen because there is a high quantity of ice margin position data (since the LIA) as well as an absence of documented surge-activity (e.g. Hagen and others, 1993; Rachlewicz and others, 2007). The retreat pattern of Nordenskiöldbreen can thus be used to illustrate the relationship between retreat rate and climate drivers. We also explain its interconnection with the increasing regional air temperature trend observed since the 1900s. We take advantage of the recent shift from a marine-terminating to a land-based glacier system to illustrate the impact of this shift on the retreat rate and how monitoring of a retreat rate provide us with information on shift in the glacier regime.

Study site

Glaciers in central Svalbard are affected by a relatively dry quasi-continental climate with high summer temperatures and lower snow accumulation compared to coastal locations (Przybylak and others, 2014; Gjelten and others, 2016) resulting in quick glacier mass loss and retreat (Małecki, 2016, 2022). Most of the glaciers are valley type, with the exception of the large Lomonosov ice cap extending from the eastern high elevation region. Nordenskiöldbreen (78°40′N 17°E) is a westward-flowing outlet glacier descending from the high-elevated Lomonosovfonna summit (~1200 m a.s.l.) down to Adolfbukta (Fig. 1). Nordenskiöldbreen is the largest and only calving glacier in Billefjorden in central Spitsbergen (Rachlewicz and others, 2007). The glacier area is ~206 km^2 and it has a length of ~22 km (GLIMS ID G017371E78745N; Raup and others, 2007). The surface mass balance of the glacier has been negative since at least the late 1980s (van Pelt and others, 2012), but was very likely negative for the whole of the 20th century (Plassen and others, 2004). A modelling study by van Pelt and others (2012) indicated a glacier-wide surface mass balance of −0.4 m w.e. for the period 1989–2010, whereas direct glaciological measurements over 2005–2018 yielded a mass balance of ~−0.1 m w.e. (Schuler and others, 2020). The equilibrium line altitude of Nordenskiöldbreen is ~600–700 m a.s.l. (van Pelt and others, 2012). The ice flow velocity (40–55 m a^{-1}, den Ouden and others, 2010) is relatively low for a Svalbard glacier of this size and type (compare with Milczarek and others, 2022). The highest ice velocities of up to 60 m a^{-1} were found along the northern flowline between De Geerfjellet and Terrierfjellet (Fig. 1a) (den Ouden and others, 2010). This corresponds well with the area where the bedrock topography was identified by GPR surveying as being below sea level (areas highlighted in red in Fig. 1a) (van Pelt and others, 2013). The below sea level bedrock topography suggests that calving (presently almost non-existent) could recommence in the next decades at least in the northern ice flow area if/when the glacier retreats to a position behind a bedrock rise/knob and enters a new basin. The exact ice volume lost to the fjord via frontal ablation, i.e. a major component to the total mass balance covering calving and submarine melting, is, however, unknown but van Pelt and others (2012) argued it might play a considerable role in the overall mass balance of the glacier. The terrestrial forefield of the glacier was recently studied for its geomorphologic evidence of retreat-related processes (Allaart, 2016; Ewertowski and others, 2016; Nehyba and others, 2017; Allaart and others, 2018).

The glacier itself was frequently visited by different scientific expeditions at the end of the 19th and the beginning of the 20th century (e.g. de Geer, 1908; Wordie, 1921; Frazer, 1922; Walton, 1922; Slater, 1925; or other references in Liljequist, 1993) and detailed information on its frontal positions is documented in historical archives. The scientific interests in Nordenskiöldbreen were later complemented by economic activities connected to mining activities in adjacent Brucebyen and especially Pyramiden – a

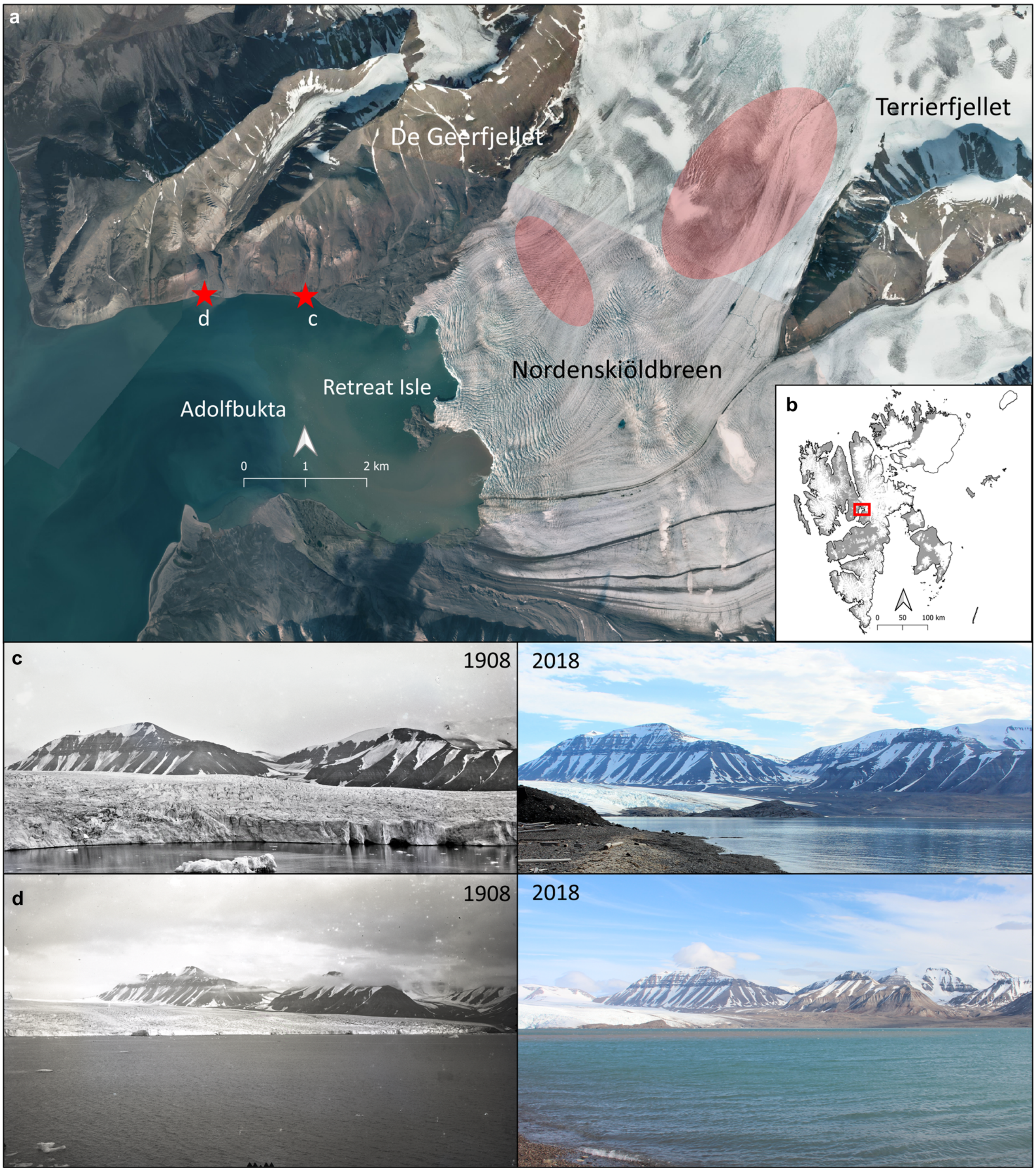

Figure 1. (a) Adolfbukta with the lower region of Nordenskiöldbreen on a 2009 aerial image from NPI (Basisdata_NP_Ortofoto_Svalbard_WMTS_25833). The positions from which photographs in panels c and d are indicated with red stars and the potential bedrock below sea level with red transparent ellipses; (b) map of Svalbard with study site in red; (c) and (d) the northern portions of the glacier margin as photographed by the de Geer expedition in 1908 and, from the same location, in 2018.

settlement on the opposite side of the fjord. The early 20th century exploration included detailed photo documentation of the area and the glacier front which enables us to compare changes in the landscape on a centennial scale (Figs 1c, d).

Methodology

Glacier front positions

We used 23 records of glacier front positions extending from 1896 to 2022. Most of the historic glacier front positions were derived from Allaart (2016) and Allaart and others (2018) and references therein. This was complemented by the recent Sentinel-2 satellite images obtained from the Sentinel Hub EO Browser (https://www.sentinel-hub.com/). These positions (Fig. 2a) were then used to quantify the retreat rate along the five profiles representing different conditions of the glacier. Profiles 'South A' and 'North A' represent the near fjord shore profile where the glacier has already completely switched from marine-terminating to a land-based glacier. Profiles 'South B' and 'North B' represent the glacier front which is currently in the transition. The 'Central' profile goes across 'Retreat Isle', a small rocky island which first became

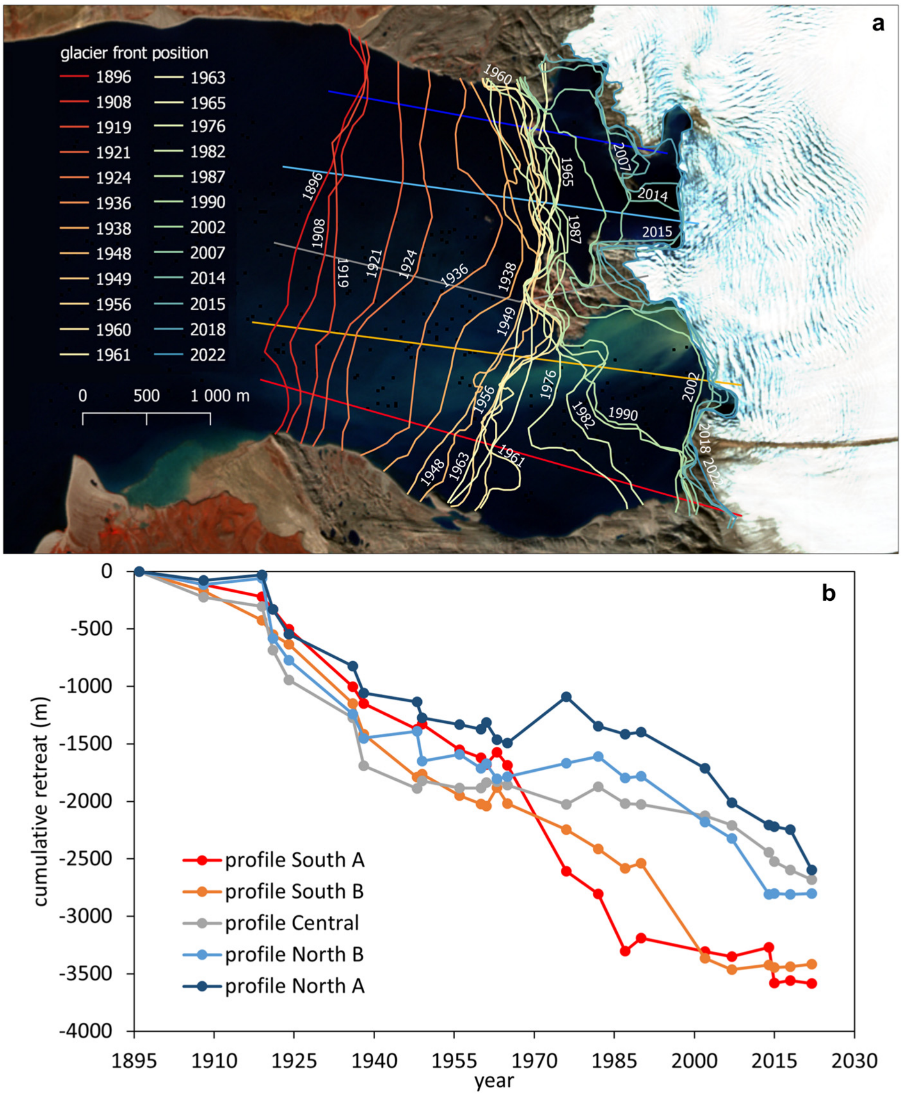

Figure 2. (a) Glacier front positions derived from historic maps, aerial photographs and satellite images, overlaying a Sentinel-2 image from 31/08 2022. (b) Cumulative retreat distance since 1895 along the five colour-coded profiles indicated in panel (a).

visible in the 1960s. The average retreat rate was calculated as an area difference between the glacier positions divided by the width of the fjord.

To illustrate the retreat of the glacier front and its surface lowering, we used historic photographs from the 1908 de Geer expedition (de Geer, 1910) taken by Oscar Halldin (Figs 1c, d). The photographs are available from the Alvin database of the Centre for History of Science, Royal Academy of Sciences, Sweden (https://info.alvin-portal.org). The photographs were taken during an expedition in July 1908. We identified the locations where the original photographs were taken, and we repeated the photographs during July 2018 fieldwork. The coordinates are 78.67475° N 16.76994°E and 78.67380°N 16.84034°E, respectively.

Glacier geometry

The ArcticDEM individual strip (Porter and others, 2022) from 3 May 2021 was used to determine the vertical profile of the frontal part of the glacier. This was complemented by digital elevation models (DEMs) from 1990 and 2009 provided by the Norwegian Polar Institute (NPI, 2022). The ArcticDEM is projected to the National Snow and Ice Data Center (NSIDC) Sea Ice Polar Stereographic North and referenced to the ellipsoidal WGS84 horizontal datum (EPSG:3413). The NPI DEMs are projected using the European Terrestrial Reference System 1989 using the GRS 1980 ellipsoid (local reference system UTM-zone 33). This results in a shift in altitude of 31.5 m for the ArcticDEM compared to the local reference system. This was checked on a set of virtual ground control points, i.e. points with known stable and identic altitude in both DEMs. We applied a simple correction for the DEMs mean sea level elevation difference and subtracted 31.5 m of difference from the ArcticDEM. We did not apply more complex corrections using the geoid difference model as the shift in altitude is within ±0.2 m on the small study site and our intention was not to provide any high precision analysis, but rather to visualize the geometric changes in the glacier frontal zone. The glacier surface elevation change was obtained by simple overlap of the two DEMs after co-registration of the 1990 and 2009 DEMs to fit on the 2021 DEM. The changes that are described later refer to the frontal area plotted in Figure 3b. All spatial analyses were conducted in QGIS 3.22.

Air temperature data and statistical analyses

To assess the effect of air temperature on retreat dynamics, we used the reconstructed monthly air temperatures from Longyearbyen airport (Svalbard Lufthavn station) starting in 1898 (Nordli and others, 2020) and complemented by the most recent data available from the Norwegian Meteorological Institute (https://seklima.met.no/observations/). A more detailed description of this dataset can be found in Nordli and others (2020).

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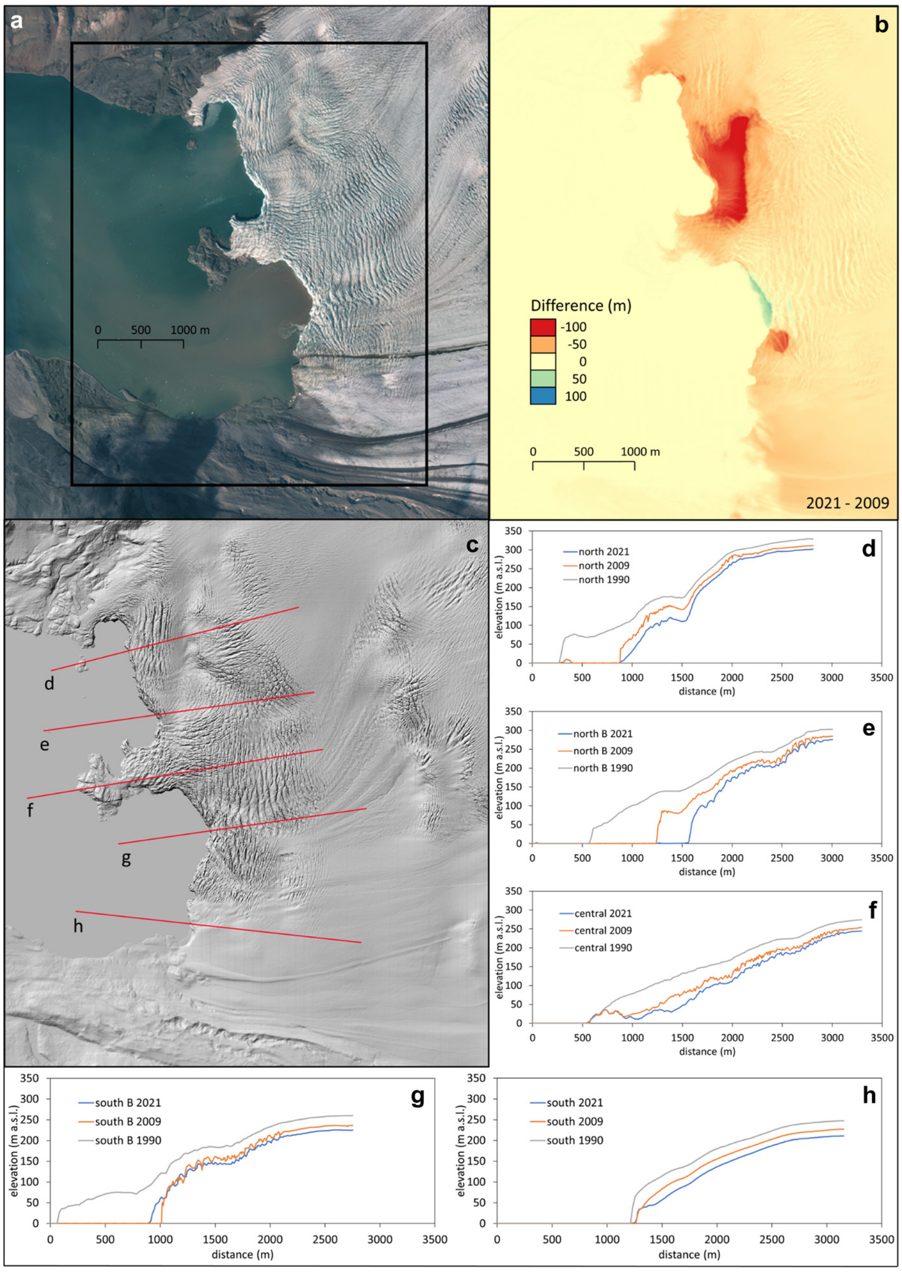

Figure 3. Spatial variability of glacier surface elevation changes between 2009 and 2021 derived from the NPI 2009 DEM and the ArcticDEM (3 April 2021); (a) black box indicating extent of panels b and c on a 2009 NPI aerial image of; (b) difference model between the 2021 and 2009 DEMs; (c) the 2009 DEM with location of the along-flow profiles in the subsequent panels; (d–h) retreat and thinning illustrated by distance and elevation profiles across the DEMs of 1990, 2009 and 2021.

The air temperature and retreat rate datasets were tested for detection of a change point with Wild Binary Segmentation (wbs; Fryzlewicz, 2014). Sharma and others (2016) recommended this method as the most effective from a set of change point detection methods. The 'wbs' package in R was used to perform the analysis (Baranowski and Fryzlewicz, 2014). Trend detection analysis was further performed using Mann–Kendall non-parametric test. The analysis was performed in R using the trend package (Pohlert, 2020). The relationship between air temperature and retreat rate was tested with Pearson's correlation coefficients for the whole dataset and later separately for datasets split in the detected change point in 1990. The significance level of the tests was set up to 95% if not stated otherwise.

Results and discussion

Retreat of the glacier front

Nordenskiöldbreen has retreated continuously since 1896 (Fig. 2a). The shape of the glacier front used to be perpendicular to the flow direction in the first half of the 20th century. Retreat became spatially variable from 1960, probably because of the complex bedrock topography at the glacier front caused by Retreat Isle. Since 1960, the retreat rate of the northern part of the glacier snout has slowed down: from 28 m a^{-1} (1921–1960) to 10 m a^{-1} (1960–2002) (Fig. 2b). This slowdown was likely caused by the retreat of the glacier margin to shallower water, exposing a number of small islands and bedrock in the very northern forefield, which previously acted as pinning points (Todd and others, 2018; Frank and others, 2022). Calving glaciers have a tendency to stabilize at pinning points and to retreat rapidly between them (Benn and others, 2007), and this mechanism would account for the spatial heterogeneity of retreat observed. A similar process has been observed at other glaciers in the region. For example, pinning points stabilized glacier fronts in Bloomstrandbreen (Burton and others, 2016) and several other glaciers in southern Spitsbergen (Shackleton and others, 2020). In contrast, accelerated retreat was observed in Hansbreen around 1990, which was attributed to a depression in the glacier bed (Vieli and others, 2002), where deeper water led to a higher

https://doi.org/10.1017/jog.2023.92 Published online by Cambridge University Press

rate of retreat. The gradual slowdown of a retreat rate detected since 1960s implies a similar bedrock control mechanism as the glacier retreated to shallow waters near the present glacier front.

The southern part of Adolfbukta is more open to the fjord compared to the northern part, has a maximum depth of 100 m (see Fig. 18a in Allaart, 2016) and the retreat was therefore much faster and pronounced there. In contrast, the retreat rate was slower in the northern part of the fjord, where water is shallower (~10–20 m depth). The general circulation pattern of ocean water in Adolfbukta is clockwise as indicated by the orientation of beach accumulations (Kavan, 2020b). The clockwise circulation is supported by the subglacial meltwater outflow located in the central part of the southern basin indicated by occurrence of sediment laden meltwater plumes (visible on aerial and satellite imagery – see Figs 1a, 5a). More frequent influx of Atlantic water to Billefjorden and accompanied increasing trend in water temperatures (0.78°C per decade in the 21st century) was detected (Bloshkina and others, 2021). However, this warming did not affect the retreat rate and in fact corresponded with a period of reduced retreat rates (Fig. 2a). Frequent easterly katabatic winds force the surface layer to move from the glacier front towards west, thus greatly limiting the rate at which waves undercut the ice cliff (see Fig. 1a). The calving front with a cliff in the central part of the two basins (profile E, G) is clearly visible also on the DEM (Figs 3a, c) and the resulting profiles (Figs 3e, g). The central part of the glacier front rests on the bedrock of the Retreat Isle in 1960 (Fig. 3f) which has been restraining glacier flow and slowing down the retreat rate in this section, likely due to limiting of front ablation, until at least 2022 where the most recent observations were made (Fig. 2).

Surface lowering

The DEM and selected profiles across the glacier front (Fig. 3c) as well as the aerial image (Fig. 3a) indicate the variable ice characteristics near the glacier front. The central part of the glacier margin has a highly crevassed surface suggesting ice flow over heterogeneous bedrock or faster ice flow in general, unlike the northern and southern lateral zones where the surface is smoother. This is especially apparent in the southern zone where the bedrock has been exposed for almost a decade. Nordenskiöldbreen is a polythermal glacier with temperate conditions in the interior and with a frozen snout, which is visible as the southern marginal zone at present appears stagnant and, therefore, likely cold-based (e.g. Hagen and others, 1993; Rachlewicz and others, 2007; Ewertowski and others, 2016). This configuration of the glacier front suggests that the remaining marine terminating front is likely grounded in the shallow water thus providing resistive stress, slowing down the ice flow and reducing thinning.

On the other hand, the central part of the glacier margin still shows clear signs of ice flow which was also reported by den Ouden and others (2010). The crevassed zone is visible on the aerial image in Figure 3a and profiles e, f, g. This is expressed in frequent minor calving events without significant retreat of the glacier front between 2009 and 2021 in the southern marine-terminating frontal zone (3 g). There is even a minor advance recorded near Retreat Isle over this period (shown in green in Fig. 3b). Despite the continuous flux of ice mass from the upper accumulation areas and relative stability of the glacier front, the glacier surface has lowered by ~14 m in total between 2009 and 2021, or ~1.2 m a^{-1}. The stability of the glacier front suggests existence of an important pinning point which is likely to stabilize the front until it thins off this point. The maximum recorded surface lowering (except where the glacier front has retreated completely) was ~30 m, or ~2.5 m a^{-1} (Fig 3b), similar to frontal thinning rates of neighbouring smaller land-based ice masses (Małecki, 2013, 2016, 2022).

Impact of air temperatures and bedrock geometry on retreat rates

Air temperature has risen in Svalbard throughout the whole 20th century, with the exception of a short hiatus in the 1960s and 1970s (Nordli and others, 2020). The period from 1990 to present is the warmest period of the entire observational record. Between 1898 and 1990, glacier retreat rate was coincident with rising air temperatures (Fig. 4). From 1990 to present, the retreat rate of Nordenskiöldbreen slowed down and decoupled from this warming trend, and retreat rate has declined despite elevated rates of warming between 1991 and 2022 (Nordli and others, 2020) (Fig. 4a). This observation is supported by correlation tests. The 23-point time series of glacier retreat rates have a weak positive correlation ($r = 0.06$). However, over the period 1898–1990, there is a positive correlation of $r = 0.43$, and a negative correlation of $r = -0.32$ between 1991 and 2022 (Fig. 4b). The entire air temperature timeseries has a significant positive trend ($p < 0.01$) according to Mann–Kendall trend test whereas an insignificant ($p = 0.27$) negative trend in the retreat rate was found. A similar trend was found when the timeseries were split into the two time periods. A significant positive trend was found for air temperature (after 1990), whereas only insignificant negative trends were found in the retreat rate. The detected change point in 1990 suggests an important switch in the controlling mechanism of the glacier retreat dynamics.

We argue that the year 1990 marks the start of a full-scale transition from a marine-terminating to a land-terminating glacier (Fig. 1). This transition was at an advanced stage by the summer of 2022, where only ~1 km of the southern ice margin still terminated in shallow water. A reduced marine terminus limits frontal ablation and leads to stabilization of the front position (e.g. Frank and others, 2022). This is in line with our observations of the declining retreat rates and their mismatch with the post-1990 air temperature (Fig 4b). The exact bedrock geometry of the frontal section of the glacier is not known, but judging from the irregular geometry of the glacier surface and its relatively steep slope we do not expect there to be any larger depressions immediately behind the present ice margin. The expected relief of the bedrock is hummocky, and generally above sea level. Further retreat of the glacier front over the coming years is, therefore, very likely to complete the transition of Nordenskiöldbreen to a land-terminating glacier and, thus, greatly reduce its frontal ablation. This might be different in the far future along the northern margin between De Geerfjellet and Terrierfjellet (~5 km from the present glacier front) where below sea level bedrock topography was recorded by van Pelt and others (2013) (see the areas highlighted in red in Fig. 1a). Given that stake observations of the glacier surface mass balance yield conditions close to steady-state due to the large high-elevation accumulation area (Schuler and others, 2020), the retreat of the glacier front from fjord to land would hypothetically help the glacier to find a new balance within the present climatic conditions.

The magnitude of retreat rate and frontal ablation is usually attributed to ocean temperatures (Luckman and others, 2015) or the intrusion of warmer water (de Rovere and others, 2022; Chudley and others, 2023) which is probably responsible for most of the retreating Arctic marine-terminating glaciers (e.g. Straneo and Heimbach, 2013; Holmes and others, 2019). Some regional differences are also attributed to topographic controls (Carr and others, 2014). However, recent accelerated retreat of marine-terminating glaciers in the Canadian Arctic Archipelago correlates well with the enhanced atmospheric warming (Cook

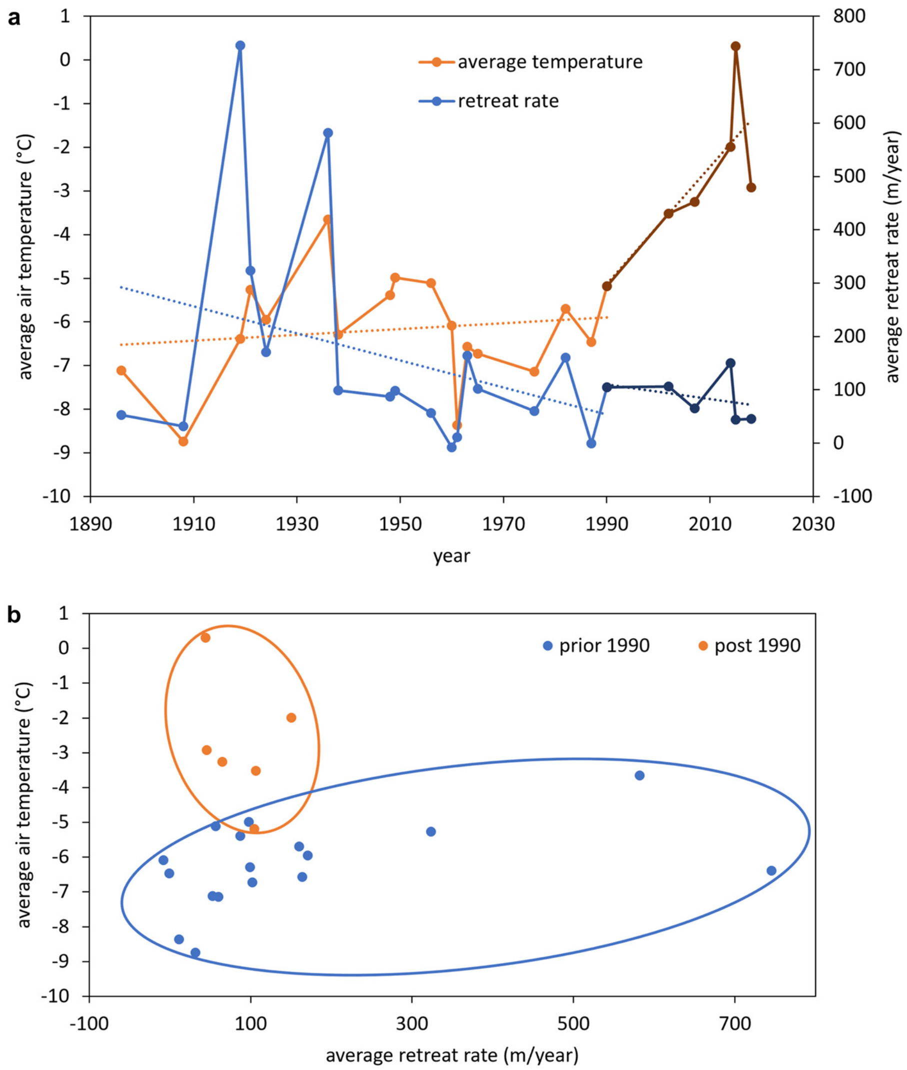

Figure 4. (a) Annual average retreat rate and annual average air temperature at Svalbard Lufthavn station (data from the Norwegian Meteorological Institute) over the study period with linear trendlines for the periods 1896–1990 and 1990–2022; (b) average air temperature and retreat rate timeseries divided into pre- and post-1990, showing that the clusters of 1896–1990 and 1990–2012 have minimal overlap.

and others, 2019). Similarly, Slater and Straneo (2022) observed amplification of submarine melting of marine-terminating glaciers in northwest Greenland by atmospheric warming which enhanced surface meltwater production and release of water into the ocean. This further exacerbates near-glacier ocean circulation and in turn the transfer of heat from ocean to ice. Increased melt in this area was also attributed to higher frequency of föhn winds (Mattingly and others, 2023). Our results show that Nordenskiöldbreen, with a large accumulation area in the high elevated ice cap (Lomonosovfonna), was probably similarly controlled by atmospheric forcing (and meltwater production which exacerbated the transfer of heat from the ocean), rather than by ocean temperatures, until the 1990s when the transition from marine to land-terminating glacier started. This is supported by the strong correlation of retreat rate and air temperature in the period prior to 1990s (Fig. 4). This interpretation cannot be directly proven due to the lack of site-specific ocean temperature data. However, warming has been observed in Billefjorden since 1912, intensifying in the last two decades (Bloshkina and others, 2021), which also does not match to the retreat rate record.

Implications for future work

Thus far medium-resolution satellite imagery has failed to clearly portray the hummocky subglacial topography beneath large sections of the present ice margin of Nordenskiöldbreen, which are evident only when observed in the field (Figs 5a, b). Our study underlines this shortcoming of remote-sensing methods (e.g. Gourmelon and others, 2022) in glaciological mapping which potentially might lead to overestimation of marine-terminating ice cliff lengths, and thus, to region-wide overestimates of frontal ablation (e.g. Kochtitzky and others, 2022). Distinguishing calving glacier fronts from already land-based glaciers might be done using information on subglacial topography where above-sea level topography would be identifiable. However, the predicted subglacial topography is also highly uncertain (compare e.g. Millan and others (2022) with Fürst and others (2018)) and cannot be reliably used to eliminate the shortcomings of the remotely sensed ice cliffs. The uncertainty of glacier thickness (and consequently subglacial topography) is high especially in unsurveyed glaciers (up to 100 m according to Fürst and others (2018)) but also in the case of well and frequently directly surveyed tidewater glaciers such as Hansbreen (Möller and others, 2023). Moreover, the uncertainties in glacier thickness estimates are generally higher in the terminus area (Recinos and others, 2019). Sixty-one out of 214 Svalbard marine-terminating glaciers have developed into land-based glaciers from 1930s to 2019 (Kavan and Strzelecki, 2023). To select glaciers which are currently undergoing a transition similar to Nordenskiöldbreen, we suggest seeking signs of front position stabilization over intervals of ~10 years to exclude short-term variability. Similar slow-down and potential switching from marine to land terminating in the near-future can be found in several glaciers around Svalbard (e.g. Vestre Torellbreen, Skimebreen, Bereznikovbreen, Havhestbreen

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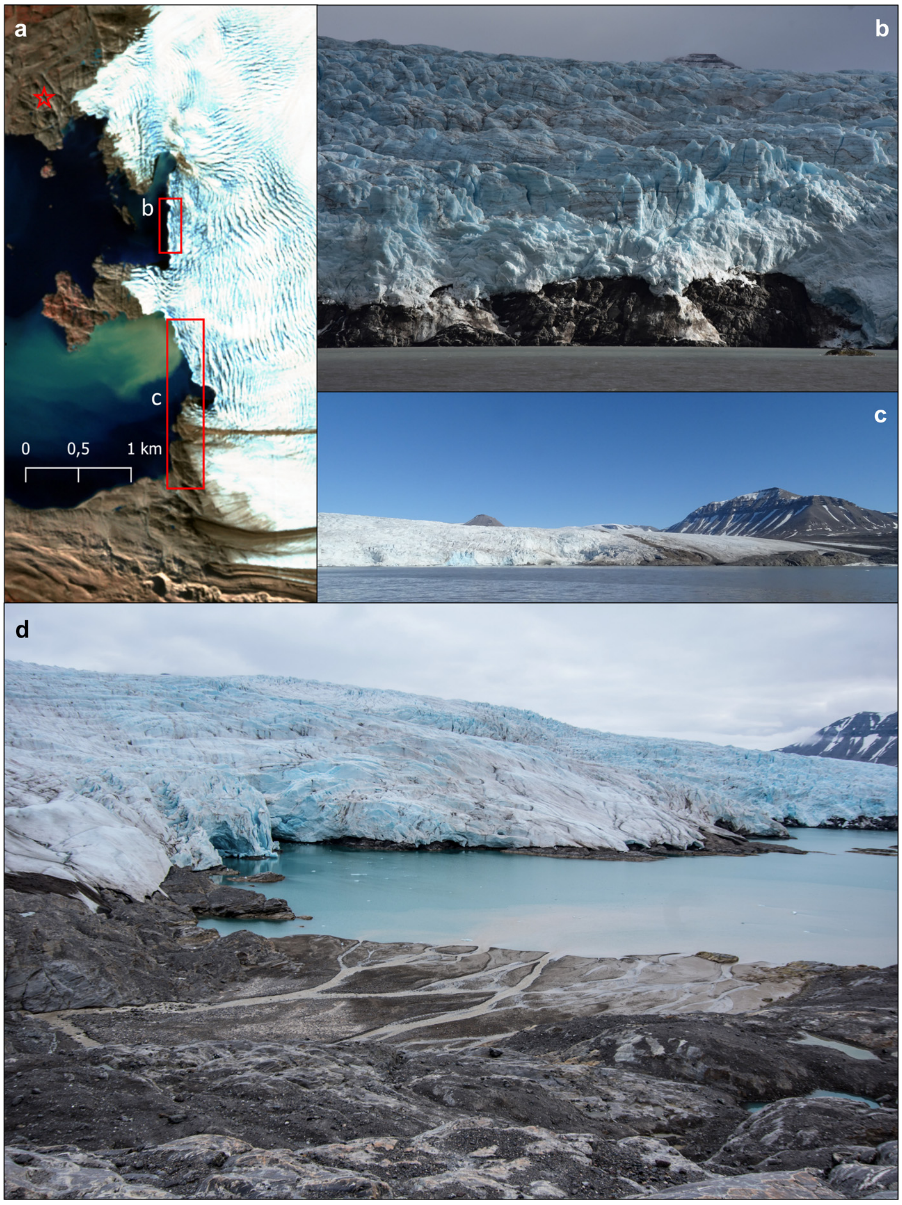

Figure 5. (a) Sentinel-2 false colour scene of 23/08/2022 of the northern section of the Nordenskiöldbreen margin. Red rectangles show the areas photographed in panels b and c, the star marks the location of the delta in panel d; (b) bedrock outcrops beneath the present ice margin of Nordenskiöldbreen in August 2022; (c) the southern glacier margin with remaining calving front; (d) delta that was formed after a sudden drainage of an ice-marginal lake, and subglacial bedrock outcrops (July 2018 photograph by Martin Luláк).

or Andrebreen). The glacier termini show similar visual signs of slowdown as reported from Nordenskiöldbreen when inspecting the aerial images (e.g. https://toposvalbard.npolar.no/). Such a separation of glacier margins from the ocean might bring important consequences for glacier thermal regimes and, hence, their dynamics. It also removes the ocean-induced melting as an important source of ice loss. Without contact with water and especially due to thinning of the frontal part, glacier marginal zones might switch from warm-based conditions to freezing of their basal sections to the bed, as documented for several smaller glaciers in Svalbard (Hodgkins and others, 1999; Hambrey and others, 2005; Bælum and Benn, 2011) or in Greenland (Carrivick and others, 2023). This might lead to a general deceleration of ice flow (Sevestre and others, 2015), and, therefore, a reduction of their ice flux to the ocean, an effect which should be accounted for in projections of future sea-level rise contribution from Arctic glaciers.

Conclusions

We have presented a comprehensive overview of the post LIA retreat of Nordenskiöldbreen and have shown its transition from a marine-terminating to a land-based glacier. We have used a set of historic glacier front positions in a high temporal resolution complemented by long-term air temperature observation. Our data indicate that a major shift in the glacier regime occurred around the year 1990 when the retreat rate slowed down despite the clear increasing trend in air temperature. It is apparent that the climatic control has not been the main driving force of the retreat since this point, likely because the glacier retreated into shallow water or in some parts subaerial environment which has restricted further calving in most of the frontal zone. The transition towards a land-terminating glacier was documented by analysis of the available historic DEMs. Despite the extreme warming in the last decade, the retreat was negligible in the southern part of the marine-based glacier front. However, a significant surface lowering (with the average lowering of 14 m and up to 30 m maximum) was recorded between 2009 and 2021. The shift towards a land-based glacier may have important implications for fjord circulation in front of the glacier with consequences for the local ecosystem. Identification of glacier fronts in transition from marine terminating towards land based (or perhaps already land based) may be crucial for precision of regional scale frontal ablation estimates based purely on remote-sensing data analysis, which may be overestimating this component in its present form.

https://doi.org/10.1017/jog.2023.92 Published online by Cambridge University Press

Acknowledgements. 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) and Arctic Field Grant project 'Glacier mass balance – central Svalbard' (ID 282536), funded by The Research Council of Norway. J. K. was supported by the Czech Antarctic Research Programme. We acknowledge the help of Veronika Kavanová for performing the statistics in R and Christopher Stringer for language checks. We also greatly appreciate help of the three anonymous reviewers and Rachel Carr as scientific editor.

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https://doi.org/10.1017/jog.2023.92 Published online by Cambridge University Press