

<https://doi.org/10.1038/s43247-024-01877-8>

Glacier surge as a trigger for the fastest delta growth in the Arctic

Check for updates

J. Kavan^{1,2}✉, M. C. Strzelecki³, D. I. Benn⁴, A. Luckman⁵, M. Roman^{2,6} & P. Zagórski⁷

The widespread retreat of Svalbard glaciers has been frequently interrupted by short-lived surge advances. In the case of marine-terminating glaciers this is often expressed in the remodelling of coastal zones. Here, we analyzed the coastal zone changes in front of the recently surging Recherchebreen. The glacier advanced ca 1200 m since 2018 and suddenly stopped in June 2020 followed by the rapid formation of a delta system in front of its subglacial meltwater outlet. The delta advanced by ca 450 m with probably the fastest progradation rate ever detected in the Arctic region (ca 7 m/day). The synchronicity of the final slow-down of the glacier with the delta building indicates that this event records the release of stored water and sediments from beneath the glacier and thus provides direct evidence of drainage reorganisation at the termination of a surge. Such behaviour is likely common among Svalbard surging glaciers, but it only rarely leaves any direct geomorphic evidence.

Svalbard has experienced significant climate warming since the end of the Little Ice Age (LIA)¹, which has resulted in widespread glacier mass loss². The warming rate in the Arctic was nearly four times faster than the rest of the globe during the last 40 years³. Such warming results in the acceleration of mass loss and thinning rates of glaciers and ice caps¹ which is likely to continue as the glaciers are highly sensitive to temperature⁵. Retreat and thinning of Svalbard glaciers have been observed throughout the archipelago^{3,6,7}.

Marine terminating glaciers represent an important proportion of Svalbard glaciers in terms of their number (15–20%)^{8,9}. In terms of area, more than 60% of all glacier fronts terminate in the sea⁸. The dynamics (advance/retreat) of the marine-terminating glaciers is often expressed in reworking of the coast directly adjacent to their fronts. These areas can thus be considered as one of the most active paraglacial landscapes of Svalbard. The dominant retreat trend has led to the origin of more than 900 km of new coasts since the 1930s, representing an increase of 16.4% in Svalbard coastline length⁶. Svalbard is the location of a major cluster of surge-type glaciers^{10,11}, so in many cases glacier retreat has been interrupted by advances of hundreds or thousands of metres^{12,13}.

The present Svalbard coast is, to a large extent, characterized by bedrock geology shaped by glacier erosion during the Last Glacial Maximum. The coastal zone was later remodelled by glacier fluctuations during the Holocene and also affected by a continuous glacioisostatic

rebound of the landmass. Uplifted beaches, marine terraces and sequences of cliffs are characteristic elements of coastal landscape formed throughout the Holocene. The largest coastal forms, however, preserved in the relict coastal landscapes are deltas, particularly those formed in the early stages of the Holocene and characterized by massive paraglacial sediment delivery from deglaciating valleys. This period was dominated by high air temperatures leading to significant meltwater production from local glaciers, thus probably corresponding to a Holocene peak water period (as defined by Huss and Hock¹⁴). Deltas are also among the most abundant modern coastal landforms in Svalbard as a result of active sediment transport carried out by both glacial-fed rivers and non-glacial streams (e.g.,^{15,16}). Their growth, however, is rather slow and does not reach the progradation rates observed in other glaciated parts of the Arctic such as Greenland¹⁷. In general, the Svalbard coastal zone has a high resilience to erosion and other extreme processes associated with climate warming—for instance, a decrease of sea-ice cover or the degradation of coastal permafrost^{18,19}. In recent years the disruption of relative stability of the Svalbard coast has been associated with the occurrence of extreme events such as glacier lake outburst floods leading to barrier breaching and lagoon inundations²⁰, or glacier surge events²¹ leading to bulldozing of beaches formed in front of glacier snouts.

We present the case of Recherchebreen in Svalbard to illustrate a previously unseen mode of coastal adaptation in the form of rapid delta

¹Centre for Polar Ecology, Faculty of Science, University of South Bohemia, České Budějovice, Czechia. ²Polar-Geo Lab, Department of Geography, Faculty of Science, Masaryk University, Brno, Czechia. ³Alfred Jahn Cold Regions Research Centre, Institute of Geography and Regional Development, University of Wrocław, Wrocław, Poland. ⁴School of Geography and Sustainable Development, University of St Andrews, St Andrews, UK. ⁵Department of Geography, Faculty of Science and Engineering, Swansea University, Swansea, UK. ⁶Centre for Glaciology, Department of Geography and Earth Science, Aberystwyth University, Aberystwyth, Wales, UK. ⁷Institute of Earth and Environmental Sciences, Maria Curie-Skłodowska University, Lublin, Poland. ✉e-mail: jan.kavan.cb@gmail.com

formation at the end of a surge—one that has exceeded previously documented delta progradation rates in the High Arctic region.

Recherchebreen is a glacier located in the southwestern part of Spitsbergen Island in the Bellsund area (Fig. 1). The glacier has an area of 136 km² (according to GLIMS database) and terminates in the so-called Recherche lagoon. The lagoon is built up from the former deltas that block the lagoon from the open sea²². The glacier itself is characterised by highly dynamic behavior with four surges identified in the last 200 years²³. However, the two surges recorded during the Little Ice Age (ca 1820 and ca 1880) terminated

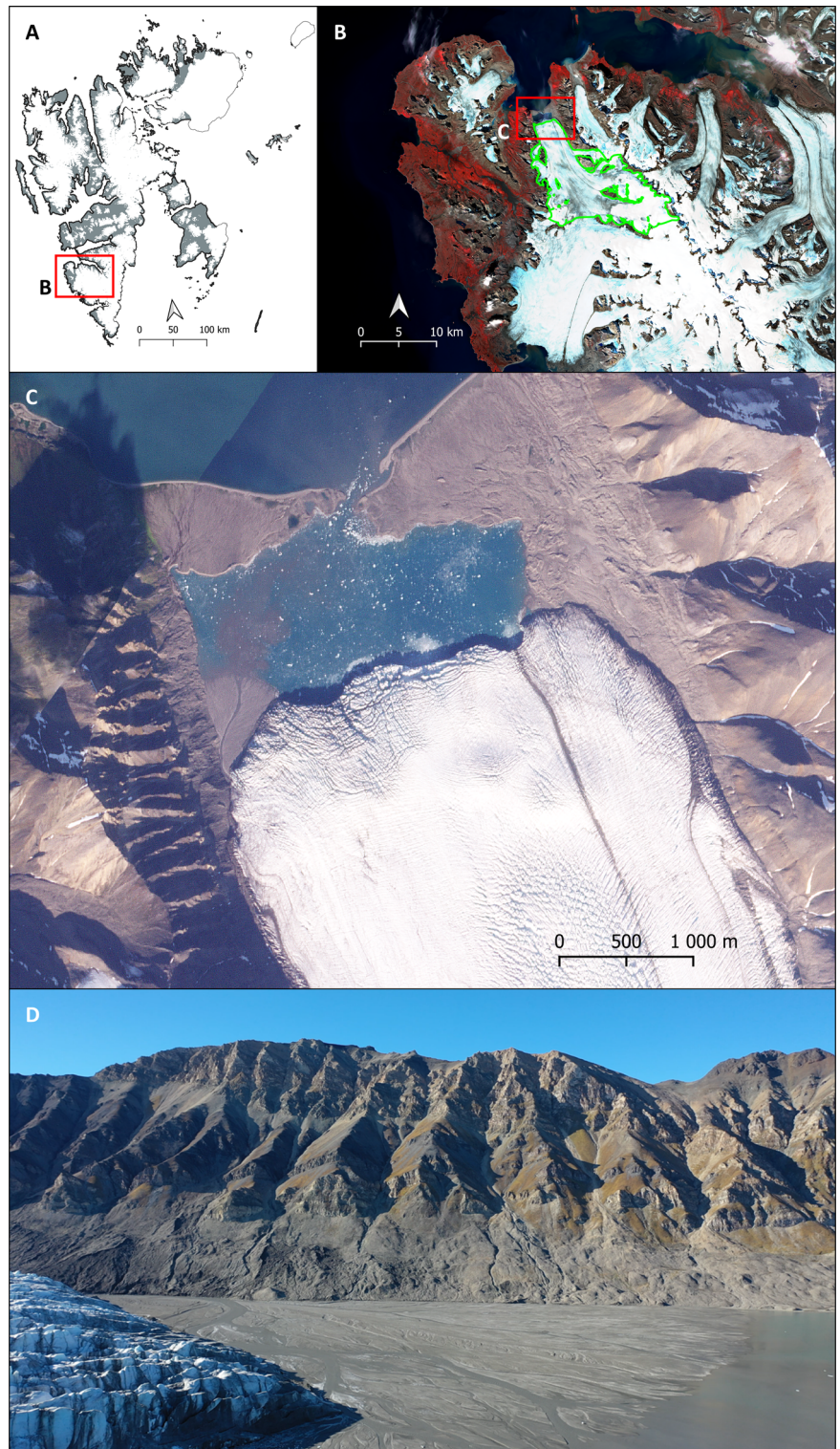
outside of the recent fjord and therefore did not leave any subaerial landforms. The latter two surges (early 1940s and 2018–2020) did not extend as far as the earlier ones and the glacier only advanced within the shallow fjord environment.

Results and discussion

Surging and delta formation

Large volumes of water can be released from surging glaciers as the result of reorganisation of the drainage system or the removal of hydraulic

Fig. 1 | Recherchebreen study site. A Svalbard archipelago with the location of the study area marked with the red rectangle; B Study area with extent of Recherchebreen indicated in green (according to GLIMS database)—Sentinel-2 false colour image from 31 July 2020 as a background; C The glacier snout and a glacier lagoon with two former deltas as a barrier, the new delta formed in 2020 in its true left frontal part—PlanetScope image from 26 August 2022; D UAV image of the delta from 29 August 2022.



barriers^{24,25}, potentially affecting spatial patterns of sediment delivery and delta formation²⁶. Extreme release of sediments connected to surge-induced outburst floods at marine-terminating glaciers can be identified in marine sedimentary records²⁷, but is hardly observable in high temporal resolution.

The main phase of the most recent surge of Recherchebreen started at the end of 2018 with a major advance recorded in 2019. Figure 2 shows the glacier snout in August 2018, a few months before the advance commenced and in June 2020, close to the end of the surge. Two later images represent building of a delta during the first few weeks after surge termination and a stabilized delta in the summer 2022.

The Recherchebreen snout advanced by about 1200 m during the surge event, with the ice flow velocities ranging between 3–4 m/day in 2019 and around 2 m/day in 2020 (Fig. 3). The final phase of the surge in June 2020 was characterised by a short speed-up followed by an almost complete cessation of glacier movement. At the same time, the delta started to form in mid-June. After the delta reached ca 450 m in centreline length by end of July the rapid growth ceased. In the course of less than 2 months, the delta therefore grew at an average rate of more than 7 m per day. This is probably the fastest delta growth episode observed in the Arctic. To the best of our knowledge, a similar rate has not yet been detected even in the case of the Greenlandic deltas¹⁷, which are fed by much larger glaciers than on Svalbard. Since that time, the delta has continued to slightly increase in area. This further growth might be attributed to the transfer of material within the delta from upstream parts to its front as documented by visible erosion of the upper part of the delta observed in the summer of 2023.

The delta centreline reached 450 m during the 2020 summer with only a minor growth in the next two years (510 m in 2021 and up to 600 m in 2022, respectively). The delta subaerial volume as calculated from the ArcticDEM (2 July 2021) is 610,000 m³. The average slope of the delta is 1.32%

in comparison to 0.94% in case of the older delta, which formed subsequent to the 1940s surge (Fig. 4, photograph from 1960). It is evident that the older deltas left behind by retreating glacier are flatter than the younger delta. This is undoubtedly related to the transformation of their surface following the cease of glacial river sediment supply. It can be reasonably assumed that in the near future, material from the upper parts of the modern delta will be transported towards the front, resulting in the formation of a wider but flatter delta. Such transformation will continue until the delta will be completely cut off the glacier meltwater inflow. Following the next phase of glacier recession and paraglacial landscape reshaping, the delta will exhibit a morphology similar to that of the older deltas. Fluvial erosion of the upper part of the delta was observed in field already in 2023.

Ice velocity and surface melt

To understand the significance of the meltwater release event implied by rapid delta formation, it is useful to consider the controls on water storage and release during the whole surge cycle. Velocity fluctuations during surges of Svalbard glaciers commonly display correlations with air temperature, reflecting routing of surface meltwater to the bed through crevassed ice^{25,28}. This can be clearly seen in Fig. 3, which shows that speedups in 2018, 2019, and 2020 coincide with the onset of sustained positive air temperatures. In 2018, a relatively limited summer speedup occurred during the summer months (May–August), broadly mirroring the air temperature record. A more sustained speed-up began in early September 2018, coincident with a succession of positive air temperature anomalies. Velocities reached a peak at the end of January 2019 followed by a gradual slowing trend. With the onset of sustained positive air temperatures in early June 2019, a major rapid speed-up occurred with velocities peaking at over 7 m day⁻¹ at the end of that month. Although air temperatures remained positive during July,

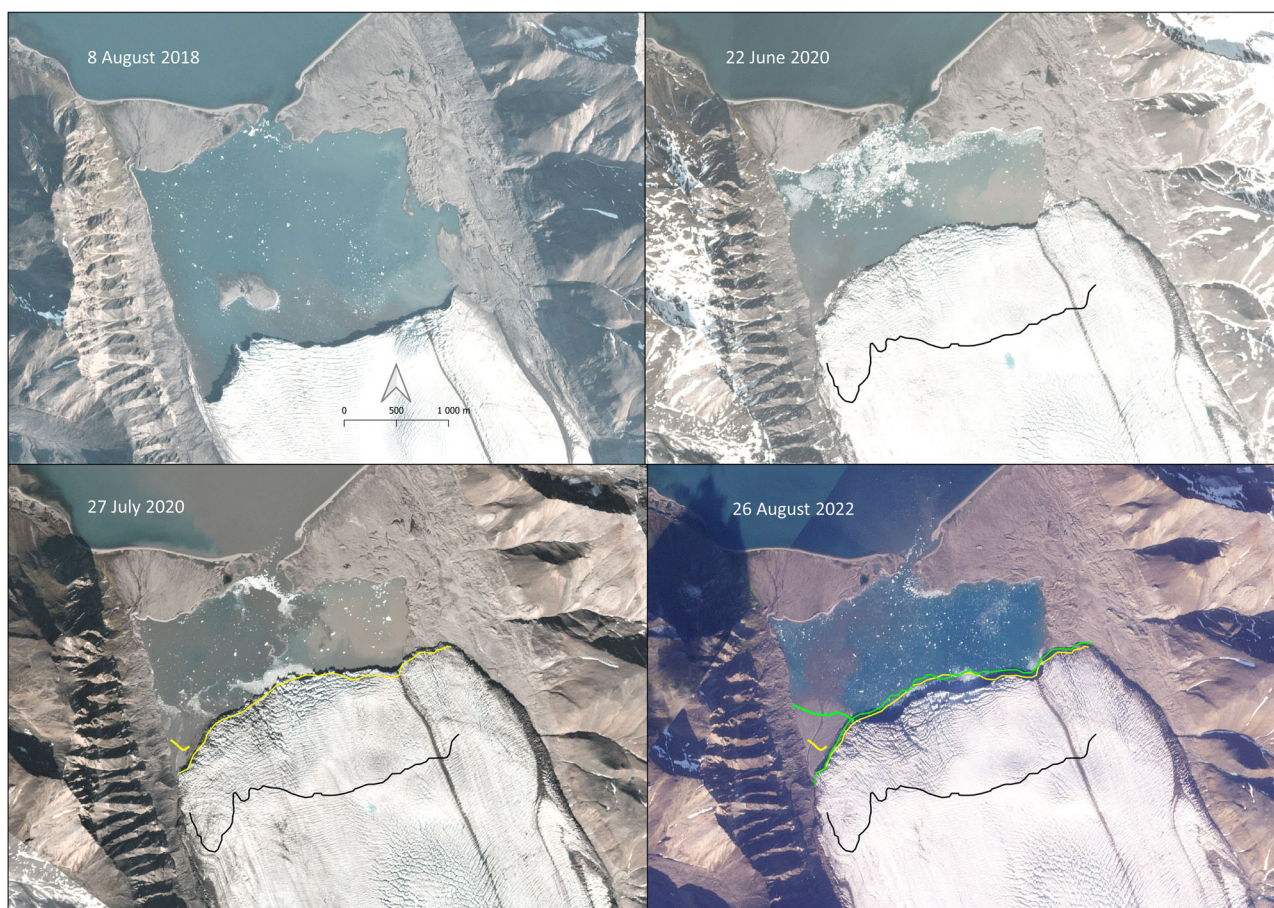


Fig. 2 | Glacier surge evolution. The 2018–2020 surge of Recherchebreen and subsequent delta formation. Coloured lines represent positions of glacier front and delta fronts from the previous panels (based on PlanetScope scenes).

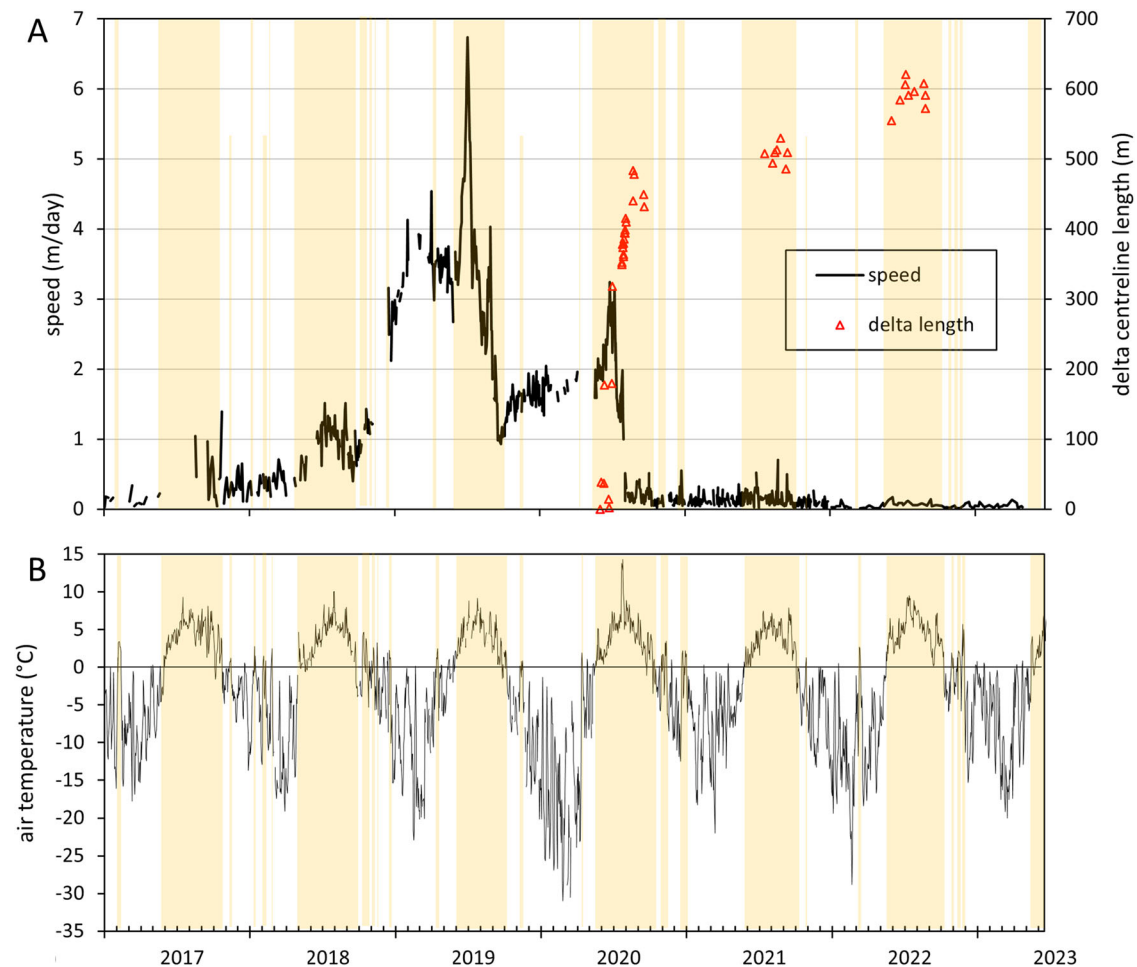


Fig. 3 | Synchronicity of glacier surge and delta formation. **A** Time series of glacier velocities and delta centreline length, showing the synchronicity of the final speed-up/slowdown event and delta formation; **B** mean daily air temperature record from

the closest weather station (Akseløya – ca. 20 km) operated by The Norwegian Meteorological Institute; above zero air temperature periods highlighted in orange.

August, and September, velocities fell dramatically, apart from a brief speed-up during a warm and wet period in August. Such summer slowdowns are common on both surging and non-surging glaciers, and reflect the development of efficient sub-glacial hydrological systems in response to high meltwater influx^{29–32}.

Following a minimum in September 2019, velocities increased slightly then maintained roughly uniform values of 1.5–2.0 m day⁻¹ throughout the winter and following spring. Melt onset in early June 2020 triggered another speed-up, peaking at ca 3 m day⁻¹ at the end of the month. The subsequent rapid slowdown marked the termination of the surge, and the associated release of stored water resulted in the period of rapid delta growth described above.

Evidence for similar past processes

Four past surges including the one described above were evidenced in Recherchebreen²³. Analysing the historical images, it is apparent that similar patterns of delta development occurred also in the past (Fig. 4). On the aerial image from 1960 we can identify the delta that formed after the surge around 1940. This delta is now positioned in front of the present delta and is completely cut off from the glacier. Between 1960 and 1990 the outlet of the subglacial river network probably switched back to its position visible on the 1936 image (the true right glacier front). This was also accompanied by the formation of the delta. These two deltas have consequently closed up the lagoon and isolated it from the open sea environment. The present lagoon is relatively shallow with maximum depths reaching down to 75 m. The zone

where the recent delta has developed had a depth of ~20 m in 2011 and 2012 when the bathymetric survey was conducted³³. Switching of the subglacial hydrological network outlet between very extreme left and right margin is likely determined by the glacier bedrock topography with an important crest below the glacier centreline diverting outflow to its lateral zones³⁴. Based on the historic evidence we can conclude that delta formation in front of Recherchebreen very likely followed the pattern described for the 2018–2020 surge event and that it is a normal mode of operation in this shallow sea environment.

Implications

From the regional perspective, it is important to note that although deltas are found frequently along the Svalbard coasts and the High Arctic is undergoing one of the fastest warming in recent decades³, there is no evidence of significant progradation of Svalbard deltas, unlike for example in Greenland¹⁷. We argue that recent climate-induced changes in the cryosphere, and consequent increase in glacial runoff and sediment transport, are insufficient to build up new or remodel the present delta systems in Svalbard. The large deltas that are found in Svalbard originated mostly in the early Holocene during the rapid deglaciation of large ice caps and glaciers from the decaying Svalbard-Barents Sea Ice Sheet, releasing massive amounts of sediment from deglaciated valleys and mountain slopes³⁵ and are currently cut off from the operation of coastal processes due to still ongoing glacioisostatic uplift^{36–38}. Formation of similar massive new deltas in the present climate conditions, with limited glacier extent and lack of

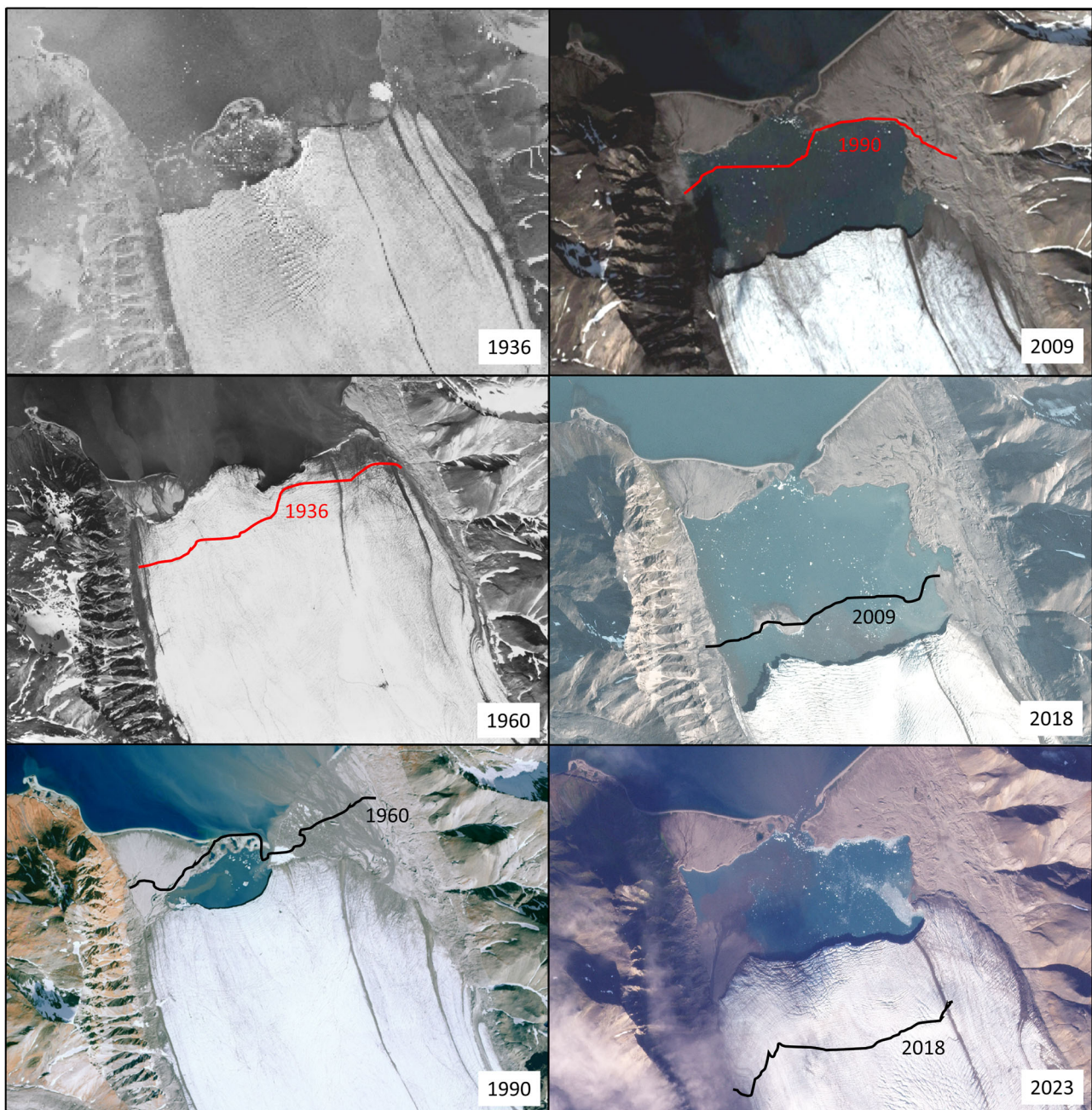


Fig. 4 | Surging history since Little Ice Age. Long-term evolution of the glacier front/deltas based on the historic aerial images (acquired by NPI); white arrows mark the location of subglacial meltwater outlet and sediment delivery to the lagoon.

sediment sources is therefore unlikely to occur in modern paraglacial environments. Only during extreme glacio-hydrological events such as surges (e.g., this study) or glacier lake outburst floods, as recorded in the case of Nordenskiöldbreen³⁹, are rapid episodes of sudden delta growth possible.

In the global scale, the controls and extreme rapidity of the delta formation recorded in the case of Recherchebreen offers a new perspective on deltas formation in the Arctic. Permafrost and sea-ice processes are crucial controls of Arctic deltas morphodynamics. With continued warming the near future will witness the transition from ice to non-ice-dominated systems⁴⁰. This is particularly important for deltas developing in ice-rich permafrost parts of the Arctic, where open-water conditions are expanding most rapidly and wave energy is predicted to significantly increase⁴¹. The Recherchebreen rapid delta development has revealed a new form of interaction between ice and coast in the Arctic. The ice does not protect and

stabilise the delta, but is directly responsible for sediment supply and delta formation. Importantly, in this young paraglacial environment, freshly exposed from the ice and subsequently re-eroded by the surge, there is neither space nor time for the formation of permafrost. In addition, the proximity of the ice cliffs means that the shores and surfaces of the deltas are subject to extreme wave action from glacier calving or icebergs rolling⁴². The presence of glacial ice also determines the duration of sediment supply and the subsequent survival of landforms along the shores of glaciated fjords or bays. Their short-lived character and direct threat of extreme wave impact reduce the importance of new deltas as wildlife oases or opportunities for economic exploitation, e.g., sand mining as in Greenland⁴³. This distinguishes deltas formed in close proximity of marine-terminating glaciers from deltas described in the literature in Arctic permafrost environments, e.g., Yukon, Alaska, Siberia⁴⁰, or deltas known in Greenland, Svalbard, or the Canadian High Arctic that are fed by glacial rivers or snow-fed streams^{44,45}.

Conclusions

We have documented the evolution of a surge advance of Recherchebreen connected to the formation of a new delta in its true left margin just after the advance has slowed down. The glacier advanced ca 1200 m in 2019–2020 with the highest flow velocities reaching up to 7 m day⁻¹. The surge finished in June 2020 directly followed by the build-up of a 450 m long delta during June and July 2020. The synchronicity of surge speed up followed by a sudden slow down and start of building a delta indicates that this event was caused by the release of stored water from beneath the glacier. This involved the development of an efficient conduit, and possibly also the removal of a barrier to water flow. Overall, it demonstrates the hydraulic switching at the end of a surge as a key control of glacier dynamics.

The shallow nearshore environment of a fjord and glacier bed topography is favorable for the development of such surge-related events. This is well demonstrated in the presence of similar delta landforms located in front of the present glacier front. These deltas were formed during the 20th century very likely in a similar manner to the most recent one. In a wider perspective, the example of Recherchebreen demonstrates that the formation of deltas in glaciated parts of Arctic is currently connected to extreme glacial events, such as surges or glacier lake outburst floods. This new type of ice-dominated deltas is profoundly different from the Arctic deltas controlled today by permafrost and sea ice or the palaeo-deltas, which expanded rapidly after the ice sheet decay. The unique controlling factors, ephemerality, and morphodynamic processes strongly linked to the behavior of marine-terminating glaciers make those new Arctic delta systems an important subject for research, with the expected further collapse of the glaciated margins of the Arctic region.

Data and methods

Remote sensing data

In this study, we combined Sentinel-1 radar images, Sentinel-2 multispectral images (available from Sentinel Hub EO browser: <https://www.sentinel-hub.com/explore/eobrowser/>) and Planet images. This was complemented by use of individual ArcticDEM strips from 2021 to evaluate the volumetric changes in the glacier foreland⁴⁶. All the spatial analyses and calculations were done in QGIS 3.22.

Glacier velocity calculations

Glacier velocities were derived by feature tracking between consecutive images from the EU Copernicus Sentinel-1 mission. From September 2016 to December 2021, the mission comprised two satellites (Sentinel-1A and 1B) which allowed 6-day tracking. Outside of these dates, only one satellite was available with a 12-day repeat. The spatial resolution of Sentinel-1 is ~5 × 20 m which, when projected onto ground coordinates is around 10 × 10 m. Feature tracking was accomplished using standard techniques implemented in Gamma software; details of the technique and robustness are given in ref. 47. Specifically, features were tracked between consecutive pairs of Sentinel-1 images using tracking windows of 416 × 128 pixels (~1 km in map coordinates) and sampled every 2 × 10 pixels yielding an approximate displacement map resolution of 100 m. Velocity maps were projected onto map coordinates using a TanDEM-X DEM at a pixel size of 100 m. On the crevassed tongue of a glacier such as Recherchebreen, trackable features are plentiful, feature tracking quality is high, even between 12-day image pairs, and uncertainties in velocity are estimated at 0.2 m/day. In addition, to provide an animation of the surge, backscatter images were projected to map coordinates at a pixel size of 10 m. The velocity of Recherchebreen during the surge (Fig. 3) was extracted from a point close to the terminus which yielded a typical representation of velocities during the surge (Fig. 1C).

Delta extent mapping

Delta extent was delimited manually with use of Sentinel-2 images complemented by Sentinel-1 radar images for periods with extensive cloud

cover. Normalized Difference Water Index (NDWI) was used to aid in distinguishing between delta surface and water when the optical images were not clear enough. NDWI is a combination of bands B3 and B8 of the Sentinel-2 imagery, that facilitates distinguishment between water bodies and landmass and is directly provided by the Sentinel Hub EO browser. High-resolution PlanetScope images were also used to complete the dataset (Supplementary Table 1). The delta shoreline was then used to calculate delta centreline length for each particular image/date. It was not possible to eliminate the effect of different tidal phases at the moment of the image acquisition. The resulting time series of delta centreline length has therefore a variability of few tens of metres.

Delta volume estimation

An ArcticDEM strip acquired on 2 July 2021 was used to calculate the subaerial volume of the delta as delimited from the optical Sentinel-2 image (3 July 2021). The DEM was offset by 39.5 m from the local datum and was therefore corrected. The procedure is described for example in ref. 48. The corrected DEM was then masked, and the above-sea-level volume was calculated.

Reporting summary

Further information on research design is available in Nature Portfolio Reporting Summary linked to this article.

Data availability

Publicly available data were used for the analyses: Planet imagery (<https://www.planet.com/explorer/>), Sentinel imagery through the EO Browser (<https://apps.sentinel-hub.com/eo-browser/>) and ArcticDEM through the University of Minnesota application (<https://www.pgc.umn.edu/data/arcticdem/>). Weather data were provided by the Norwegian Meteorological Institute through the Frost API website (<https://frost.met.no>). The data derived from these archives (delta centreline length, glacier velocities) are available from the online repository at: <https://doi.org/10.5281/zenodo.10837404>.

Received: 25 March 2024; Accepted: 5 November 2024;

Published online: 14 November 2024

References

1. Nordli, Ø. et al. Revisiting the extended Svalbard Airport monthly temperature series, and the compiled corresponding daily series 1898–2018. *Polar Res.* **39**. <https://doi.org/10.33265/polar.v39.3614> (2020).
2. Geyman, E. C., van Pelt, W. J. J., Maloof, A. C., Aas, H. F. & Kohler, J. Historical glacier change on Svalbard predicts doubling of mass loss by 2100. *Nature* **601**, 374–379 (2022).
3. Rantanen, M. et al. The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.* **3**, 168 (2022).
4. Hugonnet, R. et al. Accelerated global glacier mass loss in the early twenty-first century. *Nature* **592**, 726–731 (2021).
5. Rounce, D. et al. Global glacier change in the 21st century: every increase in temperature matters. *Science* **379**, 78–83 (2023).
6. Kavan, J. & Strzelecki, M. C. Glacier decay boosts formation of new Arctic coastal environments—perspectives from Svalbard. *Land Degrad. Dev.* **34**, 3467–3474 (2023).
7. Schuler, T. V. et al. Reconciling Svalbard glacier mass balance. *Front. Earth Sci.* **8**, 156 (2020).
8. Błaszczyk, M., Jania, J. A. & Hagen, J. O. Tidewater glaciers of Svalbard: recent changes and estimates of calving fluxes. *Pol. Polar Res.* **30**, 85–142 (2009).
9. K. öng, et al. (eds) Global Land Ice Measurements from Space. (Springer, 229–239).
10. Hagen, J. O., Liestøl, O., Roland, E. & Jørgensen, T. (1993). Glacier atlas of Svalbard and Jan Mayen. Meddelelser, 129. Norsk Polarinstittutt, 140 p.

11. Jiskoot, H., Boyle, P. & Murray, T. The incidence of glacier surging in Svalbard: evidence from multivariate statistics. *Comput. Geosci.* **24**, 387–399 (1998).
12. Lønne, I. Low-velocity glacial surges—processes unlocked by modern surge, on Svalbard. *Geology* **34**, 553–556 (2006).
13. Sund, M., Lauknes, T. R. & Eiken, T. Surge dynamics in the Nathorstbreen glacier system, Svalbard. *Cryosphere* **8**, 623–638 (2014).
14. Huss, M. & Hock, R. Global-scale hydrological response to future glacier mass loss. *Nat. Clim. Change* **8**, 135–140 (2018).
15. Mercier, D., & Laffly, D. Actual paraglacial progradation of the coastal zone in the Kongsfjorden area, western Spitsbergen (Svalbard). In Harris, C. and Murton, J. B. (Eds), *Cryospheric Systems: Glaciers and permafrost*. Special Publication 242, 111–117 (Geological Society, 2005).
16. Strzelecki, M. C. et al. 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 Degrad. Dev.* **29**, 1962–1978 (2018).
17. Bendixen, M. et al. Delta progradation in Greenland driven by increasing glacial mass loss. *Nature* **550**, 101–104 (2017).
18. Lantuit, H. et al. The ACD coastal database: a new classification scheme and statistics on Arctic permafrost coastlines. *Estuaries Coasts* **35**, 383–400 (2012).
19. Lim, M. et al. Arctic rock coast responses under a changing climate. *Remote Sens. Environ.* **236**, 11150 (2020).
20. Wołoszyn, A., Owczarek, Z., Wieczorek, I., Kasprzak, M. & Strzelecki, M. C. Glacial outburst floods responsible for major environmental shift in Arctic Coastal Catchment, Rekvedbukta, Albert I Land, Svalbard. *Remote Sens.* **14**, 6325 (2022).
21. Grabiec, M. et al. Coast formation in an Arctic area due to glacier surge and retreat: the Hornbreen–Hambergreen case from Spistbergen. *Earth Surf. Process. Landf.* **43**, 387–400 (2018).
22. Zagórski, P., Gajek, G. & Demczuk The influence of glacier systems of polar catchments on the functioning of the coastal zone (Recherchefjorden, Svalbard). *Z. Geomorphol.* **56**, 101–121 (2012).
23. Zagórski, P. et al. Surges in three Svalbard glaciers derived from historic sources and geomorphic features. *Ann. Am. Assoc. Geogr.* **113**, 1835–1855 (2023).
24. Benn, D. I., Fowler, A. C., Hewitt, I. & Sevestre, H. A general theory of glacier surges. *J. Glaciol.* **65**, 701–716 (2019).
25. Benn, D. I. et al. Mass and enthalpy budget evolution during the surge of a polythermal glacier: a test of theory. *J. Glaciol.* **65**, 717–731 (2019b).
26. Fleisher, P. J., Bailey, P. K. & Cadwell, D. H. A decade of sedimentation in ice-contact, proglacial lakes, Bering Glacier, AK. *Sediment. Geol.* **160**, 309–324 (2003).
27. Jaeger, J. M. & Nittrouer, C. A. Marine record of surge-induced outburst floods from the Bering Glacier, Alaska. *Geology* **27**, 847–850 (1999).
28. Sevestre, H. et al. Tidewater glacier surges initiated at the terminus. *J. Geophys. Res. Earth Surf.* **123**, 1035–1051 (2018).
29. Bartholomew, I. et al. Short-term variability in Greenland Ice Sheet motion forced by time-varying meltwater drainage: Implications for the relationship between subglacial drainage system behavior and ice velocity. *J. Geophys. Res. Earth Surf.* **117**, <https://doi.org/10.1029/2011JF002220> (2012).
30. Benn, D. I., Hewitt, I. J. & Luckman, A. J. Enthalpy balance theory unifies diverse glacier surge behaviour. *Ann. Glaciol.* **63**, 88–94 (2023).
31. Mair, D. et al. Hydrological controls on patterns of surface, internal and basal motion during three “spring events”: Haut Glacier d’Arolla, Switzerland. *J. Glaciol.* **49**, 555–567 (2003).
32. Meier, M. et al. Mechanical and hydrologic basis for the rapid motion of a large tidewater glacier: 1. Observations. *J. Geophys. Res.: Solid Earth* **99**, 15219–15229 (1994).
33. Moskalik, M., Zagórski, P., Łęczyński, L., Cwiąkała, J. & Demczuk, P. Morphological characterization of Recherchefjorden (Bellsund, Svalbard) using marine geomorphometry. *Pol. Polar Res.* **39**, 99–125 (2018).
34. Fürst, J. et al. The ice-free topography of Svalbard. *Geophys. Res. Lett.* **45**, 11,760–11,769 (2018).
35. Lønne, I. & Nemeček, W. High-Arctic fan delta recording deglaciation and environment disequilibrium. *Sedimentology* **51**, 553–589 (2004).
36. Forman, S. L. et al. A review of postglacial emergence on Svalbard, Franz Josef Land and Novaya Zemlya, northern Eurasia. *Quat. Sci. Rev.* **23**, 1391–1434 (2004).
37. Long, A. J., Strzelecki, M. C., Lloyd, J. M. & Bryant, C. Dating High Arctic Holocene relative sea level changes using juvenile articulated marine shells in raised beaches. *Quat. Sci. Rev.* **48**, 61–66 (2012).
38. Schomacker, A. et al. Postglacial relative sea level change and glacier activity in the early and late Holocene: Wahlenbergfjorden, Nordaustlandet, Svalbard. *Sci. Rep.* **9**, 6799 (2019).
39. Nehyba, S., Hanáček, M., Engel, Z. & Stachoň, Z. Rise and fall of a small ice-dammed lake—role of deglaciation processes and morphology. *Geomorphology* **295**, 662–679 (2017).
40. Overeem, I., Nienhuis, J. H. & Piliouras, A. Ice-dominated Arctic deltas. *Nat. Rev. Earth Environ.* **3**, 225–240 (2022).
41. Nielsen, D. M. et al. Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. *Nat. Clim. Change*, **12**, 263–270 (2022).
42. Kostrzewa, O. et al. A boulder beach formed by waves from a calving glacier revisited: multidecadal tsunami-controlled coastal changes in front of Eqip Sermia, West Greenland. *Permafr. Periglac. Process.* **35**, 312–325 (2024).
43. Bendixen, M. et al. Promises and perils of sand exploitation in Greenland. *Nat. Sustain* **2**, 98–104 (2019).
44. Bendixen, M. & Kroon, A. Conceptualizing delta forms and processes in Arctic coastal environments. *Earth Surf. Process. Landf.* **42**, 1227–1237 (2017).
45. Strzelecki, M. C., Long, A. J. & Lloyd, J. M. Post-little ice age development of a high arctic paraglacial beach complex. *Permafr. Periglac. Process.* **28**, 4–17 (2017).
46. Porter, C. ArcticDEM – Strips, Version 4.1: <https://doi.org/10.7910/DVN/C98DVS>, Harvard Dataverse, V1, [accessed 28 April 2023] (2022).
47. Luckman, A. et al. Calving rates at tidewater glaciers vary strongly with ocean temperature. *Nat. Commun.* **6**, 8566 (2015).
48. Kavan, J., Tallentire, G. D., Demidionov, M., Dudek, J. & Strzelecki, M. C. Fifty years of tidewater glacier surface elevation and retreat dynamics along the south-east Coast of Spitsbergen (Svalbard Archipelago). *Remote Sens.* **14**, 354 (2022).

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 Wrocław. JK wrote the manuscript at Alfred Jahn Cold Regions Research Centre, University of Wrocław during the SVELTA project. MR was supported by a Czech Science Foundation (GACR) grant 22-206210. M.C.S. work on paraglacial coast is funded by GLAVE project (NCN-UMO-2020/38/E/ST10/00042). Sentinel-1 data were provided by the Copernicus Program and processed by A.L.

Author contributions

J.K. designed the study, performed the spatial analysis and wrote the first draft of the manuscript. M.C.S. helped with interpretations of the coastal processes. D.I.B. helped with description of glacier surge and interpretations. A.L. performed the glacier velocity analysis and contributed to interpretations of the glacier surge interactions with the sediment release. M.R. helped to gather the remote sensing data and edited the manuscript. P.Z. provided historic aerial imagery and helped with site-specific interpretations. All authors contributed to the interpretation of the result and writing the manuscript under the coordination of J.K.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at

<https://doi.org/10.1038/s43247-024-01877-8>.

Correspondence and requests for materials should be addressed to J. Kavan.

Peer review information *Communications Earth & Environment* thanks Paul Liu and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editor: Alireza Bahadori. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2024