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Corresponding author:
Holly Wytiahlowsky;
Email: holly.e.wytiahlowsky@durham.ac.uk

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Remote sensing of glacier change (1965–2021) and identification of surge-type glaciers on Severnaya Zemlya, Russian High Arctic

Holly Wytiahlowsky, Chris R. Stokes and David J. A. Evans

Department of Geography, Durham University, Durham DH1 3LE, UK

Abstract

Glaciers in the Russian High Arctic have undergone accelerated mass loss due to atmospheric and oceanic warming in the Barents–Kara Sea region. Most studies have concentrated on the western Barents–Kara sector, despite evidence of accelerating mass loss as far east as Severnaya Zemlya. However, long-term trends in glacier change on Severnaya Zemlya are largely unknown and this record may be complicated by surge-type glaciers. Here, we present a long-term assessment of glacier change (1965–2021) on Severnaya Zemlya and a new inventory of surge-type glaciers using declassified spy-satellite photography (KH-7/9 Hexagon) and optical satellite imagery (ASTER, Sentinel-2A, Landsat-4/5 TM and 8 OLI). Glacier area reduced from 17 053 km^2 in 1965 to 16 275 in 2021 (−5%; mean: −18%, max: −100%), with areal shrinkage most pronounced at land-terminating glaciers on southern Severnaya Zemlya, where there is a recent (post-2010s) increase in summer atmospheric temperatures. We find that surging may be more widespread than previously thought, with three glaciers classified confirmed as surge-type, eight as likely to have surged and nine as possible, comprising 11% of Severnaya Zemlya's 190 glaciers (37% by area). Under continued warming, we anticipate accelerated retreat and increased likelihood of surging as basal thermal regimes shift.

1. Introduction

Arctic glaciers and ice caps are rapidly losing mass due to strong atmospheric and oceanic warming (Carr and others, 2017a; Cook and others, 2019; Tepes and others, 2021a). Due to Arctic amplification, temperatures have risen faster than the global mean, with the Arctic warming by ∼3.5°C compared to the global mean of 0.85°C, between 1880 and 2012 (Moon and others, 2018; Rantanen and others, 2022). In recent years, climatic warming has already accelerated glacier and ice-sheet contributions to sea-level rise (Mengel and others, 2016; The IMBIE Team, 2020; Edwards and others, 2021), which according to the Intergovernmental Panel on Climate Change (IPCC) will result in irreversible impacts (e.g. sea-level rise and glacier melt) if global warming exceeds 1.5°C above pre-industrial levels (Pörtner and others, 2022). Sea-level rise is anticipated to exceed 51 cm by 2100 under an unchecked emission growth scenario (Bamber and others, 2019). Between 2010 and 2017, Arctic glaciers (excluding the Greenland ice sheet (GrIS) and its peripheral glaciers) lost 609 ± 7 Gt of ice, equating to a sea-level rise of 0.240 ± 0.007 mm a^{-1} (Tepes and others, 2021a). During this period (excluding the GrIS and its peripheral glaciers), the largest mass losses in the Arctic occurred in the southern Canadian Arctic (−606 ± 44 kg m^{-2} a^{-1}) and in the Russian High Arctic, comprising the archipelagos of Franz Josef Land, Novaya Zemlya and Severnaya Zemlya (Noël and others, 2018; Zemp and others, 2019; Tepes and others, 2021a). Within the Russian High Arctic, mass loss was dominated by Novaya Zemlya in the far west of the Russian High Arctic (−385 ± 18 kg m^{-2} a^{-1}) (Tepes and others, 2021b).

Atmospheric warming is the primary driver of Arctic glacier loss, whereas oceanic warming has been largely restricted to Atlantic-influenced Greenland and the western Russian High Arctic (Straneo and Heimbach, 2013; Carr and others, 2017a; Tepes and others, 2021b; Sommer and others, 2022). The inflow of warmer Atlantic waters into the Eurasian basin is a key driver of glacier retreat in the Russian High Arctic and has resulted in reduced sea-ice concentrations surrounding Novaya Zemlya, allowing for heat fluxes to rise through the water column, interacting with the atmosphere (Polyakov and others, 2017; Tepes and others, 2021b). By comparison, there are higher sea-ice concentrations and a more pronounced ocean stratification towards Severnaya Zemlya, reducing such ocean–atmosphere heat transfer and resulting in much lower atmospheric temperatures (Tepes and others, 2021b). However, regions as far east as Severnaya Zemlya, which were previously thought to be less sensitive to ocean-climate warming, are now undergoing accelerated glacier mass loss, attributed to increasing oceanic temperatures. Notably, Severnaya Zemlya has undergone a 29% increase in specific glacier mass loss from 2003 to 2009 and 2010 to 2017 (Tepes and others, 2021b).

In recent years, Severnaya Zemlya's glaciers have not only undergone accelerated mass loss (Sommer and others, 2022), but also increasing glacier flow speeds, with some notable 'surging' activity linked to a switch in basal thermal regime (Strozzi and others, 2017). Most notable of these was the destabilisation of the western basin of Vavilov Ice Cap, which transitioned from land- to marine-terminating and advanced >8 km (Willis and others, 2018). In general, however, research on Severnaya Zemlya has been hindered by inaccessibility and poor data availability; hence both the very recent and long-term trends in glacial retreat/advance are largely unknown compared to elsewhere in the European High Arctic (e.g. Novaya Zemlya and Svalbard). The recent availability of new high-resolution imagery (e.g. Sentinel-2A and ArcticDEM) and gravimetry and altimetry data (e.g. GRACE and ICESat) has led to an increase in research on Severnaya Zemlya, which has focused on ice surface elevation changes and overall mass-balance estimates (e.g. Sharov and Tyukavina, 2009; Ciracì and others, 2020; Tepes and others, 2021b). However, while mass-balance estimates are known for the last few decades, it is not known how changes in mass balance manifest as changes in glacier surface area, nor how different types of glaciers on Severnaya Zemlya (e.g. marine- and land-terminating glaciers and surge-type glaciers) are responding to climatic drivers over longer timescales. This can be understood by interpreting a record of glacier area change, but no long-term record currently exists.

A record of long-term glacier change may be complicated by the presence of surge-type glaciers on Severnaya Zemlya (Dowdeswell and Williams, 1997; Glazovsky and others, 2015; Sánchez-Gámez and others, 2019). Climate is thought to be a first-order control on surge-type glacier distribution and recent work suggests that glaciers in cold, dry environments, such as the eastern Russian High Arctic, are less likely to be surge-type (Sevestre and Benn, 2015; Benn and others, 2019). However, surging has often been documented in polythermal and predominantly cold-based glaciers, such as in the Canadian High Arctic (e.g. Copland and others, 2003; Van Wychen and others, 2016), which is comparable to the largely cold-based glaciers and ice caps on Severnaya Zemlya. The recent and well-documented destabilisation of Vavilov Ice Cap (Willis and others, 2018; Zheng and others, 2019) and the identification of two surge-diagnostic looped medial moraines on Karpinsky Ice Cap (Dowdeswell and Williams, 1997) are significant in that they provide clear evidence of glacier surging on Severnaya Zemlya. However, the wider distribution/existence of surge-type glaciers on Severnaya Zemlya is largely unknown and is important for understanding the relationship between glacier surging and climate, a relationship that is perhaps subject to alteration on Severnaya Zemlya under future climatic change. Indeed, most observations of surging are from temperate and polythermal glaciers (e.g. Kamb and others, 1985; Raymond, 1987; Fowler and others, 2001; Quincey and others, 2011) and additional documentation of surging in mostly cold-based glaciers is beneficial for assessing whether their characteristics and geomorphological signature differ.

In this paper, we use imagery from 1965 to 2021 to assemble the first long-term record of glacier change on Severnaya Zemlya and explore spatial and temporal trends in relation to ocean-climate forcing. This includes the identification of surge-type glaciers on the archipelago by systematically investigating each glacier for glaciological and geomorphological features diagnostic of surging (following Grant and others, 2009). This record of glacier change can be used as a basis for understanding and ascertaining the impact of climatic changes on Severnaya Zemlya.

2. Study area and previous work

2.1. Location and glacial history

Severnaya Zemlya is situated north of the Taymyr Peninsula, with Franz Josef Land and Novaya Zemlya to the west and southwest, respectively (Fig. 1). The archipelago is located between the Kara and Laptev seas and is less influenced by warmer Atlantic waters than Novaya Zemlya to the west, with lower rates of precipitation than in the Barents–Kara seas (Timokhov, 1994; Schauer, and others, 2002). Glaciers further east in the Russian High Arctic are characterised by a colder thermal structure, with glaciers on Severnaya Zemlya likely to be mostly frozen to their bed (Dowdeswell and Williams, 1997). Mean annual precipitation and temperature on Severnaya Zemlya as recorded at the Vavilov Station (Fig. 1) were 423 mm w.e. and −16.5°C, respectively, for the period 1974–88 (Bassford and others, 2006b). The study area encompasses all glaciers on Severnaya Zemlya, which covered a total area of 17 500 km^2 in the glacier inventory of the USSR compiled between 1940 and 1970 (Grosval'd and Kotlyakov, 1969). A re-survey from imagery acquired between 2000 and 2010 for the Randolph Glacier Inventory (RGI) 6.0 has since estimated the glacierised area to be 16 700 km^2 (Moholdt and others, 2012a; Khromova and others, 2014).

The 1940–70 USSR inventory estimated mean glacier thickness and volume to be 200 m and 3500 km^3, respectively (Grosval'd and Kotlyakov, 1969). Glacier coverage increases towards the north, with glaciers covering 99.7% on the northwesternmost island, Schmidt Island, and most glacier volume in the Academy of Sciences Ice Cap on Komsomolets Island (Fig. 1; Sharov and Tyukavina, 2009). To the southeast of the Academy of Sciences Ice Cap, the highest elevation is the peak of Karpinsky Ice Cap, which reaches an altitude of 963 m (Sharov and Tyukavina, 2009). Most of the larger glaciers drain towards the eastern coast, with 26 outlet glaciers terminating in the Laptev Sea (Sharov and Tyukavina, 2009). Where data exist, the eastern outlets display higher velocities (e.g. the Academy of Sciences Ice Cap basins C and D – avg. 543 m a^{-1} (2016–17)) than the five to six slow-moving outlet glaciers flowing into the Kara Sea to the west (the Academy of Sciences Ice Cap basin A – 240 m a^{-1}) (Sharov and Tyukavina, 2009; Sánchez Gámez and others, 2019).

The extent of the Late Pleistocene Glaciation during Marine Isotope Stage 2 (including the Last Glacial Maximum (LGM)) is controversial on Severnaya Zemlya. The eastern margins of the former Barents–Kara ice sheet are unknown but are generally assumed to have reached the Taymyr Peninsula and not extended onto Severnaya Zemlya (Svendsen and others, 1999, 2004; Polyak and others, 2008; Hughes and others, 2016). The interpretation of lacustrine proxies on October Revolution Island suggests that it has not been covered by extensive glaciation since marine isotope stage 5d-4 (Early Middle Weichselian; Raab and others, 2003). A change to colder, drier conditions at ~22 ka following an interstadial period triggered ice-cap growth, with the LGM in the Russian Arctic being reached ~20–15 ka BP (Hubberten and others, 2004). However, the LGM on Severnaya Zemlya was likely constrained close to modern margins, with the Vavilov Ice Dome believed to be small or non-existent (Raab and others, 2003; Svendsen and others, 2004). No evidence of glacial deposits was found in a lake core from southern Bolshevik Island, supporting these assumptions (Cherezova and others, 2020). Additionally, local evidence for ice grounding on the East Siberian continental margin during the LGM suggests that the purported East Siberian ice sheets did not extend to Severnaya Zemlya (Niessen and others, 2013).

In the Russian High Arctic, the Pleistocene–Holocene transition was characterised by warming, punctuated with cooling correlated with the Younger Dryas. This was followed by an early Holocene warming peak at 10 000–9700 years BP, reaching the Boreal then Holocene thermal maxima at ~8500 and ~5500 years BP, respectively (Andreev and Klimanov, 2000). On Franz Josef Land, glaciers remained behind present margins from ~9.4 to 4.4 ka, advancing to reach present margins by 2 ka (Lubinski and others, 1999). Prominent neoglacial advances are

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Figure 1. Location map of Severnaya Zemlya and its distribution of glaciers from the 2001–10 RGI (RGI Consortium, 2017). The locations of previously identified surge-type glaciers are mapped as follows: (a, green) basins A and B of the Academy of Science Ice Cap where surge-like elevation changes were identified by Sánchez-Gámez and others (2019); (b, red) the two looped medial moraines identified by Dowdeswell and Williams (1997); (c, blue) the location of the observed surge of Vavilov Ice Cap documented by Glazovsky and others (2015).

recorded at ∼1 ka on Franz Josef Land and, on Novaya Zemlya, neoglacial moraine sequences are situated within 4 km of present margins and dated to 1300 and 800 years BP. This was followed by the Little Ice Age (LIA) advances and subsequent widespread retreat (Forman and others, 1999; Lubinski and others, 1999). No distinct signal of the Medieval Climate Anomaly or the LIA is readily detectable in the $\delta^{18}O$ ice core record from the Academy of Sciences Ice Cap (Severnaya Zemlya), suggesting they may have not been pronounced in the Barents–Kara Sea region (Opel and others, 2013). A cold period at ∼1800 followed by subsequent warming is interpreted to mark the termination of the LIA (Opel and others, 2013), although without establishing a chronology on moraine formation on Severnaya Zemlya this cannot be correlated with moraine stabilisation at surrounding localities.

2.2. Recent glacier change

No studies have assessed spatial and temporal changes in glacier extent on Severnaya Zemlya over the last few decades, with research primarily focusing on short-term changes in mass balance and ice flow dynamics (e.g. Bassford and others, 2006a, 2006b, 2006c; Tepes and others, 2021b). Several studies have used gravimetry and laser altimetry to assess recent volumetric changes of ice caps, concentrated on the Academy of Sciences Ice Cap (e.g. Moholdt and others, 2012b; Sánchez-Gámez and others, 2019, 2020; Tepes and others, 2021a, 2021b). Most mass loss on Severnaya Zemlya is attributed to three outlets (ice streams *sensu lato*) on the Academy of Sciences Ice Cap which have thinned by >1 m a^{-1} and remained in a period of fast flow since 1995, notably basins C and D, with basin A showing a threefold

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increase in velocity and an increase in thickness at its terminus (Sharov and Tyukavina, 2009; Moholdt and others, 2012b; Nela and others, 2019; Sánchez-Gámez and others, 2019). On October Revolution Island, between 2012 and 2014, the main outlets of Karpinsky Ice Cap thinned at a rate 3–4 times greater than the 30 year average following the collapse of the Matusevich Ice Shelf in 2012 (Moholdt and others, 2012b; Willis and others, 2015). In 2013, the western margin of Vavilov Ice Cap destabilised and advanced 8 km, peaking at 25 m d^{-1} (Fig. 1c). This advance is thought to reflect the impact of changing basal boundary conditions on mostly cold-based ice caps, which may be related to climate warming (Willis and others, 2018; Zheng and others, 2019).

3. Methods

3.1. Image acquisition and processing

Satellite imagery was acquired for 1965/79, 1986, 1997, 2011, 2018 (DEM) and 2021 at intervals of ~10 years to capture long-term changes (Supplementary Table S1). We use imagery from KH-7 and KH-9 'Hexagon', Landsat TM, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), ArcticDEM, Sentinel-2A and Landsat-8. Scenes were predominantly obtained from July to September when sea ice and snow cover are at a minimum and filtered for low cloud cover (<10%), to ensure accurate delineation of glacier margins. All years have full glacier coverage except for 1965, which only covers October Revolution Island and Bolshevik Island and 1979, which only covers Komsomolets Island and Pioneer Island.

KH-7 and KH-9 imagery was manually georeferenced using a 2021 Sentinel-2A base layer and co-registered to a WGS 1984 Arctic Polar Stereographic projection. A total of 23 KH-7 and two KH-9 single-image scenes were used to cover Severnaya Zemlya and were georeferenced using a spline transformation with ~30 control points chosen per tile. Fixed points such as coastlines and bedrock features were used as control points, avoiding features subject to alteration (e.g. deltas and rivers). The transformations have an RMS value close to zero (≳0.001), providing a good assessment of the transformation accuracy, although minor errors in aligning control points may not be accounted for in the RMS value.

3.2. Glacier change mapping and uncertainties

Using the RGI 6.0 data as a guide, glaciers were manually delineated using ESRI ArcGIS software, yielding a total of 190 individual glacier units. Ice divides from the RGI data were used but that inventory could not be utilised in the analysis because the year of measurement was not the same for each glacier (2000–10). Recently, a new inventory of Russian glaciers (2016–19) by Khromova and others (2021) in Global Land Ice Measurements from Space (GLIMS) provided a more up-to-date record of glacier change on Severnaya Zemlya, however, this too uses different years of measurement for each glacier. The long-term record of satellite imagery in this study also allowed for the rectification of obvious misclassifications in the RGI inventory using some of the glacier identification criteria in Leigh and others (2019). This includes six new glaciers that have since detached from large ice caps or that may have been overlooked as snow patches in the RGI and one lake misclassified as a glacier in both the RGI and GLIMS (Fig. 2). Thereafter, each glacier was manually digitised using a Lambert Equal Area Projection for 1965, 1979, 1986, 1997, 2011 and 2021 (Fig. 2). Each glacier was given an ID from 1 to 190 for identification purposes (see Supplementary spreadsheet 1). Some linear snow patches may contain glacier ice, but do not meet the criteria for glacier identification (see Leigh and others, 2019) so are excluded from the mapped glaciated area for Bolshevik Island. Despite the panchromatic KH-7 and KH-9 imagery, the textural differences between glaciers, sea ice and land cover are clear and do not provide difficulties in delineating glacier area (Fig. 2e; Leigh and others, 2019). Glacier area was calculated in square kilometres for each year

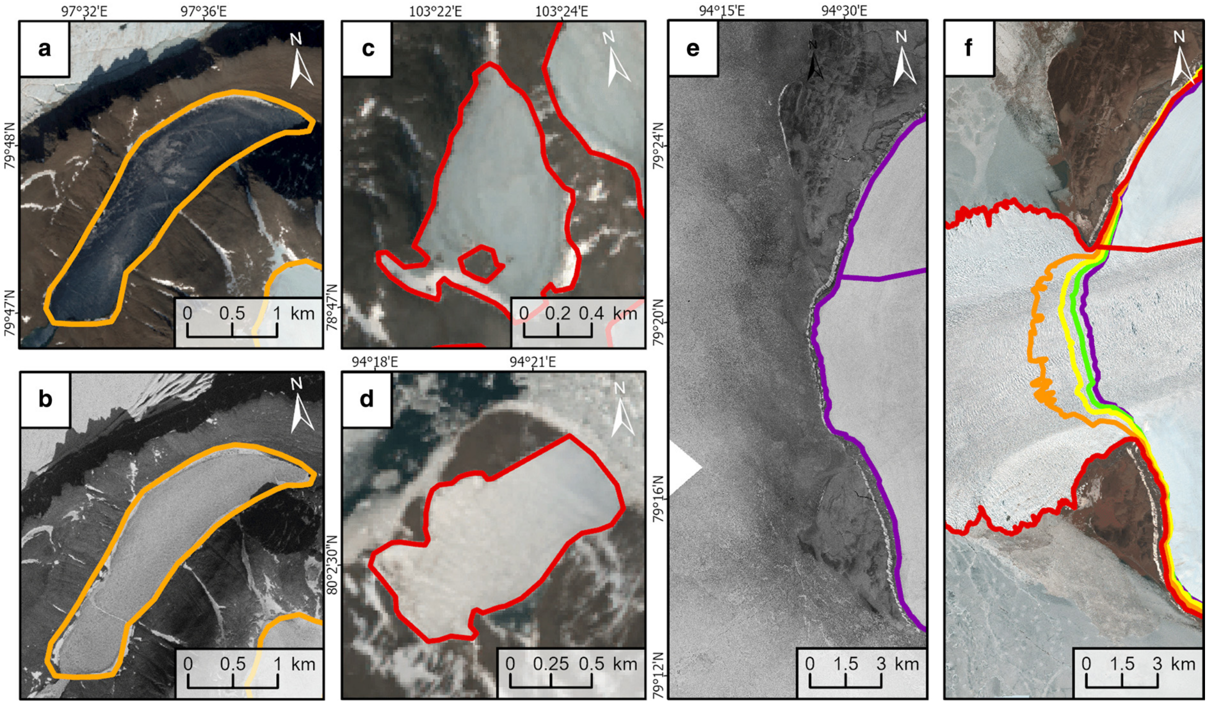

Figure 2. (a) RGI outlines (orange) overlaid over 2021 Sentinel-2A imagery of a lake misidentified as a glacier in the RGI. (b) RGI outlines overlaid on 1965 imagery – note the difference in surface texture between the lake and the glacier to the southeast and an absence of any features indicative of glacier ice (following Leigh and others, 2019). (c) New glacier that has separated from a larger ice cap (glacier 187). (d) Small glacier not identified by the RGI (glacier 174). (e) Delineation of 1965 Vavilov extent (purple). (f) Glacier outlines for 1965 (purple), 1986 (green), 1997 (yellow) and 2011 (orange) superimposed on 2021 (red) Sentinel-2A imagery.

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using ArcGIS Pro to establish rates of glacier surface area change. No classification of terminus type exists for Severnaya Zemlya, so each glacier unit was classified into one of the three terminus types: marine-terminating, land-terminating and lake-terminating.

Errors in manual glacier delineation were calculated following DeBeer and Sharp (2007), who assumed that line placement uncertainty is unlikely to be larger than the imagery resolution for debris-free glaciers on cloud-free imagery. They suggested that measurement error can be approximated by the polygon perimeter × the pixel resolution; for example, the area of glacier 1 = 120 km^2 and it has a perimeter of 66 307 m and was mapped from 10 m ground pixel resolution imagery. Thus, the line placement/mapping uncertainty is 120 ± 0.66 km^2. Errors are calculated for each glacier unit at each date (see Supplementary spreadsheet 1), with measurement errors for the total area detailed in Table 2.

3.3. Climate data

Daily air temperatures were obtained from two stations: Im. E. K. Fedorova (WMO code 20292) (77.7°N, 104.3°E, 12 m a.s.l., 1936–2021) at the north of the Taymyr Peninsula, south of Bolshevik Island; and Ostrov Golomjannyj (WMO code 20087) (79.6°N, 90.6°E, 8 m a.s.l., 1936–2021) on Golomjannyj Island 40–50 km west of October Revolution Island (see Fig. 1). Annual summer (1st June–31st August) and winter (1st December–28/29th February) means were computed for each station, with anomalies calculated from the long-term (1936–2021) mean. Data used for climate plots were accessed from the National Oceanic and Atmospheric Administration (NOAA) (https://www.noaa.gov/). Long-term (1981–2022) composite plots of surface skin temperature (SST_{skin}), precipitation and air temperature (2 m) were produced from NOAA plotting tools, which use National Centres for Atmospheric Prediction (NCEP) re-analysis data. Surface skin temperature refers to the temperature of water at a depth of ~10–20 μm. Additionally, NCEP re-analysis data were used to compare recent 21st-century climatic changes (2000–22) against the climate normal time period (1991–2020).

3.4. Identification of surge-type glaciers

Each of the 190 glaciers on Severnaya Zemlya was examined for the presence or absence of features that may be diagnostic of surging (Table 1). These criteria for identifying surge-type glaciers have been adapted from Grant and others (2009) and Copland and others (2003) and modified to reflect that we did not observe any smaller-scale subglacially derived components in our imagery (e.g. crevasse-squeeze ridges). Each criterion was weighted to reflect whether it is primarily diagnostic of surging (e.g. looped medial moraines) or may only be diagnostic of surging in conjunction with other criteria (e.g. heavy surface crevassing) (Table 1). The highest weighting of 5 was assigned to looped medial moraines and localised abnormal advances as they are robust indicators of surging (Meier and Post, 1969; Lawson, 1996; Evans and Rea, 1999, 2003; Hewitt, 2007; Paul, 2015). Due to potential equifinality associated with thrust block/glacitectonic composite moraines (4) and crevassing up-glacier (3), they are not weighted high enough to individually result in a surge-type classification (Fitzsimons, 1996, 1997, 2003; Evans and Rea, 1999, 2003; Evans, 2009; Benn and Evans, 2010). However, they are weighted more heavily than supraglacial ponding (1) and shear margins (1). Following weighting, each glacier is classified as either category 1 – confirmed surge-type (>10, active phase observed and 3 surge-indicative criteria present), category 2 – likely to have surged (>7, indirect evidence), category 3 – possible surge-type (4–6, indirect evidence) or non-surge-type (0–3). Glaciers are only classified as confirmed surge-type if a localised anomalous advance has been observed during the study period (which is assumed to be the active phase) and if three other surge-indicative criteria are present. Where localised anomalous advances occur but are only short-lived and minor, we do not consider these to be an active phase and instead restrict their classification to likely to have surged. We acknowledge that our method is biased towards the surge classification of land-terminating glaciers because of the additional criteria that may be present within their exposed forelands (as opposed to submarine geomorphology proximal to marine-terminating glaciers but we are not aware of any bathymetric datasets available around Severnaya Zemlya).

4. Results

4.1. Glacier change

Between 1965 (17 053 ± 38 km^2) and 2021 (16 275 ± 69 km^2), glaciers on Severnaya Zemlya lost a combined area of 778 km^2 (5% area decrease) at an average rate of 13.9 km^2 a^{-1} (Table 2; Fig. 3). By region, Bolshevik Island accounts for 55% of glacier area loss (−426 km^2), October Revolution Island for 30% (−230 km^2) and Komsomolets, Pioneer and Schmidt islands for 16% (−122 km^2). From 1965 to 2021, 95.7% of glaciers showed a decline in surface area and eight glaciers increased in overall area, with ten separate

Table 1. Criteria used for identification of surge-type glaciers (following Grant and others, 2009)

Criteria	Description	Weighting
Glaciological		
Looped moraines	Produced when medial moraines are deformed due to the combination of fast- and slow-flowing ice within adjacent glaciers	5
Localised abnormal advance	Indicative of the active phase of the surge cycle	5
Highly digitate terminus	Terminus is splayed into lobes by longitudinal crevasses	3
Heavy surface crevassing up-glacier	Indicative of the active phase of the surge cycle and develop due to increased longitudinal stresses	3
Deformed ice structures	Form in a similar manner to looped moraines	1
Shear margins	Develop at the boundary between fast- and slow-flowing ice	1
Heavy surface crevassing at the terminus	Formed during the surge phase	1
Surface potholes	Typically appear during the quiescent phase; they form in crevasses formed during the surge phase or in depressions between transverse ridges	1
Geomorphological		
Thrust-block/push moraines	Form as a result of marginal thrusting due to ice advance into proglacial sediments and can form in belts of arcuate thrust ridges. In areas where sediment is limited, low-amplitude push moraines develop	4
Overridden thrust-block moraines	Formed thrust blocks are overridden by ice and form ice-moulded 'cupola' hills	1
Hummocky moraine	Produced in belts at the margin of glaciers and consist of chaotic landscape with kame and kettle topography, which evolves from the thrusting, squeezing and bulldozing of sediments and meltout of buried glacier ice (however, other origins are possible)	1

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Table 2. Summary statistics of glacier surface area change on Severnaya Zemlya

	1965(*79)	1986		1997		2011		2021		1965–2021	
	Area km^2	Area km^2	Change km^2 a^{-1}	Area km^2	Change km^2 a^{-1}	Area km^2	Change km^2 a^{-1}	Area km^2	Change km^2 a^{-1}	Change km^2	Change km^2 a^{-1}
All glaciers	17 053.4 ± 38	16 774.2 ± 221	−13.3	16 713.9 ± 216	−5.48	16 429.2 ± 22	−20.34	16 275.4 ± 69	−15.4	−778.1	−13.9
Mean	90.1	90.2	−0.1	89.9	0.0	90.6	−0.1	85.7	−0.1	−2.2	−0.1
Median	21.8	21.8	0.0	21.6	0.0	22.4	−0.1	19.7	−0.1	−1.8	0.0
SD	173.4	174.1	0.3	174.3	0.2	175.0	0.2	171.6	0.1	16.1	0.3
Min	0.4	0.4	2.9	0.2	1.8	0.5	0.1	0	0.0	141.5	2.5
Max	1243.7	1246.2	−2.0	1246.1	−0.7	1243.7	−1.7	1243.1	−1	−42.8	−1.8
Komsomolets, Pioneer and Schmidt*	6407.8 ± 7	6422.3 ± 44	2.1	6395.8 ± 44	−2.4	6328.7 ± 22	−4.8	6285.5 ± 30	−4.3	−122.3	−2.2
Mean	305.1	305.8	0.1	304.6	−0.1	301.4	−0.2	299.3	−0.2	−5.8	−0.1
Median	157.7	157.7	0.0	157.2	0.0	155.7	−0.1	154.8	−0.1	−0.7	0.0
SD	363.2	366.3	0.8	365.8	0.3	364.6	0.4	363.6	0.5	11.3	0.3
Min	1.3	1.4	2.9	1.9	0.4	0.7	0.2	0.5	0.4	3.9	0.1
Max	1243.7	1246.2	−1.1	1246.1	−0.7	1243.7	−1.1	1243.1	−1.6	−39.9	−3.0
October Revolution	7628.8 ± 17	7507.6 ± 101	−5.8	7513.2 ± 98	0.5	7413.4 ± 49	−7.1	7398.7 ± 32	−1.5	−230.3	−4.1
(-Vavilov)	7285.4 ± 16	7164.2 ± 98	−5.8	7166.3 ± 96	0.2	6903.02 ± 47	−18.8	6913.6 ± 30	1.1	−371.8	−6.7
Mean	117.4	115.5	−0.1	116.0	0.0	112.3	−0.1	112.1	0.0	−3.6	0.0
Median	58.2	55.6	0.0	55.3	0.0	54.4	0.0	53.8	0.0	−2.1	0.0
SD	144.6	142.6	0.3	144.0	0.3	142.5	0.3	143.4	1.8	23.3	0.4
Min	1.3	1.5	0.4	1.5	1.8	1.1	0.8	1.1	12.7	141.5	2.5
Max	594.1	594.8	−2.0	594.0	−0.4	593.3	−1.7	591.8	−5.4	−99.8	−1.8
Bolshevik	3016.6 ± 13	2844.3 ± 76	−8.2	2805.0 ± 74	−3.6	2687.0 ± 36	−8.4	2591.2 ± 23	−9.6	−425.5	−7.6
Mean	30.8	28.4	−0.1	28.0	0.0	26.6	−0.1	25.2	−0.1	−4.5	−0.1
Median	11.3	9.8	0.0	9.6	0.0	8.2	0.0	7.4	−0.1	−2.0	0.0
SD	49.9	47.8	0.1	47.5	0.1	46.0	0.1	45.0	0.0	7.5	0.1
Min	0.5	0.4	0.0	0.2	0.0	0.2	0.0	0	0.0	1.2	0.0
Max	335.8	323.2	−0.8	320.0	0.0	306.5	−1.0	296.5	−1	−44.8	−0.8

Uncertainties are provided for the overall and regional total areas (for individual glaciers see Supplementary spreadsheet 1). * Indicates that 1979 imagery was used to delineate glacier outlines for Komsomolets Island where 1965 imagery was not available.

advances (>0.5 km^2 and exceeding error margins) recorded between these dates (Table 2; Supplementary spreadsheet 1). The mean glacier areal shrinkage between 1965 and 2021 was −17%, however, one very small glacier (glacier 178) disappeared during this time period, with others (e.g. glacier 87, −93%) also undergoing large shrinkages.

In terms of temporal changes, glaciers and ice caps shrank at a rate of −13.3 km^2 a^{-1} between 1965/79 and 1986, which decreased to −5.5 km^2 a^{-1} between 1986 and 1997. However, due to the larger error margins for 1986 and 1997, there is low confidence in a significant deceleration in retreat rate (Table 2; Fig. 3). A notable acceleration in retreat is recorded between 1997 and 2011 (−20.3 km^2 a^{-1}), which continues through to 2011–21 (−15.4 km^2 a^{-1}).

Komsomolets Island experienced the smallest amount of glacier retreat (−2.2 km^2 a^{-1}, 1979–2021 = 1.9% area decrease), compared to Bolshevik Island in the south of Severnaya Zemlya (−7.6 km^2 a^{-1}, 1965–2021 = −14.1% area decrease; Table 2; Fig. 3). Nonetheless, glaciers and ice caps on Komsomolets Island underwent a progressive acceleration in retreat rates between each date, with a small increase in area between 1979 and 1986 (2.1 km^2 a^{-1}), followed by a period of glacier retreat between 1986 and 1997 (−2.4 km^2 a^{-1}). Annual retreat rates doubled between the periods 1986–97 and 1997–2011 (−4.8 km^2 a^{-1}) and decelerated slightly to −4.3 km^2 a^{-1} between 2011 and 2021, which is lower than the rate of change on Bolshevik Island between 1965/79 and 1986 (−8.2 km^2 a^{-1}). The largest rates of retreat (in terms of percentage) have preferentially occurred on the smaller Arctic Ice Cap (glacier 17) and Separate Ice Cap (glacier 147), with minimal retreat of the Academy of Sciences Ice Cap (Fig. 4). Between 1965/79 and 2021, five separate advances (that exceed error margins) are recorded for the Academy of Sciences Ice Cap, although only basin A (Fig. 5a) and glacier 154 showed an overall net increase in area from 1965 to 2021.

Glaciers on October Revolution Island have undergone the second-highest rate of area loss on Severnaya Zemlya, with a −4.1 km^2 a^{-1} surface area loss (−3.0% area decrease) between 1965 and 2021 (Table 2). Net retreat between 1965 and 1986 (−5.8 km^2 a^{-1}) was interrupted by an increase in overall area between 1986 and 1997 (0.5 km^2 a^{-1}), attributed to an advance from a western basin of Vavilov Ice Cap (41.18% increase in km^2), which by 2021 had advanced 13.5 km from its 1965 position (Fig. 5h). Despite the continued advance of Vavilov Ice Cap, the glaciated area of October Revolution Island declined between 1997 and 2011 (−7.1 km^2 a^{-1}), with the tributary glaciers feeding the former Matusevich Ice Shelf experiencing rapid retreat post-2012 (Fig. 6). Between 2011 and 2021, glaciers on October Revolution Island showed a reduction in retreat rate (−1.5 km^2 a^{-1}). However, this overall rate of change is skewed due to a large gain in area from the advance of Vavilov Ice Cap (Fig. 5h).

The southernmost island, Bolshevik Island, has shown the greatest reduction in glacier area of −7.6 km^2 a^{-1} (−14.1% decrease, −426 km^2) from 1965 to 2021, with no advances recorded (Table 2). Between 1965 and 1986, glacier surface area declined at a rate of −8.2 km^2 a^{-1}, preferentially affecting small ice caps in the southwest of the island (Fig. 4). Glacier retreat rates declined to −3.6 km^2 a^{-1} between 1986 and 1997, although the error margins are large due to the coarse imagery, so a significant deceleration in the retreat rate is uncertain. Post-1997, the rate of glacier retreat increased at each date, with the greatest increase in retreat rates occurring between 1986 and 1997 (−3.6 km^2 a^{-1}) and 1997 and 2011 (−8.4 km^2 a^{-1}). The fastest rate of retreat occurred between 2011 and 2021 (−9.6 km^2 a^{-1}), which exceeded both Komsomolets (−4.3 km^2 a^{-1}) and October Revolution islands (−1.5 km^2 a^{-1}) during the same period.

The overall spatiotemporal trends in surface area change show a north-to-south gradient of increased retreat, concentrated on Bolshevik Island, where most glaciers are land-terminating

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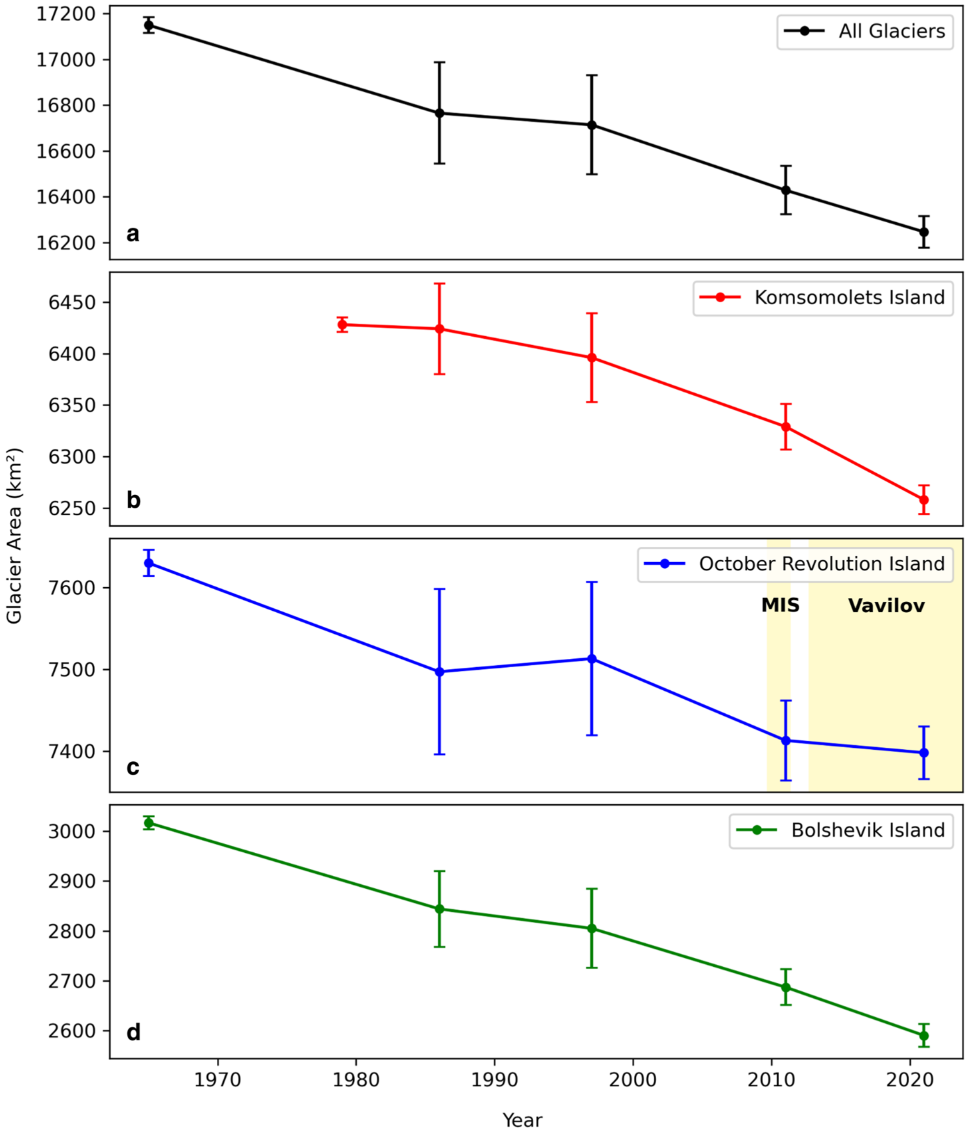

Figure 3. Glacier change on Severnaya Zemlya by region. Error bars reflect the minimum and maximum possible extents of glacier area at each date. (a) Overall glacier change – note that data from Komsomolets Island in 1979 are included in the 1965 data point. (b) Glacier change on Komsomolets Island from 1979 to 2021. (c) Glacier change on October Revolution Island from 1965 to 2021 – note the 2010 collapse of the Matusevich Ice Shelf (MIS) and the advance of Vavilov Ice Cap post-2013 (in yellow). (d) Glacier change on Bolshevik Island from 1965 to 2021.

(Fig. 4). Observations show a recent (post-1997) acceleration in retreat rates on northern Severnaya Zemlya, albeit not strongly on October Revolution Island, whereas glaciers on Bolshevik Island have notably retreated across the entire observational period (1965–2021) (Fig. 3).

4.2. Climate change

Continentally influenced Im. E. K. Fedorova (−14.4°C, 1936–2021) and marine-influenced Ostrov Golomjannyj (−14.2°C, 1937–2021) are characterised by similar annual air temperatures, despite Im. E. K. Fedorova being 2° further south (Fig. 1; Figs 7a, b). A stronger trend in mean annual warming temperature is recorded at Ostrov Golomjannyj, which has warmed by 3°C ($R^2 = 0.24$), 1°C more than that at Im. E. K. Fedorova ($R^2 = 0.10$), with both trends being statistically significant ($p < 0.05$) (Figs 7a, b). Im. E. K. Fedorova is characterised by warmer summers (average −0.08°C, 1936–2021) and post-2000 has recorded a progressive increase in positive temperature anomalies (Fig. 7c). Ostrov Golomjannyj is characterised by slightly colder summers (−0.2°C, 1936–2021) and shows no discernible trend of summer warming (Fig. 7d). Ostrov Golomjannyj (−26.2°C, 1937–2021) has a similar winter temperature to Im. E. K. Fedorova (−26.9°C) despite being 2° further north, and while both stations have seen an increase in positive temperature anomalies post-2005, only Ostrov Golomjannyj shows a statistically significant ($p < 0.05$) linear trend in winter warming ($R^2 = 0.08$) (Figs 7e, f). Long-term trends from both stations show that the 1930s/40s were generally warmer than the long-term annual average (Im. E. K. Fedorova: −14.4°C, Ostrov Golomjannyj: −14.2°C), followed by cooling between the 1950s and 1990s, which was more pronounced at Im. E. K. Fedorova (Figs 7a–f). Post-2000, both stations showed rapid warming and consistent positive temperature anomalies (Figs 7a–f).

Long-term (1981–2022) spatial trends in surface air temperature show that the warmest temperatures occurred on southern Severnaya Zemlya (western Bolshevik and October Revolution islands) (Fig. 8a). Temperatures decrease northwards towards Komsomolets Island and to the east of Bolshevik Island on the Laptev Sea coast (Fig. 8a). Since the 21st century, mean annual surface air temperature has increased across the entirety of Severnaya Zemlya, with the strongest warming concentrated

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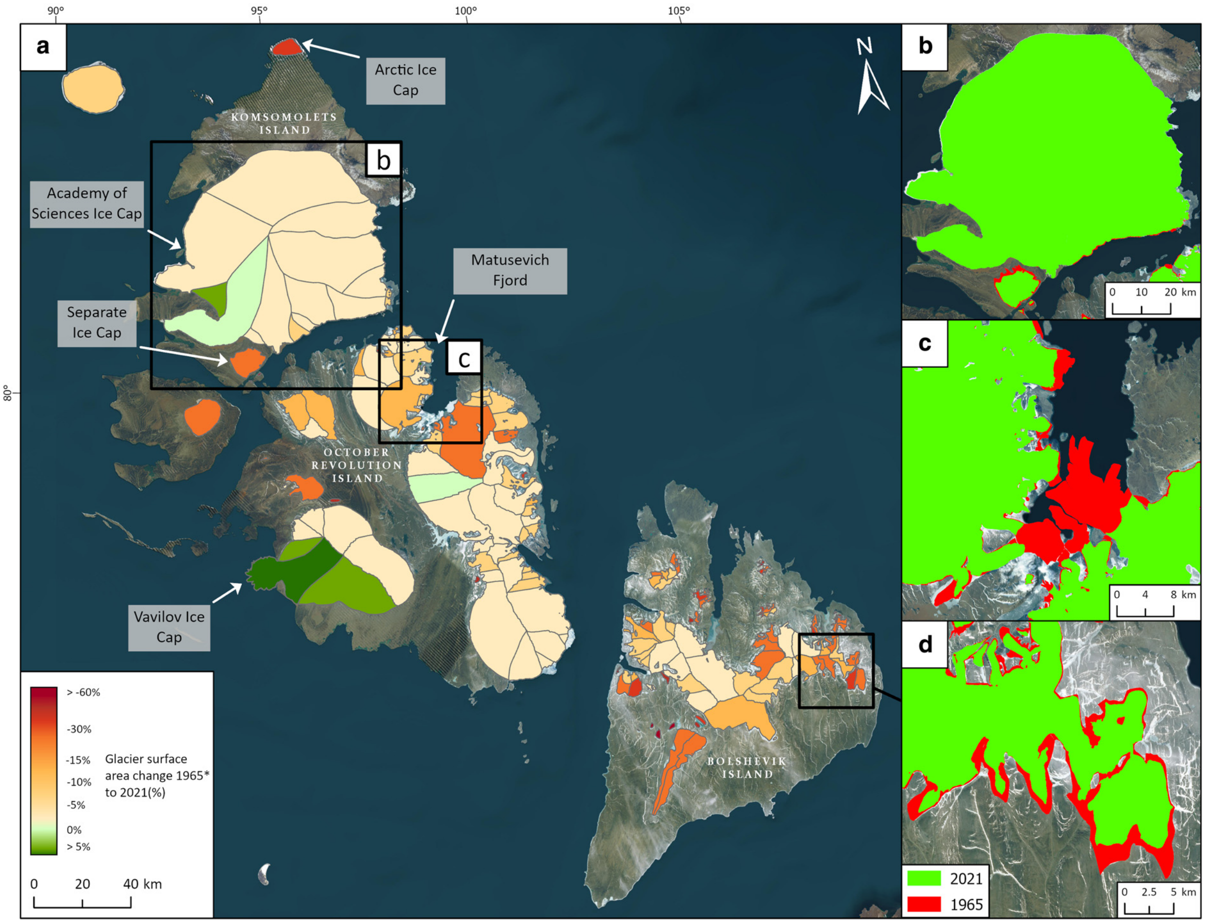

Figure 4. (a) Overall glacier surface area changes between 1965 and 2021 (%). * Indicates that 1979 imagery was used for Komsomolets Island as imagery was not available for 1965. Negative (red) and positive (green) changes are scaled to reflect the amount of glacier change. (b) Changes in glacier ice margins from 1965 (red) to 2021 (green) on the Academy of Sciences Ice Cap (top), note that ice margins have remained relatively stable. (c) Changes in ice margins surrounding Matusevich fjord and the breakup of the former Matusevich Ice shelf. (d) Changes in ice margins on south-eastern Bolshevik Island.

around the northern cape, and the weakest trends of warming occurring on Bolshevik Island (Fig. 8b). Spatial trends in mean annual SST_{skin} mostly correspond with mean surface air temperature, with colder temperatures to the north and warmer temperatures on the Kara Sea coast (Figs 8a, c). Note that the NCEP reanalysis dataset incorporates some classified meteorological stations (Kalnay and others, 1996), one of which is at the centre of the modelled isopleth bullseye effect of abnormally warm SSTs off northern Bolshevik Island. Thus, we deem it a probable cause of this effect, although cannot verify with any certainty. Positive SST_{skin} anomalies are highest in the Arctic and Kara seas, with evidence of warming but to a lesser extent in the Laptev Sea (Fig. 8d). Negative SST_{skin} anomalies are confined to the northern coast of Bolshevik Island and eastern October Revolution Island (Fig. 8d). The highest rates of precipitation have been historically concentrated around northern Bolshevik Island and southern October Revolution Island (Fig. 8e). Since 2000, mean annual precipitation rates have increased compared to the climate normal time period (1991–2020) on October Revolution and Komsomolets Islands, whereas they have undergone a slight decline around the precipitation high on Bolshevik Island (Fig. 8f).

4.3. Identification of surge-type glaciers

The 190 glaciers on Severnaya Zemlya were systematically investigated for evidence regarded as diagnostic of active and former surging. Using the criteria in Table 1, it is suggested that three glaciers are of confirmed surge-type (category 1) (1.6%), eight are likely to have surged (category 2) (4.2%) and nine are possible surge-type (category 3) (4.7%) (Table 3; Fig. 9). Potential surge-type glaciers tend to be larger than non-surge-type glaciers, with those classified as confirmed surge-type representing 8% of the 2021 glacier surface area of Severnaya Zemlya, likely to have surged representing 13%, and possible representing 15%. Where surging is identified, the most commonly identified surge-diagnostic features include surface potholes, a localised abnormal ice-front advance and heavy surface crevassing (Table 3).

Evidence of surging predominantly occurs north of 79°N on October Revolution Island and Komsomolets Island (Fig. 9). Surge-type glaciers (including category 2 – likely to have surged and category 3 – possible surge-type) all originate from large ice caps, primarily clustered around the Academy of Sciences, Rusanov and Karpinsky ice caps with no evidence of surging in the Albanov, University Ice Cap or on Bolshevik Island. Glaciers with evidence of surging have a mean size of 312 km^2 (median: 284.5 km^2) compared to 86 km^2 for non-surge-type glaciers. All category 1 – confirmed surge-type glaciers are marine-/lake-terminating, although this is less prominent (65%) when category 2 – likely to have surged and category 3 – possible surge-type glaciers are included (Table 3).

Between 1965 and 2021, ten localised abnormal advances (>0.5 km^2) were observed at various times and of varying durations (see Supplementary spreadsheet 1). The western margins of Vavilov Ice Cap exhibited the largest advance between any date, extending ~11 km further into the Kara Sea than its position in 2011 (Fig. 5h). The surrounding basins of Vavilov Ice Cap underwent a minor advance as the western margin surged. The

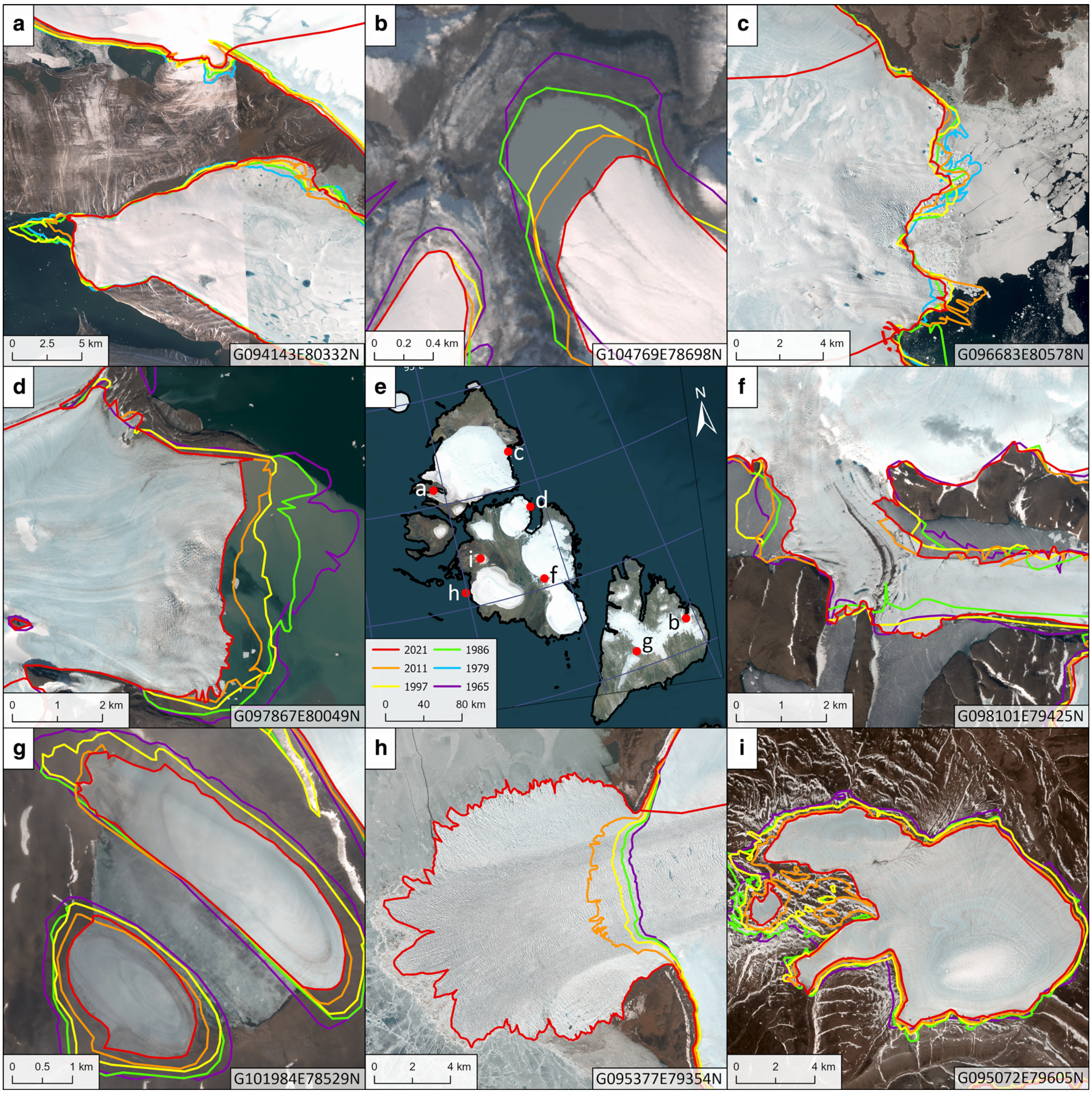

Figure 5. Glacier change outlines at dates from 1965 to 2021 overlaid on 2021 Sentinel-2A imagery, including RGI IDs. (a) Basin A of the Academy of Sciences Ice Cap. (b) Glacier 41 – retreated from controlled moraines damming a proglacial lake. (c) Basin D of the Academy of Sciences Ice Cap. (d) Glacier 1 – marine-terminating on the north-eastern margin of Rusanov Ice Cap. (e) Location of glaciers shown within Severnaya Zemlya. (f) Glacier 105 – observed to surge twice. (g) Glaciers 160 and 176 – lacustrine-terminating glaciers on Bolshevik Island. (h) Surge of the western Vavilov basin. (i) The separation of Dezhnev Ice Cap.

highest confidence classification is glacier 105, a lake-terminating glacier, which is observed to actively surge between 1987 and 2011 and shows evidence of having formerly surged at least twice; the surge classification is strengthened by the presence of a looped medial moraine (Figs 10c, d; Supplementary Video S2).

Surging prior to 1965 is mainly recorded by preserved thrust block/glacitectonic composite moraines, which likely record numerous advances due to surging, primarily on eastern October Revolution Island (e.g. Fig. 10a), which is one of the few areas to contain extensive forelands of deformable sediment. There are no preserved moraines beyond the limit of the possible surge moraines, most of which are still in contact with the ice front. As the surge diagnostic nature of thrust block/glacitectonic composite moraines is not entirely unequivocal (cf. Sharp, 1985, 1988; Fitzsimons, 1996, 1997, 2003; Evans and Rea, 1999, 2003; Ingolfsson and others, 2016), their presence in the absence of other surge criteria is not regarded as sufficient evidence for a classification of possible surge-type (category 3). On Bolshevik Island, four small cirque glaciers are not classified as surge-type despite potential thrust-block/glacitectonic composite moraines at their termini due to a possible, alternative, controlled moraine interpretation of such forms (Evans, 2009).

5. Discussion

5.1. Glacier change and climatic forcing

5.1.1. Spatiotemporal trends in glacier change

Our results show that almost all glaciers (96%) on Severnaya Zemlya have, overall, retreated between 1965 and 2021 (Fig. 4; Table 2). The reduction in glacierised area is attributed to atmospheric warming, with annual average air temperature increases of ~2–3°C (1936–2021) and an increase in warmer than average SSTs surrounding Severnaya Zemlya compared to the climate normal time period (1991–2020) (Figs 7, 8). Glaciers and ice caps have retreated the least in the north of Severnaya Zemlya, with retreat rates increasing along a southward gradient (Fig. 4; Table 2). Until 1997, glaciers on northern Severnaya Zemlya

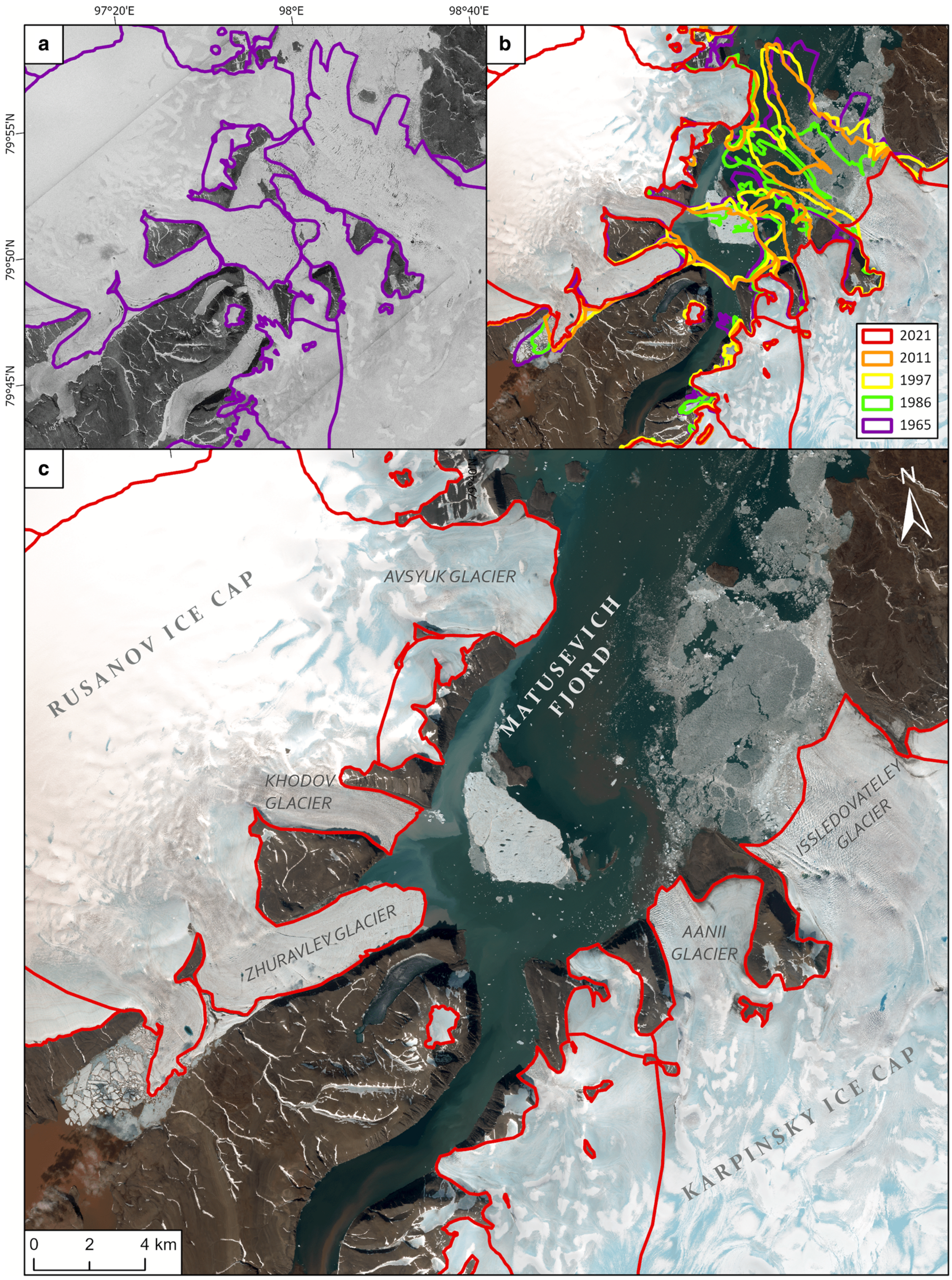

Figure 6. Glacier area change in Matusevich fjord. (a) The extent of the former Matusevich Ice shelf in 1965 KH-7 imagery. (b) Glacier change outlines from 1965 to 2021. Note the advance of the Issledovateley glacier between 1986 and 2011. (c) The state of Matusevich fjord in 2021, including glacier names.

were relatively stable, whereas on southern Severnaya Zemlya, glacier retreat was observed between 1952 and 1975 from a comparison of cartographic maps and aerial photography (Govorukha and others, 1987). Rates of glacier retreat notably accelerated in all regions post-1997, correlating with the transition between the colder period of the 1950s–90s and rapid warming at the end of the 20th century (Figs 3, 7).

Between 1965 and 2021, the largest losses in glacier area occurred on Bolshevik Island (−14.1%), in the south of Severnaya Zemlya (Table 2). Retreat rates have increased between each time slice post-1997, peaking at $-9.6\ \mathrm{km^2\ a^{-1}}$ (2011–21) and of a magnitude higher than retreat rates elsewhere on Severnaya Zemlya (Table 2). Bolshevik Island is influenced by warmer surface air temperatures and SSTs on the Kara Sea coast and receives the most precipitation on Severnaya Zemlya, but precipitation totals have slightly fallen between 1981 and 2022 (Fig. 8). The closest weather station to Bolshevik Island, Im. E. K. Fedorova, shows a clear increase in summer air temperatures, unlike Ostrov Golomjannyj on western Severnaya Zemlya which shows no trend of summer warming (Figs 1, 7). Glacier mass balance

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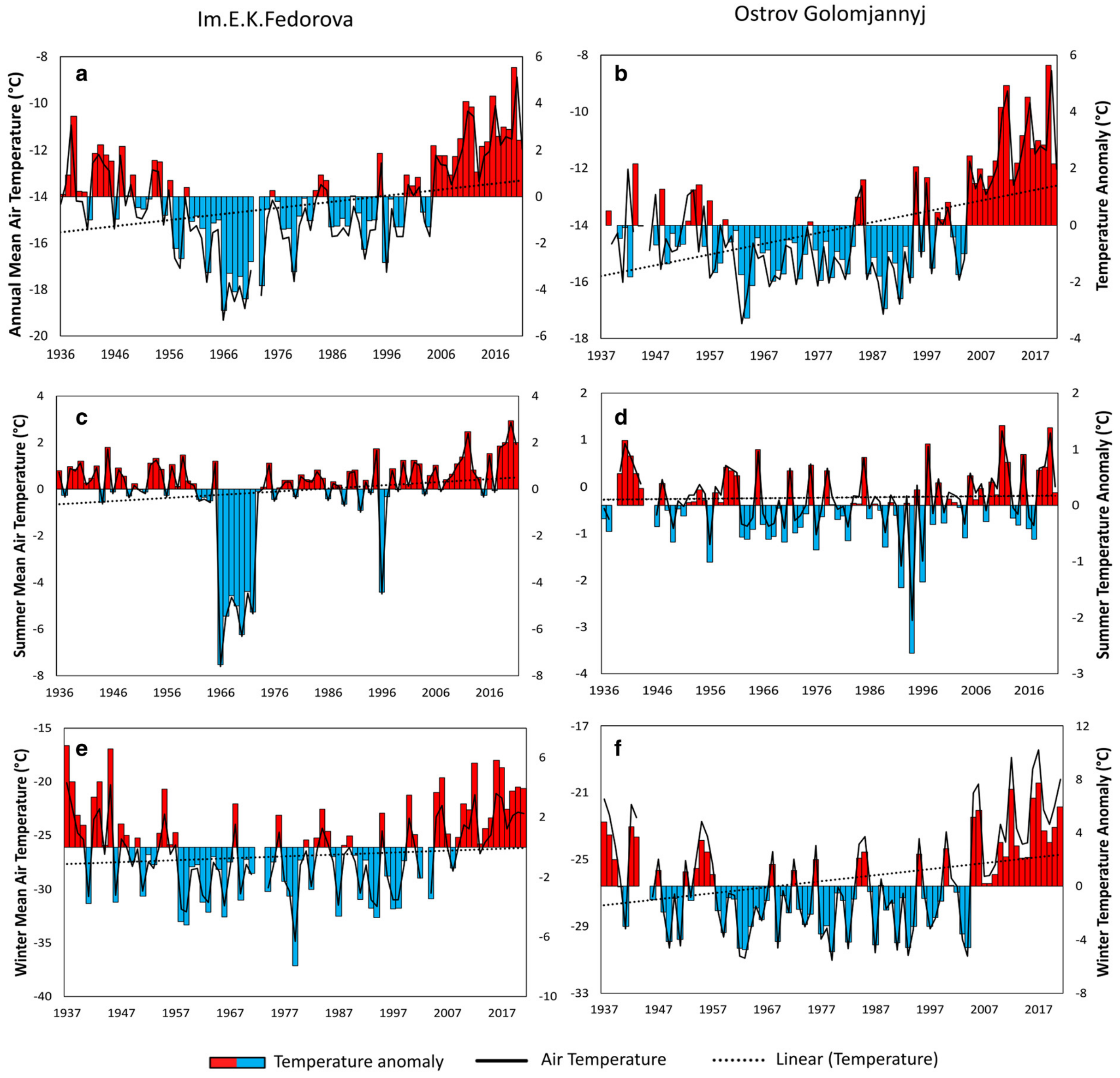

Figure 7. Seasonal and annual average air temperatures at Im. E. K. Fedorova (left) and Ostrov Golomjannyj (right). The location of each weather station is shown in Figure 1. Negative anomalies (blue) and positive anomalies (red) are shown by the bar chart, along with linear trend lines in surface air temperatures which are plotted against a 1936/37 to 2021 mean. Temperature is plotted on the primary axis (left), with anomalies on the secondary axis (right). (a) Annual average air temperature at Im. E. K. Fedorova. (b) Annual average air temperature at Ostrov Golomjannyj. (c) Summer average air temperature at Im. E. K. Fedorova. (d) Summer average air temperature at Ostrov Golomjannyj. (e) Winter average air temperature at Im. E. K. Fedorova. (f) Winter average air temperature at Ostrov Golomjannyj.

is most strongly controlled by summer climate (Möller and Kohler, 2018) and when increased summer ablation is combined with a decrease in winter precipitation (Fig. 8e), glacier mass balance will become increasingly negative. This combination of summer atmospheric warming occurring at a magnitude higher than the rest of Severnaya Zemlya and no change or a slight decrease in mean annual precipitation on Bolshevik Island specifically, provides a likely explanation for the southwards increase in retreat rates. It should be noted that glaciers on Bolshevik Island are smaller, and retreat is likely to be greater in terms of percentage than larger glaciers (cf. Stokes and others, 2018). However, 55% of the total 1965–2021 glacier area loss (−426 km^2) occurred there, thus showing that retreat is occurring disproportionately towards the south.

Northwards, glaciers and ice caps on October Revolution Island (−3.0%, 1965–2021) have retreated at a slower rate than on Bolshevik Island (−14.1%, 1965–2021), but recent observations indicate more dramatic changes (Table 2). The region underwent slow but incremental retreat until 2011 when the westernmost basin of Vavilov Ice Cap underwent a rapid advance (Fig. 5h; Willis and others, 2018) and the Matusevich Ice Shelf collapsed (Fig. 6; Willis and others, 2015). Until its collapse, the Matusevich Ice Shelf was the largest floating ice shelf in the Russian High Arctic and had historically undergone cyclical terminus fluctuations due to large calving events and subsequent advances (Williams and Dowdeswell, 2001). In the 3 years preceding the collapse, summer temperatures were 1, 1 and 2°C higher than normal, and one tributary glacier (Issledovateley) advanced, destabilising the Matusevich Ice Shelf and leading to its collapse in 2012 (Fig. 6; Willis and others, 2015). Post-collapse (2012–14), a reduction in buttressing from the Matusevich Ice Shelf resulted in thinning rates that exceed the 30 year average rate for Severnaya Zemlya (Willis and others, 2018). By 2021, imagery shows that a large tabular iceberg from the breakup of the Khodov terminus remains grounded in Matusevich fjord and former Matusevich Ice Shelf outlet glaciers show an increase in crevassing at their terminus (Fig. 6). Additionally, it is likely that the now exposed terminus of the Zhuravlev Glacier (Rusanov Ice Cap) is at risk

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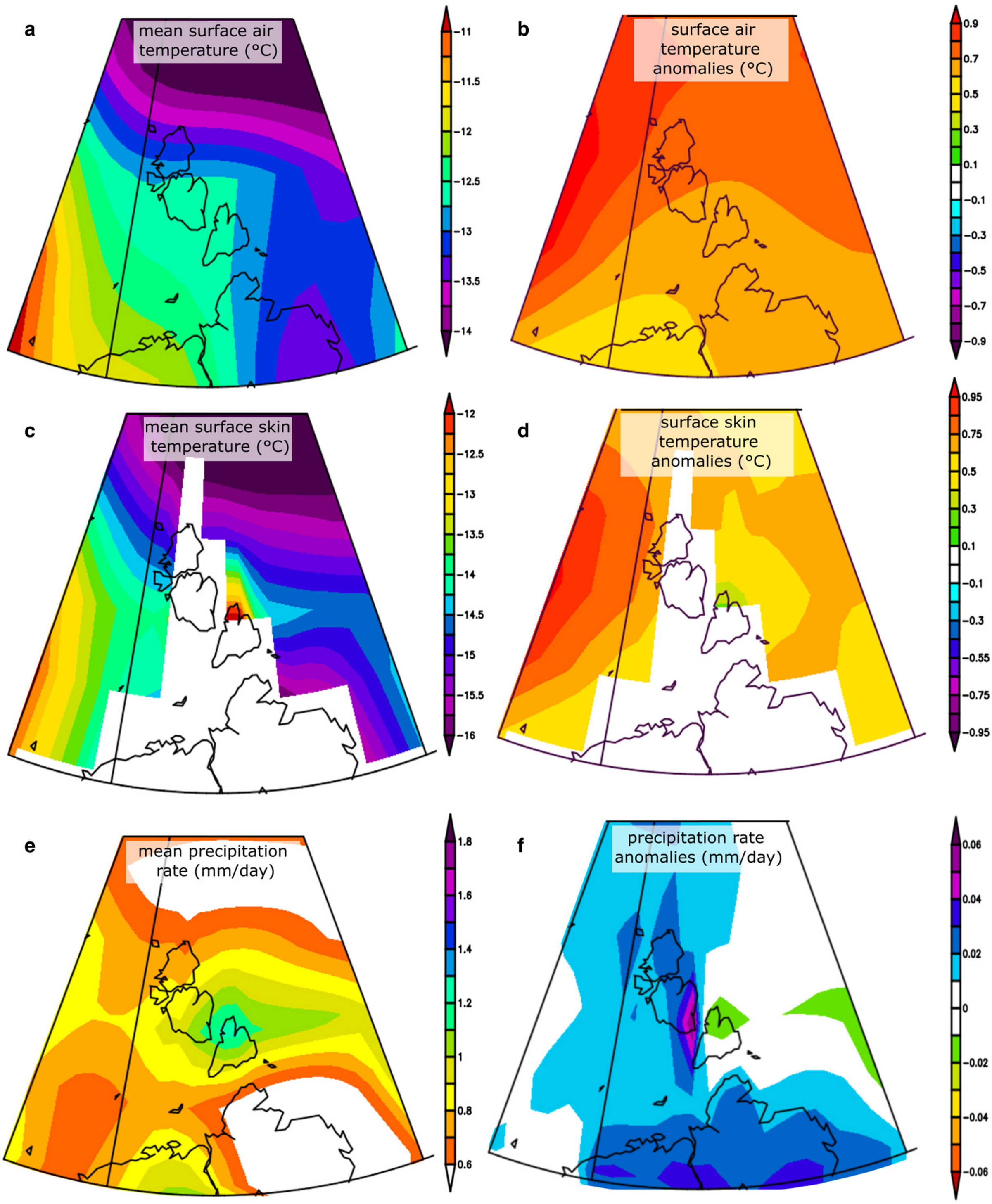

Figure 8. Long-term (1981–2022) mean annual climatologies (left) plotted using NOAA NCEP reanalysis monthly/seasonal climate composite tools (available at: https://psl.noaa.gov/) (Kalnay and others, 1996). Anomaly plots that show recent 21st-century (2000–22) trends plotted against the new climate normal time period (1991–2020) (right). (a) Mean surface (2 m) air temperature (°C). (b) 2 m air temperature anomalies (°C). (c) Mean surface skin temperature (°C). (d) Surface skin temperature anomalies (°C). (e) Mean annual precipitation (mm d^{-1}). (f) Mean annual precipitation anomalies (mm d^{-1}).

of collapse from a lack of buttressing (Fig. 6). Due to warmer SSTs and a Severnaya Zemlya-wide pattern of retreat (1965–2021), a regeneration of the Matusevich Ice Shelf is deemed highly unlikely (Figs 4, 8). The exposure of marine-terminating (Matusevich Ice Shelf-fed) outlet glaciers to warmer SSTs poses a risk of accelerated melting of the Rusanov and Karpinsky ice caps, which already have exhibited some of the highest rates of surface area loss on October Revolution Island.

Komsomolets Island (northernmost Severnaya Zemlya) shows the lowest overall change of the three main islands, having lost the least glacierised area between 1979 and 2021 (−1.9%; Table 2). The Academy of Sciences Ice Cap occupies most of Komsomolets Island and has had a mass balance close to zero for the last four decades (Bassford and others, 2006a; Sánchez-Gámez and others, 2019). However, between 1965 and 2021, two basins have increased in surface area and multiple basins of the Academy of Sciences Ice Cap show evidence of cyclical advance and retreat patterns (Moholdt and others, 2012b). The majority of advances observed in this study (from 1979 to 2021) are from one of the four fast-flowing Academy of

Table 3. Presence of surge-type glaciers on Severnaya Zemlya

Glacier	Terminus	2021 area km^2	RGI ID	Looped/deformed medial moraines	Deformed ice structures	Shear margins	Surface crevassing up-glacier	Heavy surface crevassing at the terminus	Localised abnormal advance	Highly digitate terminus	Surface potholes	Thrust-block/ push moraines	Total (weighted)
105	Lacustrine	350.7	G098101E79425N	a	cdef		def	acd	c-e		acdef		16
128	Marine	493.6	G098527E79706N				f	acdef	c-d	acde	acdef		13
76	Marine	485.1	G095377E79354N			f	f	ef	e-f		cd		11
138	Land	56.9	G099222E79553N	acdef						acdef		acdef	12
161	Marine	145.6	G099370E79446N	acdef				acdef			acdef	acdef	11
93	Marine	293.7	G097064E79876N				cdef	adef	c-e		acdef		10
43	Marine	411.1	G094682E80294N				abcdef	abcdef	a-b				9
67	Land	24.7	G099506E79382N						a-c	acdef			8
38	Marine	712.5	G094143E80332N					bcdef	b-f		bcdef		7
139	Marine	168.1	G096735E80048N					ab	a-b		abcdef		7
143	Marine	468.8	G096683E80578N					bcdef	d-e		bcdef		7
49	Marine	196.5	G096576E80253N					abcdef	a-b				6
70	Land	87.5	G098974E79688N	cdef	b								6
1	Marine	120.6	G097867E80049N					a				acdef	5
137	Marine	828.5	G096063E80433N				def	bdef			cdef		5
2	Marine	275.4	G095561E80299N				aef	abcdef			c		5
31	Land	93.3	G094665E79378N			f	f	f					5
77	Land	511.3	G096205E79192N						c-f				5
104	Land	419.0	G096481E79287N						c-f				5
154	Land	103.8	G093581E80318N						d-f				5

Lettering indicates the presence of a feature at an individual date: a – 1965, b – 1979, c – 1986, d – 1997, e – 2011, f – 2021. A weighted total of 0–3 = non-surge, 4–6 = category 3 – possible surge-type, >7 = category 2 – likely to have surged, with glaciers classified as category 1 – confirmed surge-type if they score >10, an advance is observed (active phase), and 3 or more surge-indicative features are present. See Table 1 for the weighting of each criterion. The colour of the weighted total corresponds with the classification in Figure 9.

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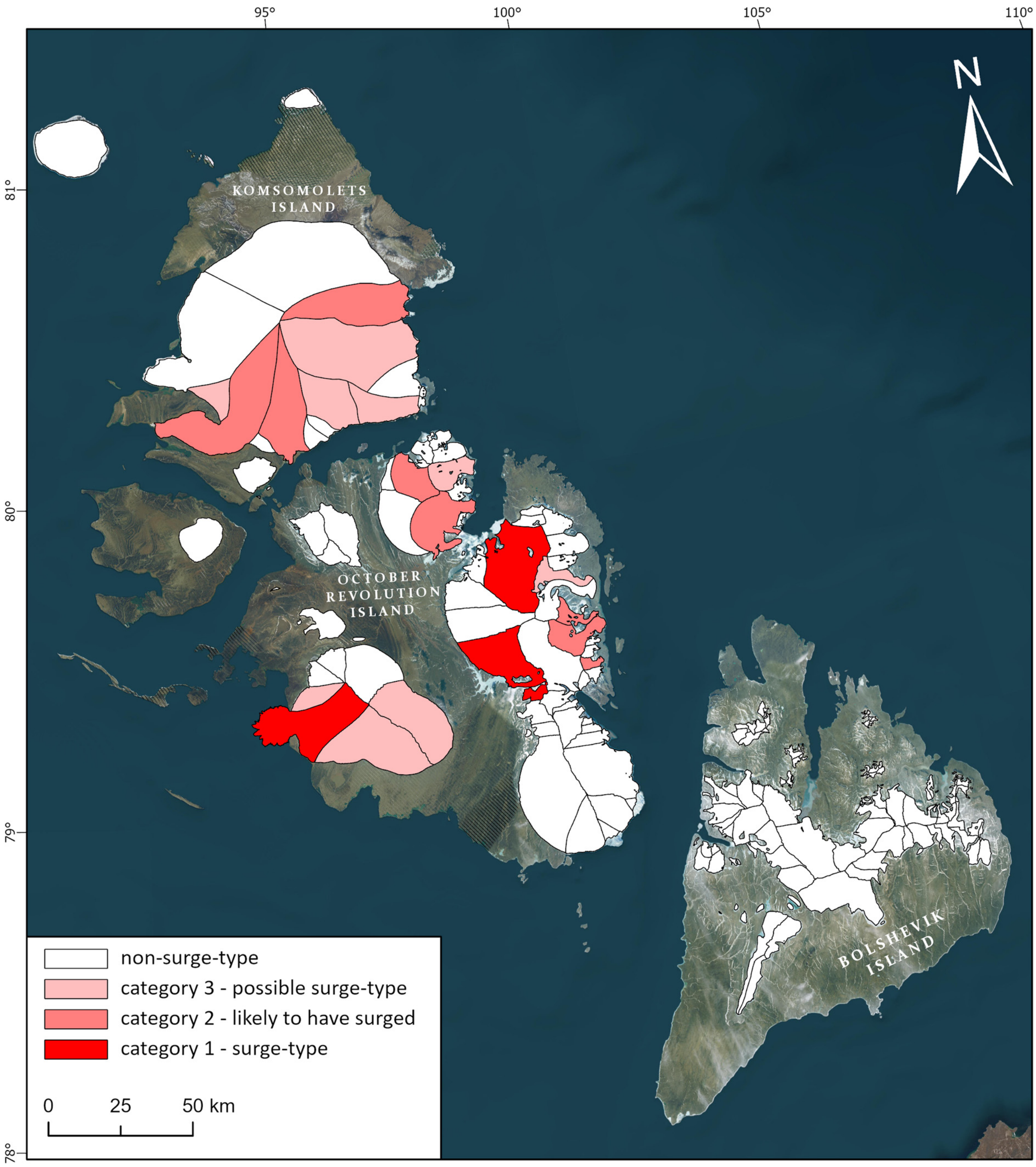

Figure 9. Classification of glaciers by likelihood of being surge-type based on a systematic identification of each glacier for surge-indicative features (see Table 1).

Sciences Ice Cap 'ice streams', which have velocities of a magnitude higher than the rest of Severnaya Zemlya (Table 3). It is not known what causes these ice streams to advance, although it has been argued that their sub-glacial geology, if deformable, could support transient subglacial deformation, or that drainage of water to the bed could explain glacier speed-up events (Moholdt and others, 2012b). Hence, it is suggested here that this is a viable explanation, as the drainage and re-appearance of large meltwater lakes on most of the 'ice streams' is observed, which may route meltwater to the glacier bed and result in glacier speed-up events. These advances are unlikely to be primarily driven by climate as they are asynchronous and the ice cap's mass balance remains close to zero (Moholdt and others, 2012b; Navarro and others, 2020). Thus, it is most probable that the speed-up events are due to the characteristics of the ice cap or another mechanism (e.g. surging).

Overall, accelerated glacier retreat on Severnaya Zemlya is attributed to a 2–3°C increase in mean annual surface air temperatures on the northern Taymyr Peninsula (the most proximal meteorological station to Bolshevik Island) and offshore from October Revolution Island (1936–2021; Figs 7a, b). The highest rates of retreat occurred at land-terminating glaciers on Bolshevik Island and are likely due to increasing summer atmospheric surface temperatures on the proximal Taymyr Peninsula (Fig. 7c). Summer warming is the primary control on glacier retreat, leading to increased ablation, which may be exacerbated by a lengthened melt season due to annual warming trends resulting in an increase in days above 0°C, particularly in spring and autumn. Increased ablation, which on Bolshevik Island has not been counteracted by increased precipitation, has likely resulted in an increasingly negative glacier mass balance, which has manifested as a reduction in glacier surface area (Figs 8e, f). In

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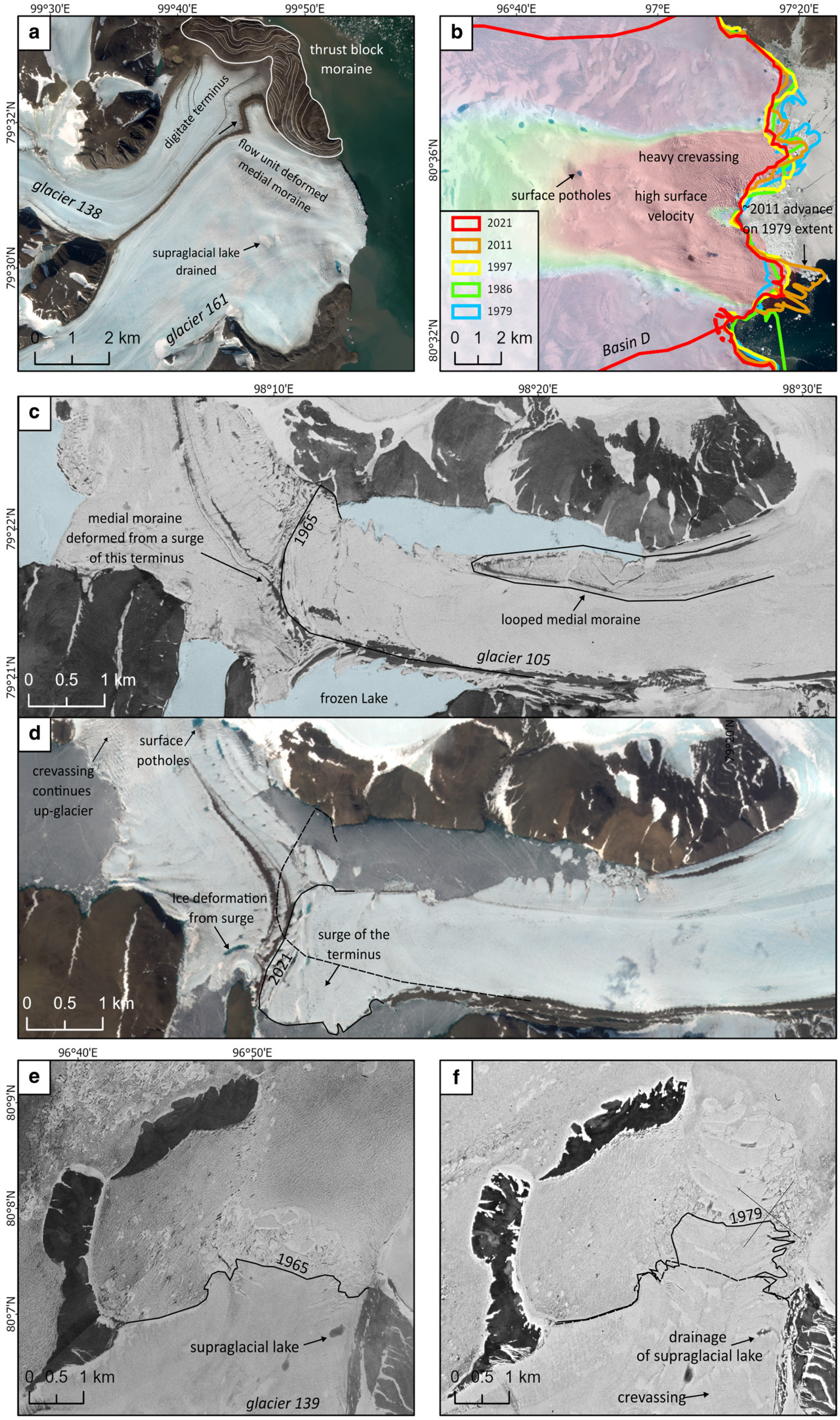

Figure 10. Evidence of surge-type glaciers. (a) Glaciers 138 (north) and 161 (south) on eastern Karpinsky Ice Cap, including the presence of a deformed medial moraine and a thrust block moraine in contact with the ice margin at the terminus of glacier 138. (b) Localised advance to the south of basin D of the Academy of Sciences Ice Cap between 1979 and 2011, including heavy crevassing and surface potholes. (c) 1965 KH-7 imagery of glacier 105. The frozen lake is artificially coloured blue to aid visibility. Note the presence of a looped medial moraine. (d) 2021 Sentinel-2A imagery of glacier 105. (e) 1965 KH-7 imagery of glacier 139. (f) KH-9 1979 imagery showing a rapid localised advance of the terminus of glacier 13.

contrast, further north there is no apparent trend in summer warming and the rate of precipitation (1936–2021) has remained steady or has increased (Figs 7d, 8e, f). Although the melt season may have become longer in the north, retreat has occurred at a slower rate due to lower rates of summer warming and ablation compared to Bolshevik Island (Figs 7c, f). Additionally, there is evidence that declining sea-ice concentrations due to oceanic warming may allow for increased heat flux transfer from the ocean to the atmosphere (Rodrigues, 2008; Tepes and others, 2021b), with a statistically significant correlation between reduced late-summer sea-ice concentrations and earlier surface snowpack melt (Zhao and others, 2014). This trend in oceanic warming is attributed by Tepes and others (2021b) to be the primary driver of mass loss on Severnaya Zemlya. However, as the highest reductions in surface area are observed at land-terminating glaciers on Bolshevik Island, it is suggested that atmospheric warming is more influential than previously thought, especially on small, land-terminating glaciers in the south. It is anticipated that Severnaya Zemlya will become increasingly negative in mass balance as summer warming trends are likely to increase, while sea-ice concentrations are likely to decrease, resulting in higher rates of ablation that cannot be sustained by the current rates of precipitation.

5.1.2. Comparison to other Arctic regions

The absence of summer warming trends in surface air temperature (1936–2021) on northern Severnaya Zemlya is in accordance with Novaya Zemlya (1990–2011) (Carr and others, 2014), although Novaya Zemlya has since become a hotspot for warm anomalies (2011–16) (Ciracì and others, 2018). South of Severnaya Zemlya, the Taymyr Peninsula on mainland Russia has seen an increase in positive summer air temperature anomalies, which may also have occurred on southern Severnaya Zemlya (Fig. 7c). Similar to Severnaya Zemlya, Svalbard exhibits a strong trend of winter warming (1.6°C decade^{-1}, 1961–2012) and, to a lesser degree, summer warming (0.2°C decade^{-1}, 1961–2012). The latter has been pinpointed as the key driver of glacier thinning on Svalbard and, when combined with the trend of declining summer precipitation, has resulted in glaciers experiencing a negative mass balance (van Pelt and others, 2016; Geyman and others, 2022). The warming trends and resulting glacier retreat observed in the western Barents–Kara region (i.e. Svalbard and western Novaya Zemlya) can be used as a predictor for the future glaciological changes on Severnaya Zemlya, as its warming is delayed with respect to the western Barents–Kara Sea region (Tepes and others, 2021b).

Strong winter warming trends in the Barents Sea have been linked to sea-ice decline and a subsequent acceleration of glacier retreat (Carr and others, 2014; Tepes and others, 2021b). In addition, the increased encroachment of warmer Atlantic waters into the Eurasian basin has been attributed to changes in the Atlantic Multi-decadal Oscillation and North Atlantic Oscillation, leading to further sea-ice decline (Carr and others, 2017b; Carvalho and Wang, 2020). There is also evidence that, in recent decades, Ural blocking events, which are blocking anticyclonic anomalies over the Eurasian subarctic region, have contributed to reduced sea-ice concentrations and warmer air temperatures in the Barents–Kara Sea region (Luo and others, 2016, 2019). The strength of Ural blocking events has also been linked to different phases of El Niño-Southern Oscillation (ENSO); hence ENSO may be an additional driver of changing sea-ice concentrations in the Eurasian Arctic (Luo and others, 2021). The effect of long-term sea-ice decline has been observed in the Arctic, notably in Greenland, where retreat rates have increased during phases of low or no sea ice (Reeh and others, 2001; Amundson and others, 2010; Moon and others, 2015). At present, sea-ice concentrations have declined around Severnaya Zemlya, but still remain relatively high, and thus there is no difference in retreat rates (outside of error margins) between land- and marine-terminating glaciers (Rodrigues, 2008; Onarheim and others, 2018). In contrast, glacier retreat at marine-terminating outlets on neighbouring Novaya Zemlya and Franz Josef Land is observed to have occurred at a disproportionally faster rate compared to land-terminating glaciers (Carr and others, 2014; Moon and others, 2015; Zheng and others, 2018). On Novaya Zemlya, marine-terminating glaciers have retreated 3.5 times faster than land-terminating glaciers (Carr and others, 2017b). The results presented here show that the largest reductions in glacier surface area have occurred at land-terminating glaciers in the far south of Severnaya Zemlya (Fig. 4). Hence, we deduce that glacier retreat at land-terminating glaciers on southern Severnaya Zemlya is primarily driven by atmospheric and not oceanic warming. Marine-terminating glaciers are likely to respond in a more complex manner, in that their dynamics can be forced by both atmospheric and oceanic warming, along with changing sea-ice concentrations (Moon and others, 2015; Carr and others, 2017b). It is anticipated that under continued sea-ice decline due to climatic warming over the next few decades, the magnitude of marine-terminating glacier retreat on Severnaya Zemlya is likely to greatly exceed that of land-terminating glaciers.

5.2. Identification of surge-type glaciers

5.2.1. Occurrence

Within the Russian High Arctic, glacier surging has been perceived to be confined to the more temperate climate of Novaya Zemlya (Grant and others, 2009). In contrast, predominantly cold-based glaciers, as seen further east (e.g. Severnaya Zemlya), have not traditionally been associated with surge-type behaviour, despite some clear evidence to the contrary (e.g. Hattersley-Smith, 1969; Copland and others, 2003; Van Wychen and others, 2016). Models predict that surging may occur on Severnaya Zemlya and note the need for further investigation in the region (Sevestre and Benn, 2015). The notion that surging occurs on Severnaya Zemlya was supported by the identification of two looped medial moraines by Dowdeswell and Williams (1997) from 30 m imagery on eastern Karpinsky Ice Cap. More recently, a large destabilisation of western Vavilov Ice Cap in 2012 implied that surge-like behaviour may be more widespread on Severnaya Zemlya than previously thought (Willis and others, 2018). This ‘surge’, or more correctly ‘speed-up event’, shared similar properties to that of a large fast-flow event at Austfonna, Svalbard (Dunse and others, 2011; Gong and others, 2018) and numerous other active phases of surging observed in more temperate Svalbard. Contrary to the Svalbard polythermal glacier regime, glaciers on Severnaya Zemlya are thought to be predominantly cold-based and receive less precipitation, meaning the quiescent period is likely to be longer. However, given the presence of the looped medial moraines observed by Dowdeswell and Williams (1997), it is likely that surging has and does occur on Severnaya Zemlya, and this is confirmed in the present study. Indeed, it is proposed that surging is more widespread on Severnaya Zemlya than initially thought, with 20 glaciers possibly of surge-type (Table 3; Fig. 9). When sub-divided by confidence, three glaciers are classified as category 1 – confirmed surge-type, eight are category 2 – likely to have surged and nine are category 3 – possible surge-type. The recent availability of higher resolution imagery (e.g. ArcticDEM, 2 m, Sentinel-2A, 10 m) and the use of multiple dates (1965, 1979, 1986, 1997, 2011 and 2021) may partly explain the increased detection of surge-type glaciers compared to previous attempts (Dowdeswell and Williams, 1997).

There are fewer glaciers classified as surge-type on Severnaya Zemlya than on Novaya Zemlya and Svalbard, but compared to

Novaya Zemlya, surge-type glaciers (including category 2 – likely to have surged and category 3 – possible surge-type) on Severnaya Zemlya occupy a disproportionate portion of its glacierised area. As a percentage of glacierised area and including both possible surge-type glaciers and likely to have surged, the 37% surge glacier coverage of Severnaya Zemlya exceeds that of Novaya Zemlya (~18%, including possible and likely to have surged; Grant and others, 2009), but is lower than Svalbard (~46.5%; Jiskoot and others, 1998). However, if we only include those classified as confirmed surge-type, the areal proportion is 8%. The difference in surge-type glacierised area between Severnaya Zemlya and Novaya Zemlya is attributed to many surge-type glaciers on Severnaya Zemlya being concentrated around the outlets of large ice domes, which are substantially larger than any ice cap on Novaya Zemlya. Overall, the number of surge-type glaciers decreases across an eastward gradient from the surge climatically optimal region of Svalbard to Novaya Zemlya and Severnaya Zemlya (Sevestre and Benn, 2015).

It is probable that surging on Severnaya Zemlya occurs less frequently than further west due to Severnaya Zemlya's lower rates of precipitation, increasing the time required for glaciers to re-gain enough mass to surge. As precipitation is a control on the length of the quiescent period (Eisen and others, 2001), it makes identifying multiple surges unlikely in colder, dryer climates like Severnaya Zemlya. Traditional surge definitions state that advances must be cyclical for a glacier to be surge-type. Thus, without observing cyclical behaviour it cannot be confirmed whether externally forced one-off speed-up events rather than cyclical/repeated surges occur on Severnaya Zemlya. However, one glacier (105) is observed in its active phase (~1986–2010) and has a looped medial moraine in 1965 imagery, which presumably formed before the active phase commenced. Hence, it is likely a relic from a prior surge, implying that the glacier has surged at least twice (Figs 10c, d).

The presence of surge-indicative features is less common on Severnaya Zemlya than on Svalbard, with notable differences in foreland geomorphology. Any geomorphological record of surging on Severnaya Zemlya is likely represented by the superimposition of proglacial thrust masses as glacier extent has remained close to modern margins since the LGM (Raab and others, 2003), illustrated by the thrust block moraines on eastern October Revolution Island (Fig. 10a). Many glaciers remain in contact with thrust block moraines at their terminus, with no inner zone in which to identify other surge diagnostic forms such as long flutings, geometric ridge networks or zigzag eskers (Evans and Rea, 2003; Ingólfsson and others, 2016). Where forelands are exposed, they contain no such clear evidence of glacier surging. A similar scenario occurs in the Canadian High Arctic where glaciers that have constructed thrust moraines are not traditionally interpreted as surge-type (cf. Evans and England, 1991, 1992; Ó Cofaigh and others, 1999, 2003; Copland and others, 2003). Consequently, future research needs to further investigate the landsystem imprint typical of cold-based glacier systems in order to assess the presence, both former and contemporary, of High Arctic glacier surges.

5.2.2. Distribution

Surging on Severnaya Zemlya is primarily clustered around north-eastern Severnaya Zemlya, on the Academy of Sciences Ice Cap, Karpinsky and Rusanov ice caps (Fig. 9). Within these ice caps, individual basins classified as surge-type display no preferential aspect. The geomorphological imprint of surging is primarily clustered around Karpinsky Ice Cap, in eastern Severnaya Zemlya, where glaciers descend from areas of higher elevation down to areas of deformable sediment on the Laptev Sea coast. Glaciers on the Laptev Sea coast are more likely to be marine-terminating and this coastal zone is characterised by colder surface air temperatures and lower equilibrium line altitudes even though there are warmer SSTs on the continental shelf here than on the Kara Sea coast (Figs 8a, c). However, it is clear that surging is not restricted to a climatic envelope on the Laptev Sea coast due to the ice-marginal speed-up event on Vavilov Ice Cap and the post-surge geometry of basin A, both of which are on the Kara Sea coast (Figs 5a, h).

If warmer ice temperatures and polythermal glacier regimes increase the likelihood of glacier surging, surging should be most prevalent on the warmer, southernmost, Bolshevik Island, which contains small glaciers and ice caps. However, there is no explicit evidence of past surging on the island, with the exception of four small (~0.5–1.5 km^2) cirque glaciers that have disproportionally large ice-cored, potentially thrust-block, terminal moraines. Using our protocol, these glaciers are not classified as surge-type due to the absence of other surge-indicative features. These small cirques differ from the characteristics typical of surge-type glaciers on Severnaya Zemlya, Novaya Zemlya and on Svalbard, which are predominantly long, have relatively steep slopes and occupy larger basins (Jiskoot and others, 2000; Grant and others, 2009; Sevestre and Benn, 2015). However, small cirque glaciers have been observed to surge in northern Iceland (Brynjólfsson and others, 2012; Ingólfsson and others, 2016) and, despite differing basal thermal regimes between Iceland and Severnaya Zemlya, these glaciers may have once surged. Notwithstanding this evidence for possible surging cirque glaciers, there is a lack of unequivocal surging activity on Bolshevik Island.

The existence of surge-type glaciers on Komsomolets Island has been debated (e.g. Moholdt and others, 2012b). However, it is suggested that evidence is sufficient to assume that surging has most likely occurred in the Academy of Sciences Ice Cap. According to our protocol, within the Academy of Sciences Ice Cap, we classify three glaciers as category 2 – likely to have surged and four as category 3 – possible surge-type. Prior research has found no evidence of past surge activity within the residency time of the ice, in the form of looped medial moraines, heavy surface crevassing or rapid localised glacier advances (Dowdeswell and others, 2002). Previous studies (Moholdt and others, 2012b; Sánchez-Gámez and others, 2019) and glacier change mapping from this study show that the ice streams of the Academy of Sciences Ice Cap (basins B, BC, C, D) alternate between periods of slow and fast flow (e.g. Fig. 10b) (we classify them as likely to have surged, possible, possible and likely to have surged, respectively). The mechanism driving this cyclical behaviour is unknown, but the notion that they are surge-type is supported by two basins (A and B) that have undergone surge-like elevation changes (Moholdt and others, 2012b) (we classify both as category 2 – likely to have surged). These changes were followed by a deceleration in ice flow velocity in basin A, which is characterised by a typical post-surge geometry (Moholdt and others, 2012b). In addition, we observe a small but steady advance of basin A at the north-eastern margin of its low-gradient lobe and a small advance between 1979 and 1997 at its terminus (Fig. 5a). Despite there being alternative explanations for the existence of some surge-indicative features (e.g. shear margins are also typical of ice streams), some features, such as the large low-gradient lobe characteristic of a post-surge terminus, are difficult to attribute to another mechanism (Fig. 5a). Thus, it is deemed likely that surging has occurred in the Academy of Sciences Ice Cap, but there is no chronological constraint on when it occurred.

Similar issues of equifinality exist when determining whether the glaciers that fed the former Matusevich Ice Shelf on October Revolution Island are of surge-type. Before its collapse

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in 2012, there was evidence of an acceleration in ice flow velocity in the ice shelf's tributary glaciers between 1965 and 1995 (Sharov and others, 2015). As this velocity speed-up was synchronous with other glaciers this behaviour can be dismissed as surging. Additionally, observations show a notable localised advance of one tributary glacier (Issledovateley) between 1986 and 1997, which in conjunction with its heavy crevassing classifies this glacier as surge-type using our protocol (Fig. 6). Nevertheless, we suggest that this advance may not be due to surging *sensu stricto* as the ice shelf is known to undergo cyclical patterns of disintegration and re-establishment every 30 years (Williams and Dowdeswell, 2001). As the last advance was between 1962 and 1973 (Willis and others, 2015), the advance recorded between 1986 and 1997 is ∼30 years later and therefore appears to be part of the cyclical behaviour that drives speed-up events. Moreover, it is unlikely that a quiescent phase would be as short as ∼30 years when such phases are typically 50–100 years in duration on Svalbard (Dowdeswell and others, 1991).

5.2.3. Characteristics

Surge-type glaciers are typically characterised by an imbalance whereby they are not able to efficiently regulate mass, resulting in a surge/quiescent cycle (Sevestre and Benn, 2015; Benn and others, 2019). Glacier length and slope appear to be the key differentiators between surge-type and non-surge-type glaciers, with surge-type glaciers most likely to be longer with shallower slope angles (Clarke and others, 1986; Jiskoot and others, 1998; Grant and others, 2009; Sevestre and Benn, 2015). Our results show that surging on Severnaya Zemlya is mainly restricted to long outlet glaciers descending from larger ice caps, notably around Mount Karpinsky, the highest point on Severnaya Zemlya (Fig. 9). Marine- and lake-terminating glaciers are most likely to surge on Severnaya Zemlya and account for 65% of glaciers classified as potential surge-type. However, the number of marine-terminating surge-type glaciers may be underestimated due to the absence of bathymetric datasets, which would otherwise allow for the identification of landforms characteristic of the tidewater surge-type glacier landsystem model (Ottesen and others, 2008; Flink and others, 2015).

We assume that surge-type glaciers on Severnaya Zemlya are characterised by a longer quiescent and active surging phase than glaciers in warmer climates with higher rates of precipitation. The observation of active surging on glacier 105, for example, occurred for ∼24 years between 1986 and 2010 (Supplementary Video S2). Additionally, the surge of Vavilov Ice Cap has continued for >10 years post-destabilisation in 2011. In comparison, surges on Svalbard can be as short as 2 years (e.g. Tunabreen) but may last longer than 10 years in some cases (e.g. Basin 3, Austfonna) (Dunse and others, 2015; Benn and others, 2023). If these slow advances on Severnaya Zemlya are due to surging, as assumed, the active phase duration may be similar to glaciers in the cold, dry Canadian High Arctic, where the active phase has exceeded 20–50 years for some glaciers (Copland and others, 2003; Van Wychen and others, 2016; Lauzon and others, 2023). Despite the fact that surging has not been observed with sufficient frequency to accurately constrain the duration of the active and quiescent phases, it can be assumed that the duration required for replenishing the mass to enable surging would take longer than in areas with higher rates of annual snowfall (e.g. Svalbard and Alaska) (Eisen and others, 2001; Harrison and others, 2008; Kochtitzky and others, 2020). Thus, it is suggested that surging occurs less frequently on Severnaya Zemlya than in areas westwards towards the Barents Sea, where annual rates of snowfall are higher. Indeed, glaciers further west in the Barents Sea region may offer a useful analogue as to how glacier dynamics will change on Severnaya Zemlya under increasing oceanic and atmospheric temperatures, which could affect the occurrence of surging. At some temperate and polythermal glaciers in the Yukon, Canada and on Svalbard, increased temperatures may have resulted in a reduction in surging due to insufficient mass to surge (e.g. Małecki and others, 2013; Kochtitzky and others, 2020), whereas for cold-based glaciers, the transition to a polythermal regime may increase surging (e.g. Willis and others, 2018). Under continued warming, we anticipate accelerated retreat and increased likelihood of surging on Severnaya Zemlya as basal thermal regimes shift from predominantly cold-based to polythermal/warm-based.

6. Conclusions

This study finds that Severnaya Zemlya has undergone substantial glacier surface area loss (−778 km^2, −5%) from 1965 (17 053 ± 38 km^2) to 2021 (16 275 ± 69 km^2) and shows increasing evidence of glacier response to climatic warming. Spatiotemporal trends show that glacier retreat has accelerated post-1997, with retreat mostly concentrated around land-terminating glaciers on southernmost Severnaya Zemlya (Bolshevik Island). We attribute higher rates of retreat southwards to increased evidence of summer atmospheric warming, which is not yet evident in northern Severnaya Zemlya. As land-terminating glaciers also retreated in the north, albeit to a lesser degree, it is probable that annual atmospheric warming has lengthened the melt season. In addition to oceanic warming, which has previously been identified as a driver of glacier retreat on Severnaya Zemlya (Tepes and others, 2021b), we suggest that atmospheric warming is also playing a key role.

Building upon the previous identification of two potential surge-type glaciers for the area and the destabilisation of Vavilov Ice Cap (Dowdeswell and Williams, 1997; Willis and others, 2018), our findings suggest that surging is more common on Severnaya Zemlya than previously thought. Most glaciers are not surge-type, but we confirm that three glaciers out of 190 glaciers on Severnaya Zemlya are surge-type (category 1: 1.6%), eight are likely to have surged (category 2: 4.2%) and nine are possible surge-type (category 3: 4.7%). Although small by number, these three categories represent 37% of the glacierised area of Severnaya Zemlya, or 8% if only confirmed surge-type glaciers are included. Surge-type glaciers on Severnaya Zemlya occupy large, long, marine- or lake-terminating basins and are primarily concentrated around Karpinsky Ice Cap. The quiescent phase is assumed to be longer than Novaya Zemlya and Svalbard due to lower rates of precipitation, a colder climate and the observation of only three active surge phases between 1965 and 2021 on glaciers confirmed as surge-type. From the three active phases observed, we suggest that the active phase of surging on Severnaya Zemlya is also longer than average, but further observation and monitoring of these glaciers is required.

Under continued amplification of Arctic warming, we anticipate accelerated rates of mass loss from the Russian High Arctic. On Severnaya Zemlya, climatic warming is likely to result in increasingly negative glacier mass balance. A transition from mostly cold-based thermal regimes to polythermal is also probable, together with increased surface melting and the potential for increased accumulation, which may lead to a change in glacier dynamics on Severnaya Zemlya. This may result in the destabilisation of larger ice caps and increased surge-like behaviour that could increase the rate of sea-level rise contributions from the Russian High Arctic.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/jog.2023.60.

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