

Greenland-wide accelerated retreat of peripheral glaciers in the twenty-first century

In the format provided by the
authors and unedited

Contents:

Supplementary Table 1: Image sources, frontal change rates and uncertainties by region
Supplementary Table 2: Zero-order correlations between regional retreat rates, MAR output and DMI station data
Supplementary Figure 1: Historical aerial photographs
Supplementary Figure 2: Orthorectification and georeferencing of historical aerial photographs
Supplementary Figure 3: Late 20th century ortho-mosaic
Supplementary Figure 4: Schematic of methods for calculation of GIC frontal changes
Supplementary Figure 5: Spatial distribution of frontal change for South Greenland GICs
Supplementary Figure 6: Spatial distribution of frontal change for North Greenland GICs
Supplementary Figure 7: Spatial distribution of frontal change for Central-west Greenland GICs
Supplementary Figure 8: Spatial distribution of frontal change for Southwest^a Greenland GICs
Supplementary Figure 9: Spatial distribution of frontal change for Southwest^b Greenland GICs
Supplementary Figure 10: Spatial distribution of frontal change for Southeast Greenland GICs
Supplementary Figure 11: Spatial distribution of frontal change for Northwest and Northeast Greenland GICs
Supplementary Figure 12: Cumulative length lost in the twenty-first century
Supplementary Figure 13a: Characteristics of GICs by region
Supplementary Figure 13b: Hypsometry of GICs by region
Supplementary Figure 14: Regional climate and surface mass balance from MAR
Supplementary Figure 15: Relationship between regional surface mass balance, retreat rate and climate from MAR

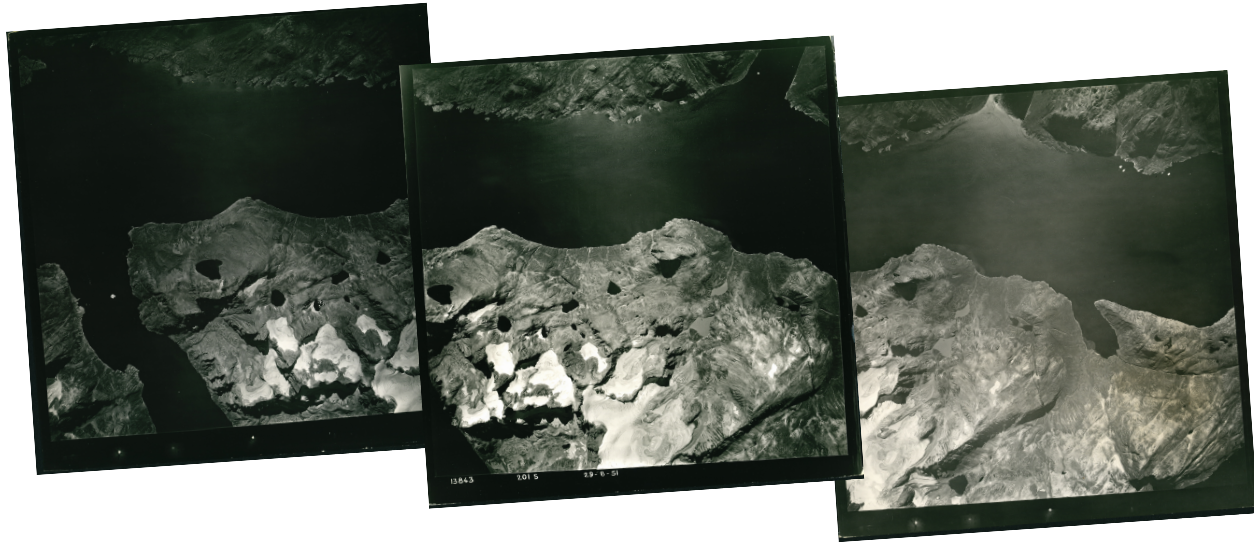
SOUTH	Data source	Orthophoto	Aerial photos	Orthophoto	Landsat 7 satellite	Landsat 8 satellite	Sentinel 2 satellite			
	Digitizing accuracy	10 m	12.5 m	4 m	16.7 m	16.7 m	10 m			
	Frontal change rate and uncertainty	$-9.5 \pm 0.4 \text{ m yr}^{-1}$		$-3.9 \pm 0.5 \text{ m yr}^{-1}$	$-1.6 \pm 1.3 \text{ m yr}^{-1}$	$-7.4 \pm 1.8 \text{ m yr}^{-1}$	$-8.2 \pm 2.4 \text{ m yr}^{-1}$			
NORTH	Data source	Orthophoto	Landsat 7 satellite	Landsat 7 satellite	Landsat 8 satellite	Landsat 8 & 9 satellite				
	Digitizing accuracy	4 m	16.7 m	16.7 m	16.7 m	16.7 m				
	Frontal change rate and uncertainty	$-3.2 \pm 0.8 \text{ m yr}^{-1}$		$-8.0 \pm 3.9 \text{ m yr}^{-1}$	$-8.1 \pm 2.6 \text{ m yr}^{-1}$	$-19.5 \pm 4.7 \text{ m yr}^{-1}$				
SOUTHEAST	Data source	Aerial photos	Aerial photos	CORONA satellite	Landsat 1 satellite	Orthophoto	Landsat 7 satellite	Landsat 7 satellite	Sentinel 2 satellite	
	Digitizing accuracy	60.5 m	12.5 m	12.5 m	30.9 m	4 m	16.7 m	16.7 m	10 m	
	Frontal change rate and uncertainty	$-23.0 \pm 6.2 \text{ m yr}^{-1}$		$-6.1 \pm 1.2 \text{ m yr}^{-1}$	$-5.3 \pm 4.8 \text{ m yr}^{-1}$	$-6.3 \pm 3.5 \text{ m yr}^{-1}$	$-10.2 \pm 1.0 \text{ m yr}^{-1}$	$-15.9 \pm 2.4 \text{ m yr}^{-1}$	$-22.9 \pm 1.8 \text{ m yr}^{-1}$ *	
NORTHWEST	Data source	Orthophoto	Aerial photos	CORONA satellite	Orthophoto	Landsat 7 satellite	Landsat 8 satellite	Sentinel 2 satellite		
	Digitizing accuracy	10 m	12.5 m	12.5 m	4 m	16.7 m	16.7 m	10 m		
	Frontal change rate and uncertainty	$-10.7 \pm 0.3 \text{ m yr}^{-1}$		$-13.0 \pm 1.1 \text{ m yr}^{-1}$	$-7.9 \pm 0.9 \text{ m yr}^{-1}$	$-9.2 \pm 1.0 \text{ m yr}^{-1}$	$-16.6 \pm 2.0 \text{ m yr}^{-1}$	$-20.8 \pm 3.2 \text{ m yr}^{-1}$ *		
NORTHEAST	Data source	Orthophoto	Aerial photos, terr. photos	CORONA satellite	Landsat 1 satellite	Orthophoto	Landsat 7 satellite	Landsat 7 satellite	Sentinel 2 satellite	
	Digitizing accuracy	10 m	60.5 m	12.5 m	30.9 m	4 m	16.7 m	16.7 m	10 m	
	Frontal change rate and uncertainty	$-22.1 \pm 6.4 \text{ m yr}^{-1}$		$-6.3 \pm 1.8 \text{ m yr}^{-1}$	$-3.9 \pm 4.8 \text{ m yr}^{-1}$	$-7.7 \pm 2.2 \text{ m yr}^{-1}$	$-6.7 \pm 1.3 \text{ m yr}^{-1}$	$-12.2 \pm 1.8 \text{ m yr}^{-1}$	$-11.8 \pm 2.4 \text{ m yr}^{-1}$ *	
CENTRAL-WEST	Data source	Orthophoto	Aerial photos	Orthophoto	Landsat 7 satellite	Landsat 7 satellite	RapidEye satellite	Landsat 8 & 9 satellite		
	Digitizing accuracy	10 m	12.5 m	4 m	16.7 m	16.7 m	3 m	16.7 m		
	Frontal change rate and uncertainty	$-11.3 \pm 0.3 \text{ m yr}^{-1}$		$-7.2 \pm 0.6 \text{ m yr}^{-1}$	$-4.2 \pm 1.3 \text{ m yr}^{-1}$	$-13.5 \pm 2.4 \text{ m yr}^{-1}$	$-12.2 \pm 2.4 \text{ m yr}^{-1}$	$-20.8 \pm 3.4 \text{ m yr}^{-1}$		
SOUTHWEST ^a	Data source	Orthophoto	Aerial photos	Aerial photos	Aerial photos	Orthophoto	Landsat 7 satellite	Landsat 7 satellite	RapidEye satellite	Landsat 8 & 9 satellite
	Digitizing accuracy	10 m	12.5 m	12.5 m	12.5 m	4 m	16.7 m	16.7 m	3 m	16.7 m
	Frontal change rate and uncertainty	$-10.4 \pm 0.4 \text{ m yr}^{-1}$		$-2.8 \pm 2.1 \text{ m yr}^{-1}$	$-7.4 \pm 1.3 \text{ m yr}^{-1}$	$-3.4 \pm 1.1 \text{ m yr}^{-1}$	$-4.3 \pm 1.3 \text{ m yr}^{-1}$	$-13.3 \pm 2.4 \text{ m yr}^{-1}$	$-13.7 \pm 2.4 \text{ m yr}^{-1}$	$-25.5 \pm 3.4 \text{ m yr}^{-1}$
SOUTHWEST ^a	Data source	Orthophoto	Aerial photos	Orthophoto	Landsat 7 satellite	Landsat 7 satellite	RapidEye satellite	Landsat 8 & 9 satellite		
	Digitizing accuracy	10 m	12.5 m	4 m	16.7 m	16.7 m	3 m	16.7 m		
	Frontal change rate and uncertainty	$-8.5 \pm 0.3 \text{ m yr}^{-1}$		$-2.3 \pm 1.1 \text{ m yr}^{-1}$	$-4.4 \pm 1.3 \text{ m yr}^{-1}$	$-9.9 \pm 2.4 \text{ m yr}^{-1}$	$-15.2 \pm 2.4 \text{ m yr}^{-1}$	$-19.9 \pm 3.4 \text{ m yr}^{-1}$		
ALL	Frontal change rate and uncertainty	$-7.7 \pm 5.1 \text{ m yr}^{-1}$		$-14.8 \pm 5.4 \text{ m yr}^{-1}$		$-10.6 \pm 6.2 \text{ m yr}^{-1}$				

Supplementary Table 1. Image sources, frontal change rates and uncertainties by region. Data sources, digitizing accuracies, frontal change rates and uncertainties for GICs in South (this study), North (this study), Southeast¹, Northwest², Northeast², Central-west (this study), and two Southwest (this study) Greenland regions. Starred frontal change rates in recent observational periods in Southeast, Northwest, and Northeast Greenland were measured in this study. Digitizing accuracies and frontal change rate uncertainty calculations between observations are adopted from ref. 2. Gray italicized LIA-deglaciation dates and post-LIA rates are gleaned from historical accounts and the positions of undated glacial moraines and are thus more uncertain. Following ref. 2, we add ± 5 years to the post-LIA observational periods to account for poor constraint on the timing of regional deglaciation and report the largest uncertainty. *In the South, glacier length data were acquired from historical aerial photographs taken in 1951, 1953, and 1958. We use the mean year (i.e., 1954) to characterize the first two observational periods.

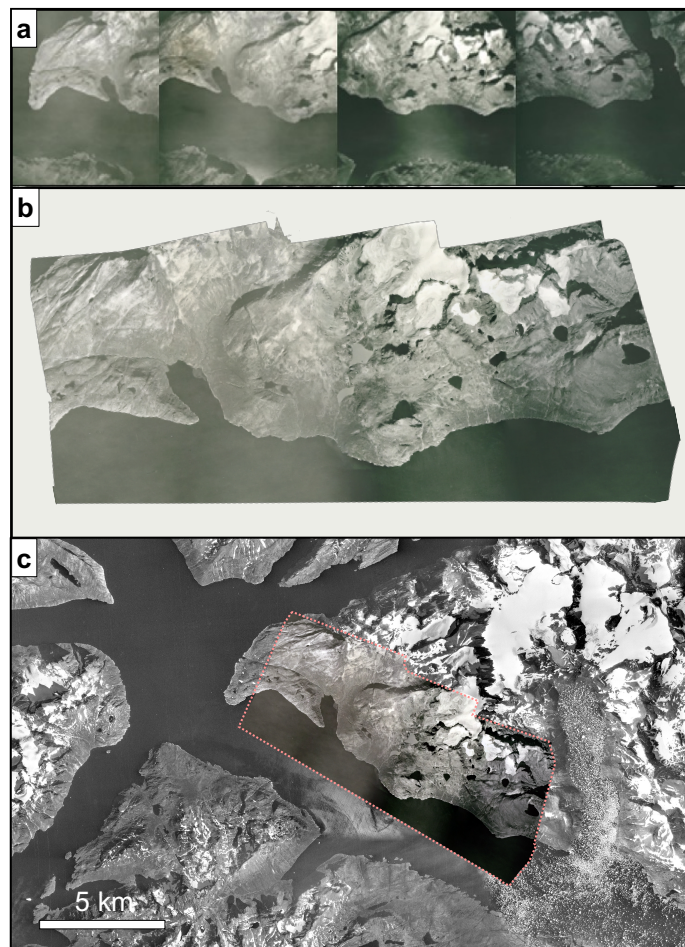
Region	Variable	Source	r
South	Summer temperature	MAR	0.69**
	Snowfall	MAR	-0.35**
	Surface mass balance	MAR	-0.63**
	Summer temperature	DMI	0.42**
	Winter precipitation	DMI	-0.37*
North	Summer temperature	MAR	0.75**
	Snowfall	MAR	-0.56**
	Surface mass balance	MAR	-0.76**
	Summer temperature	DMI	0.69**
	Winter precipitation	DMI	0.25
Southeast	Summer temperature	MAR	0.84**
	Snowfall	MAR	0.55**
	Surface mass balance	MAR	-0.65**
	Summer temperature	DMI	0.58**
	Winter precipitation	DMI	-0.13
Northwest	Summer temperature	MAR	0.85**
	Snowfall	MAR	-0.20
	Surface mass balance	MAR	-0.83**
	Summer temperature	DMI	0.65**
	Winter precipitation	DMI	-0.16
Northeast	Summer temperature	MAR	0.88**
	Snowfall	MAR	0.35**
	Surface mass balance	MAR	-0.63**
	Summer temperature	DMI	0.87**
	Winter precipitation	DMI	0.49**
Central-west	Summer temperature	MAR	0.80**
	Snowfall	MAR	-0.03
	Surface mass balance	MAR	-0.76**
	Summer temperature	DMI	0.26**
	Winter precipitation	DMI	-0.27*
Southwest ^a	Summer temperature	MAR	0.84**
	Snowfall	MAR	-0.24*
	Surface mass balance	MAR	-0.80**
	Summer temperature	DMI	NA
	Winter precipitation	DMI	NA
Southwest ^b	Summer temperature	MAR	0.90**
	Snowfall	MAR	-0.34**
	Surface mass balance	MAR	-0.86**
	Summer temperature	DMI	0.75**
	Winter precipitation	DMI	0.22*

Note. * indicates $p < .05$ and ** indicates $p < .01$.

Supplementary Table 2. Zero-order correlations between regional retreat rates, MAR output and DMI station data. Summer temperature, snowfall, and surface mass balance are given as decadal mean anomalies relative to the baseline 1971-2000. Winter precipitation (half-year; ONDJF sum) is given as the 5-year moving mean.

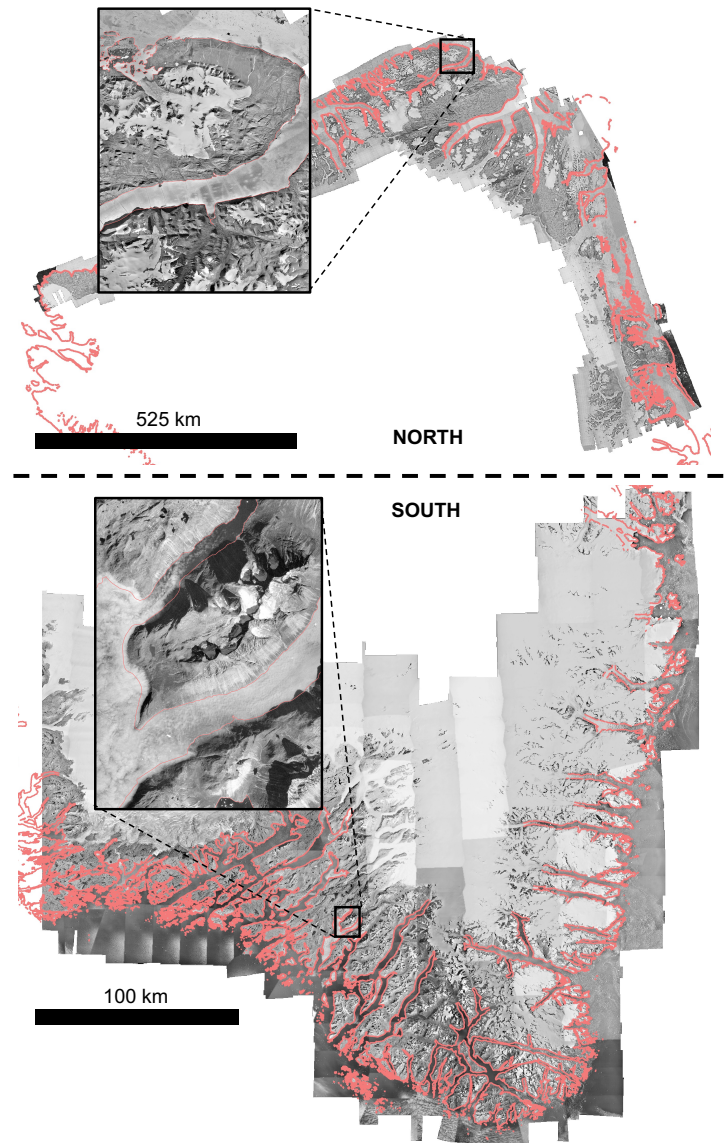


Supplementary Figure 1. Historical aerial photographs. Examples of twentieth-century vertical aerial photographs used in this study from South Greenland. The uncropped images are from late August 1951 and are scanned from paper copies at a resolution of 600 dpi. Historical aerial photographs were accessed from the Danish National Archives.

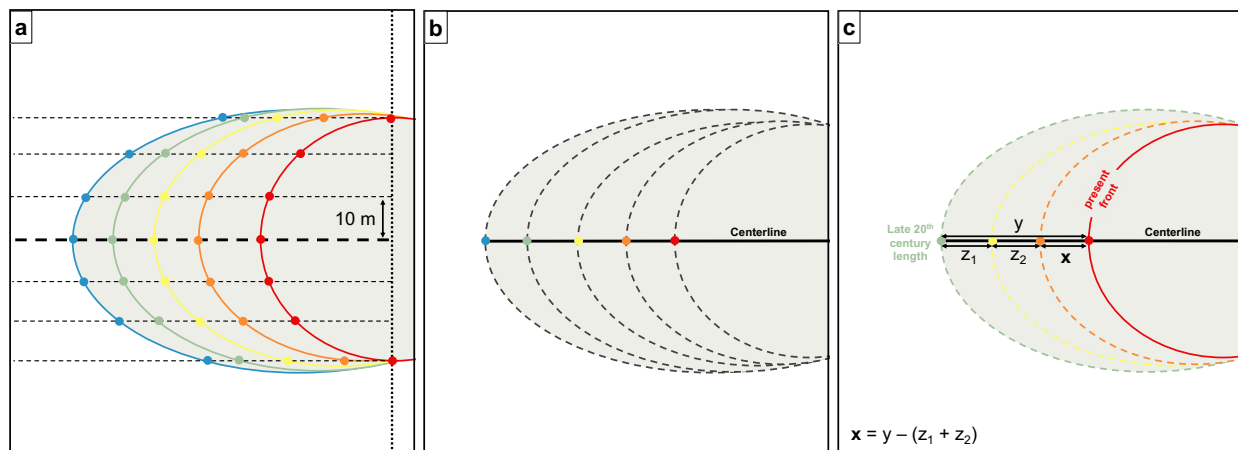


Supplementary Figure 2. Orthorectification and georeferencing of historical aerial photographs.

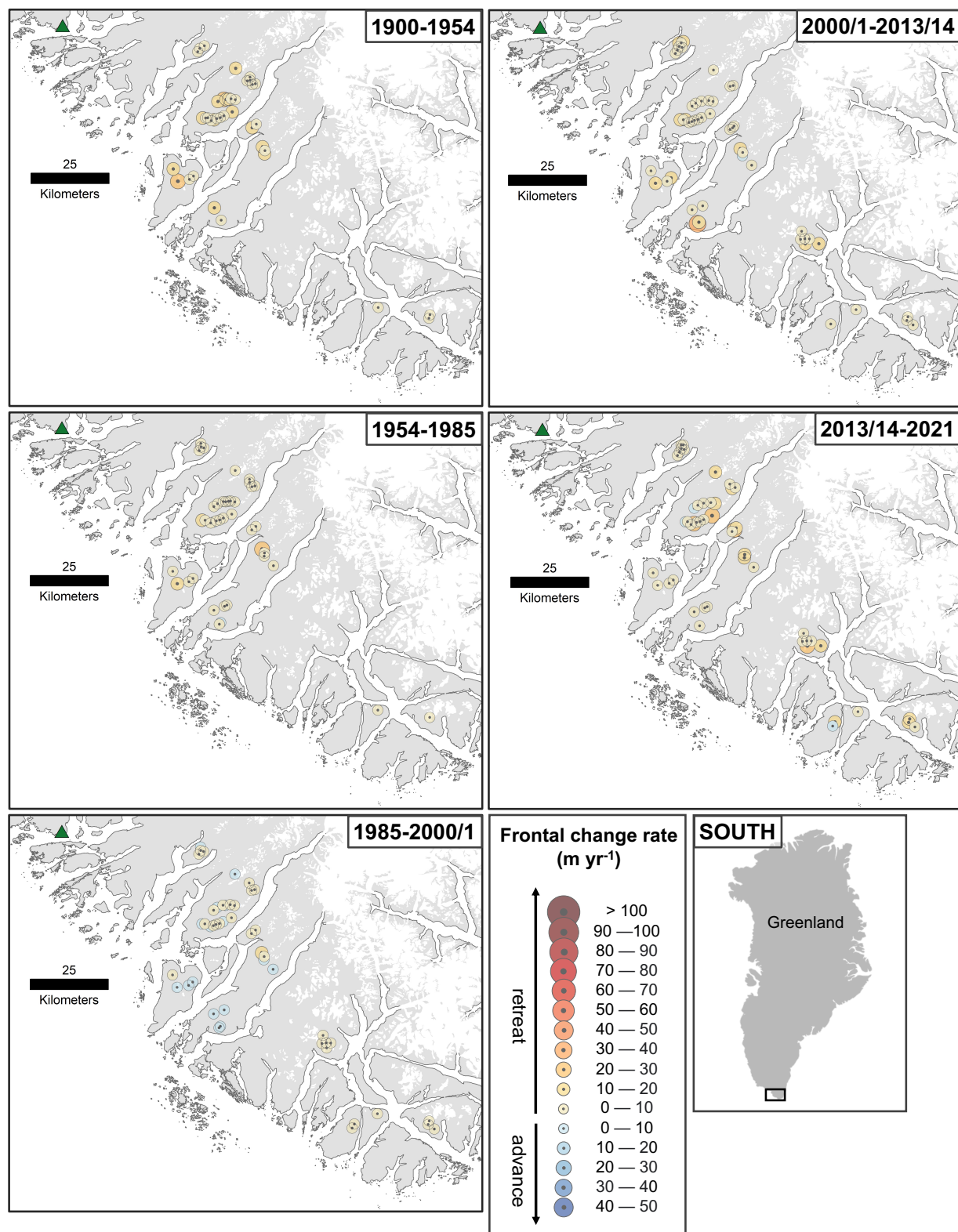
a) Four cropped late summer historical air photos from 1951 from South Greenland. b) Orthophoto generated in Agisoft Professional from the above set of overlapping historical images. c) The above orthophoto (outlined in the red dotted line) georeferenced to the reference dataset (the late twentieth century 2 m ortho-mosaic³). Historical aerial photographs were accessed from the Danish National Archives.



Supplementary Figure 3. Late 20th century ortho-mosaic. Example of late 20th century vertical aerial photos covering the north and south Greenland coast. The ortho-photograph, derived from ~3,500 vertical aerial photographs acquired between 1978-1987, covers the entire periphery of Greenland, has a high resolution of 4 meters³, and was used as the horizontal reference for rectification of all earlier 20th century historical air photos used in this study. The pink line outlines Greenland's coast.

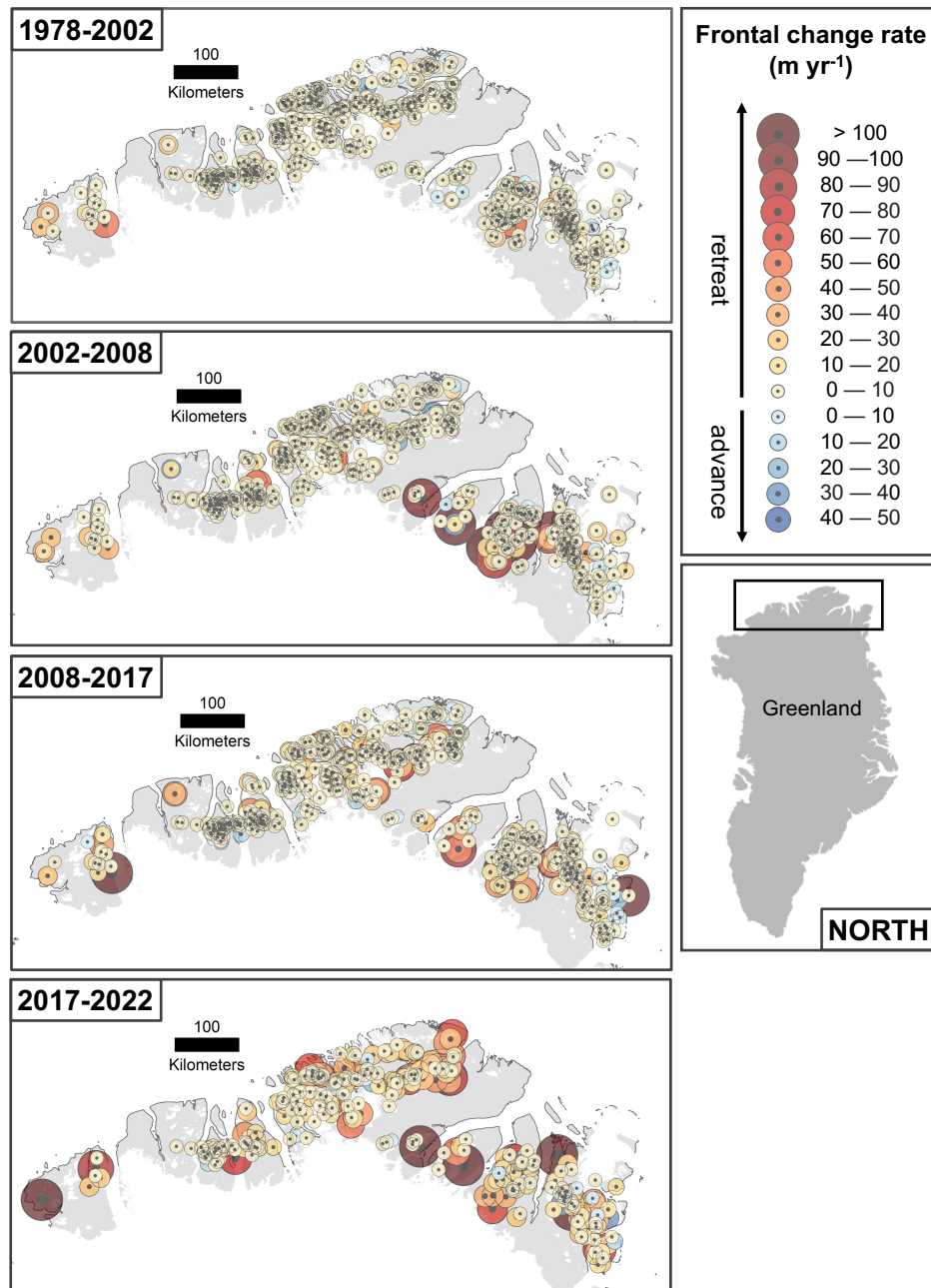


Supplementary Figure 4. Schematic of methods for calculation of GIC frontal changes. a) The frontal change rate (m yr⁻¹) is calculated via the Margin change Quantification Tool (MaQiT)⁴ using the multi-centerline method which quantifies the front change between each observation, every 10 m across the entire glacier margin (applied to Southern glaciers). b) The frontal change rate (m yr⁻¹) is calculated by measuring the straight-line distance between point features, divided by the number of years between observations (applied to Northern and Western glaciers). In the West, we note that in certain cases (glaciers with irregular termini, and/or retreat with non-uniform geometry), the two-dimensional Glacier Termini Tracking (GTT) tool⁵ was used. c) Method used to extend datasets from the Southeast¹, Northwest and Northeast² to present (2021). The front change for the most recent subperiod (x) equals the total length change between the late twentieth century observation and present (y) minus the sum of the length change that occurred in the previous two subperiods (z₁ and z₂). The frontal change rate (m yr⁻¹) for the most recent subperiod is calculated by dividing the total length change (x) by the number of years between the final two observations.

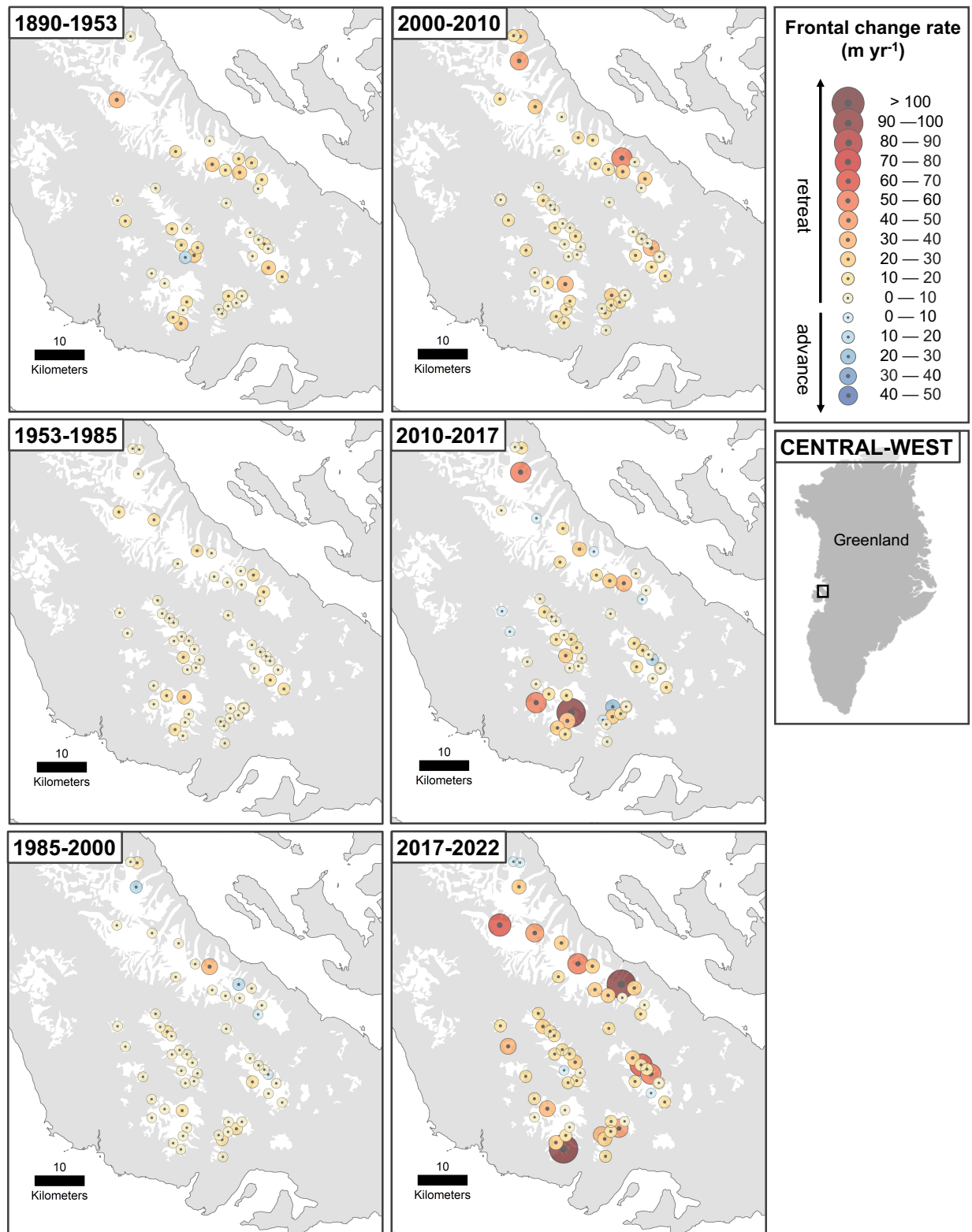


Supplementary Figure 5. Spatial distribution of frontal change for South Greenland GICs. The period ~1900-2021 is divided into five sub-periods according to data availability. The circles correspond to frontal change rates of individual GICs. Circle size is proportional to the magnitude of retreat (yellow/red)

or advance (blue) in meters per year. The green triangle shows the location of Qaqortoq meteorological station.

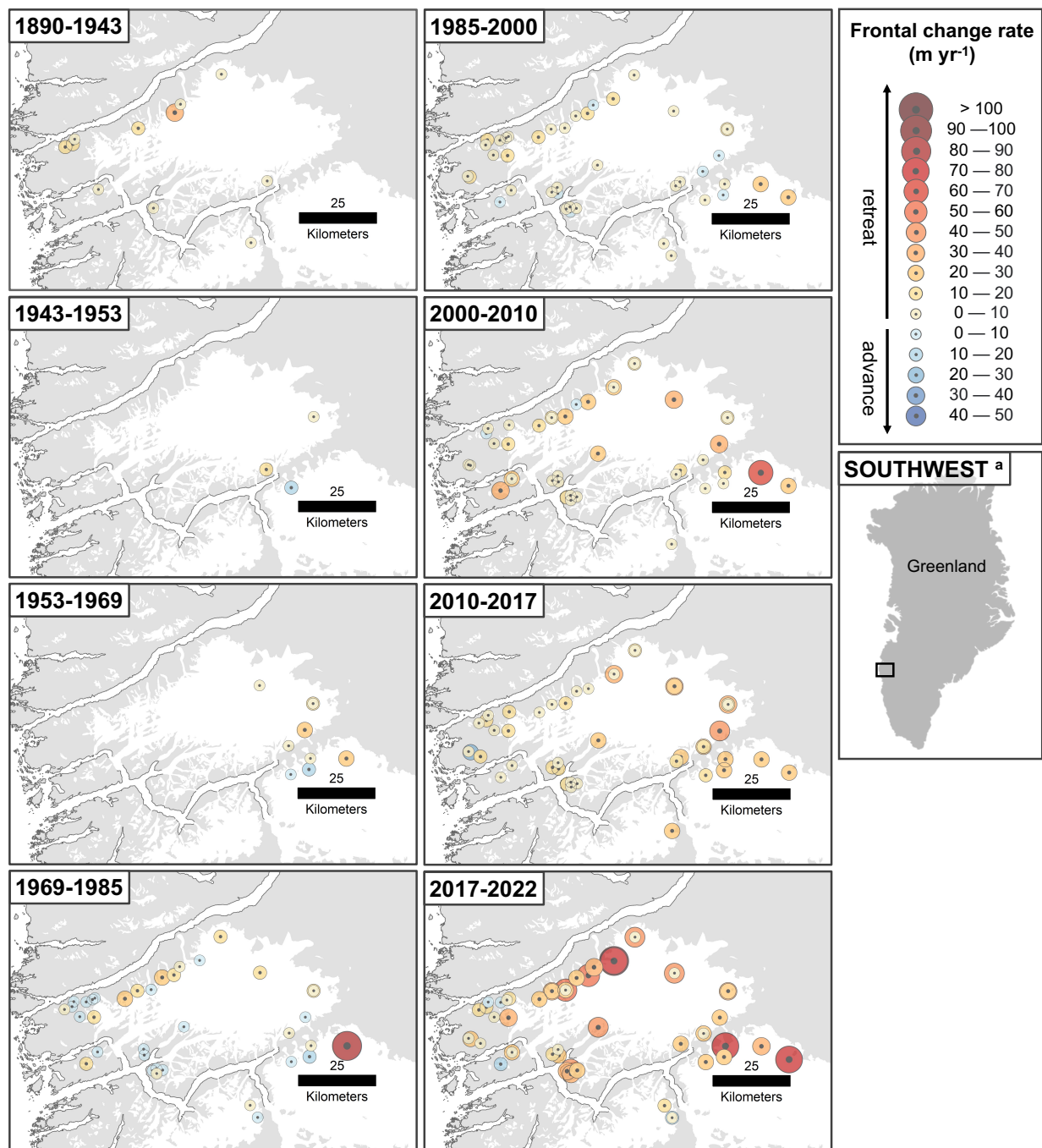


Supplementary Figure 6. Spatial distribution of frontal change for North Greenland GICs. The period 1978-2022 is divided into four sub-periods according to data availability. The circles correspond to frontal change rates of individual GICs. Circle size is proportional to the magnitude of retreat (yellow/red) or advance (blue) in meters per year.



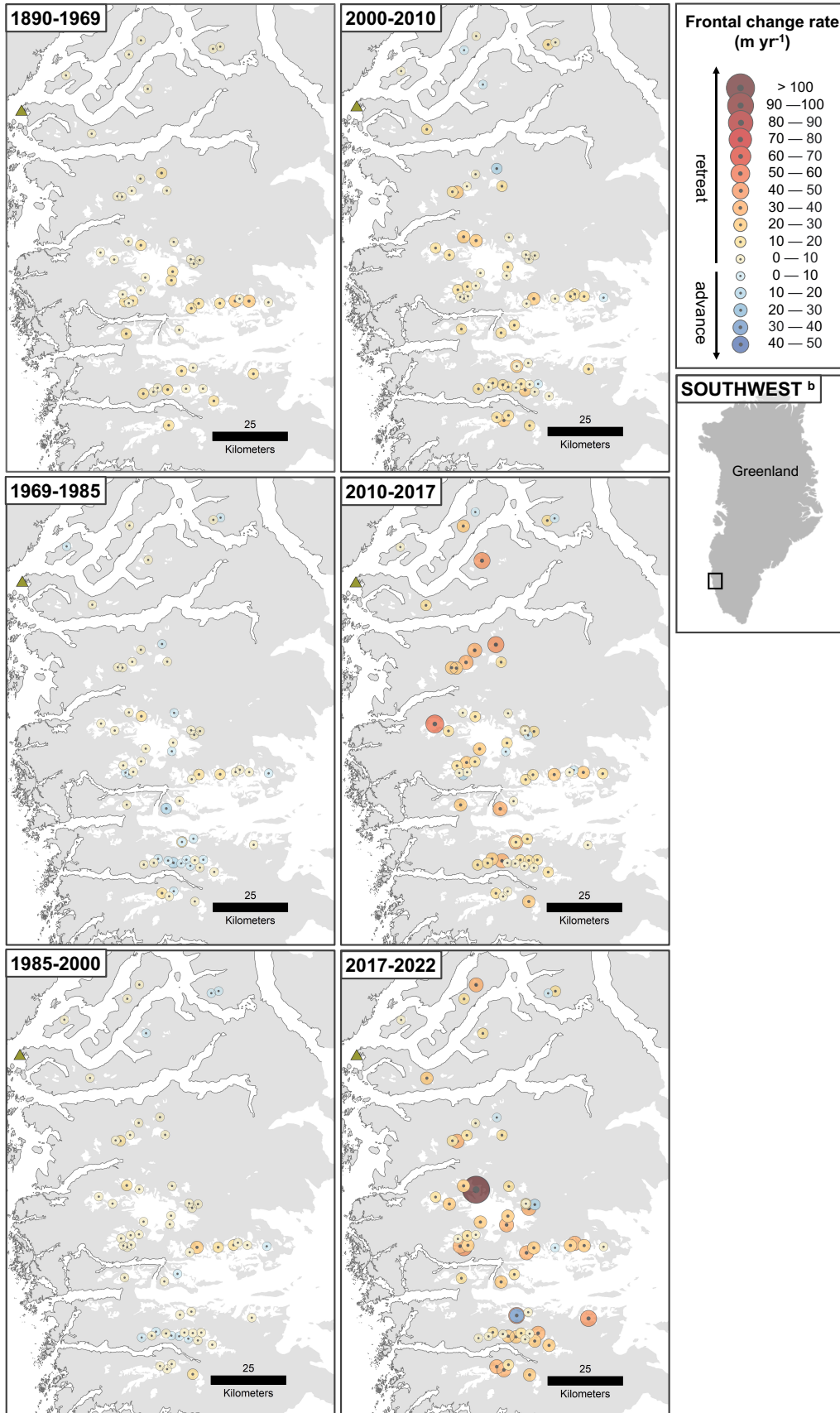
Supplementary Figure 7. Spatial distribution of frontal change for Central-west Greenland GICs.

The period ~1890-2022 is divided into six sub-periods according to data availability. The circles correspond to frontal change rates of individual GICs. Circle size is proportional to the magnitude of retreat (yellow/red) or advance (blue) in meters per year.



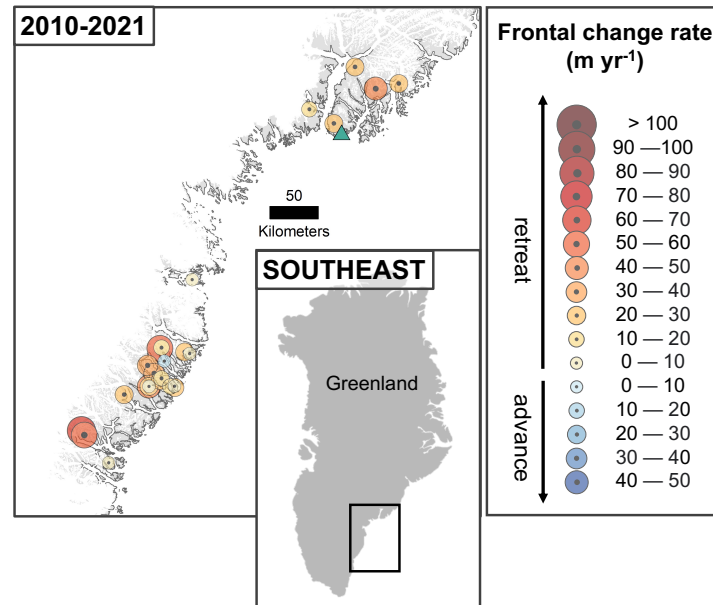
Supplementary Figure 8. Spatial distribution of frontal change for Southwest^a Greenland GICs.

The period ~1890-2022 is divided into eight sub-periods according to data availability. The circles correspond to frontal change rates of individual GICs. Circle size is proportional to the magnitude of retreat (yellow/red) or advance (blue) in meters per year.

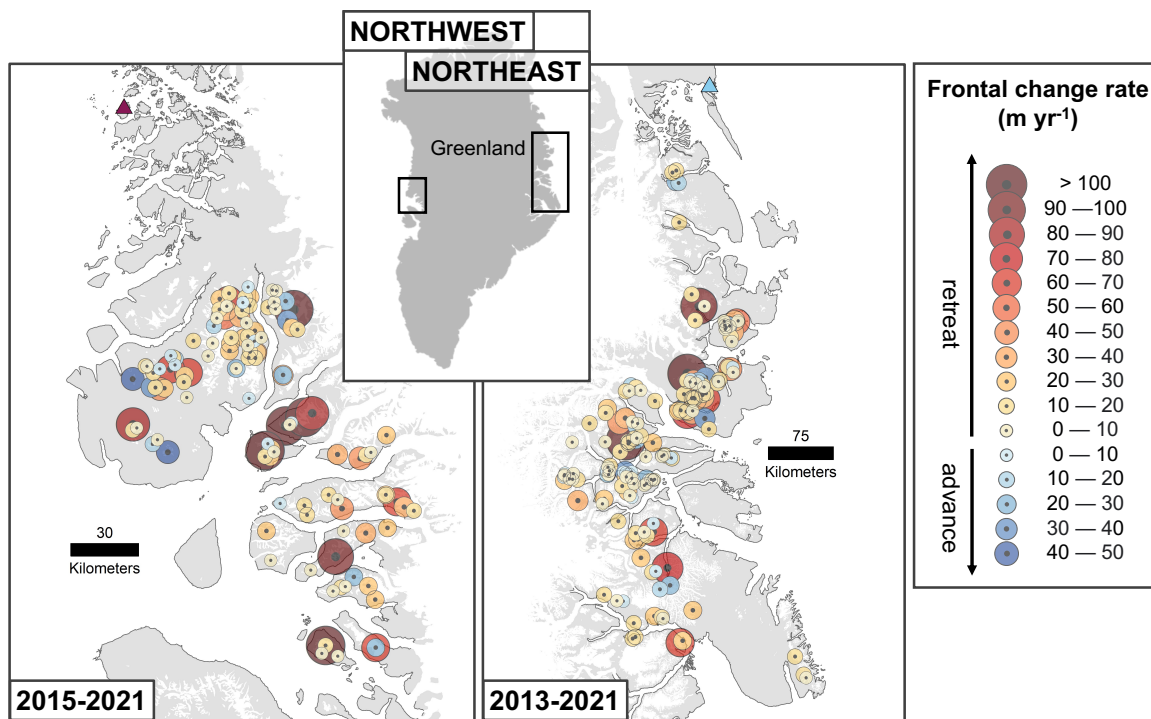


Supplementary Figure 9. Spatial distribution of frontal change for Southwest^b Greenland GICs.

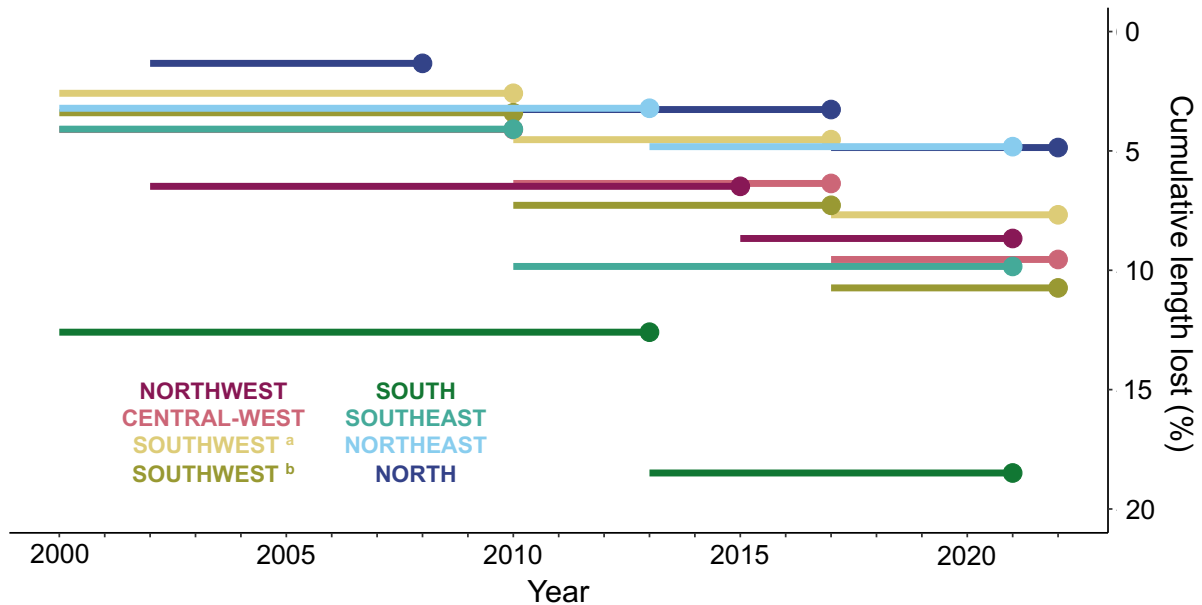
The period ~1890-2022 is divided into six sub-periods according to data availability. The circles correspond to frontal change rates of individual GICs. Circle size is proportional to the magnitude of retreat (yellow/red) or advance (blue) in meters per year.



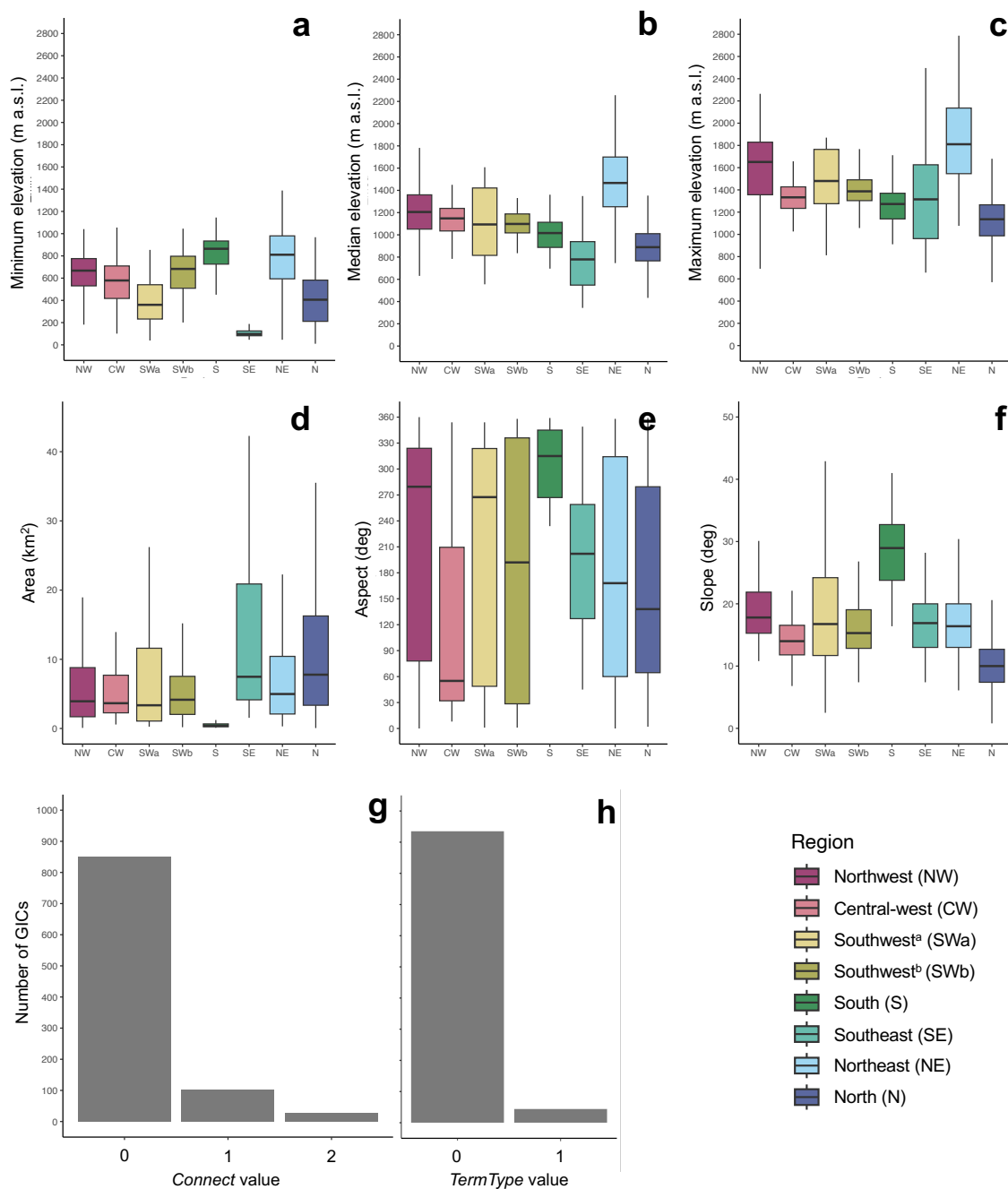
Supplementary Figure 10. Spatial distribution of frontal change for Southeast Greenland GICs. The period 2010-2021 extends GIC frontal changes from ref. 1 to present. The circles correspond to frontal change rates of individual GICs. Circle size is proportional to the magnitude of retreat (yellow/red) or advance (blue) in meters per year. The teal triangle shows the location of Tasilaq meteorological station.



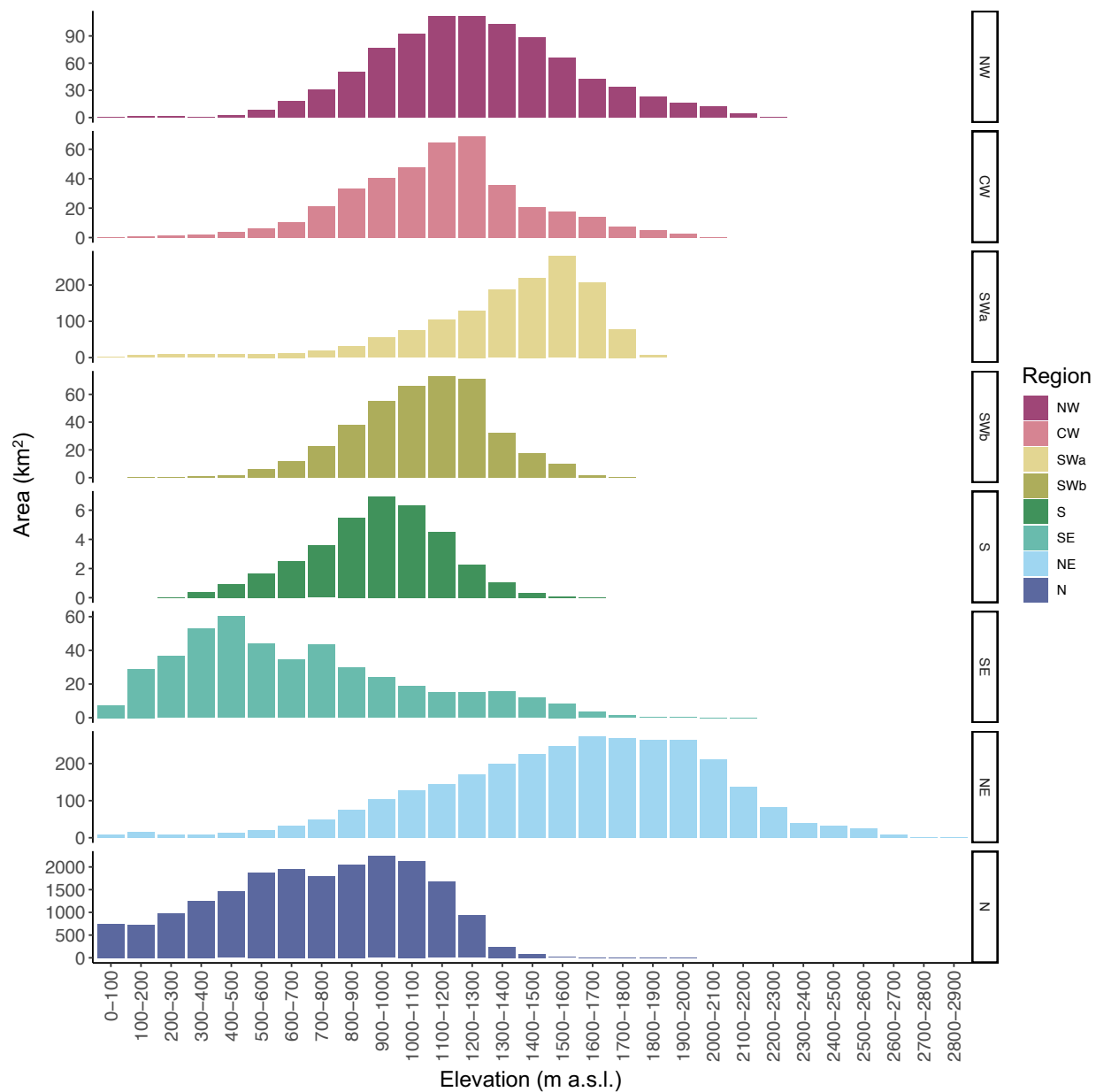
Supplementary Figure 11. Spatial distribution of frontal change for Northwest and Northeast Greenland GICs. The periods 2015-2021 (Northwest) and 2013-2021 (Northeast) extend GIC frontal changes from ref. 2 to present. The circles correspond to frontal change rates of individual GICs. Circle size is proportional to the magnitude of retreat (yellow/red) or advance (blue) in meters per year. The dark pink triangle shows the location of Upernavik meteorological station, and the light blue triangle shows the location of Danmarkshavn meteorological station.



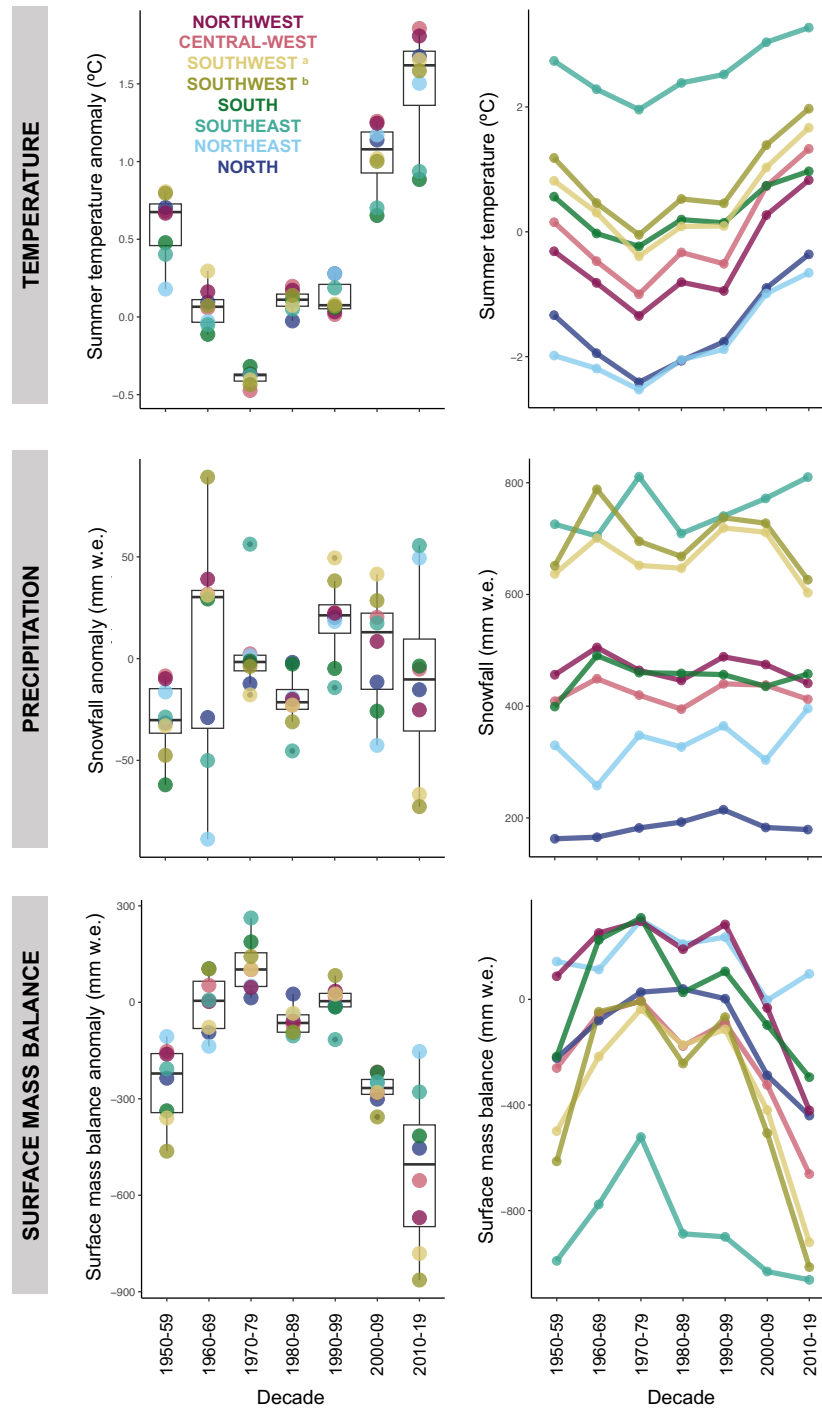
Supplementary Figure 12. Cumulative length lost in the twenty-first century. Mean percent length lost cumulatively between 2000-2022 relative to the late-twentieth century (1978–1987) length by region. Colored lines show the time span of each observational period (noted in Supplementary Table 1), while colored dots mark the end of each period. Regions are Northwest (dark pink); Central-west (light pink); Southwest^a (yellow); Southwest^b (olive); South (green); Southeast (teal); Northeast (light blue); North (indigo).



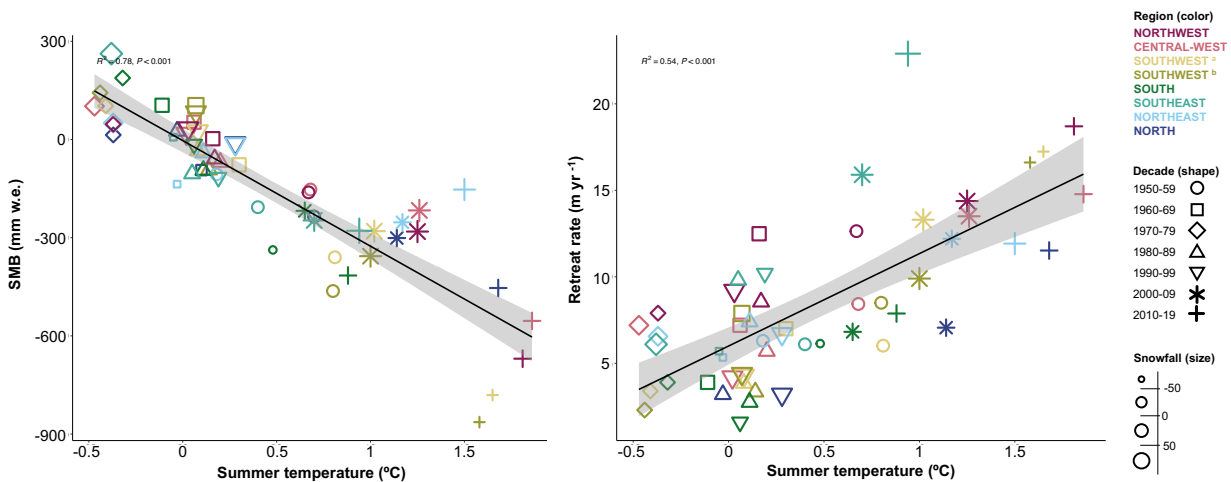
Supplementary Figure 13a. Characteristics of GICs by region. Distributions are shown without outliers for each region. **a**, Minimum elevation; **b**, Median elevation; **c**, Maximum elevation; **d**, Area; **e**, Aspect (degrees relative to 0° at due North); **f**, Mean slope of the surface; **g**, *Connect* value (0=no connection, 1=weak connection, 2=strong connection); and **h**, *TermType* value (0=land-terminating, 1=marine-terminating; see methods for details). In each box plot (**a-f**) the center line represents the median, the edges of the box represent the first and third quartiles, and the whiskers extend to span a 1.5 interquartile range from the edges. Data is from the Randolph Glacier Inventory version 6.0⁶ for all unique GIC polygons included in this study (n=979).



Supplementary Figure 13b. Hypsometry of GICs by region. Hypsometry was measured for each region using the ArcticDEM⁷ 32 m mosaic and all unique GIC polygons included in this study from the Randolph Glacier Inventory version 6.0⁶ (n=979). For each region, the total area (km²) for each 100 m elevation bin is given to show the regional area-elevation relationship.



Supplementary Figure 14. Regional climate and surface mass balance from MAR. Top: Summer temperature (°C); middle: Snowfall annual sum (mm w.e.); and bottom: Surface mass balance annual sum (mm w.e.). Values are regional (n=8) decadal mean anomalies, baseline 1971-2000 (left) and absolute (right) from the regional climate model, Modèle Atmosphérique Régional (MAR)⁹ v.3.12 forced with ERA5 atmospheric reanalysis. In box plots (left): the center line represents the median, the edges of the box represent the first and third quartiles, and the whiskers extend to span a 1.5 interquartile range from the edges. Colors correspond to region: Northwest (dark pink); Central-west (light pink); Southwest^a (yellow); Southwest^b (olive); South (green); Southeast (teal); Northeast (light blue); North (indigo).



Supplementary Figure 15. Relationship between regional surface mass balance, retreat rate and climate from MAR. Left: Relationship between surface mass balance (annual sum; mm w.e.), summer temperature (JJA; °C), and snowfall (annual sum; mm w.e.). Values are decadal mean anomalies (baseline 1971-2000) from the regional climate model, Modèle Atmosphérique Régional (MAR)⁹ v.3.12 forced with ERA5 atmospheric reanalysis. Right: Relationship between retreat rate (meters per year), summer temperature (JJA; °C), and snowfall (annual sum; mm w.e.). Retreat rates are the regional decadal mean; MAR climate data is the same as left. Linear regression models along with 95% confidence intervals (gray bands) are shown in left and right panels. Color corresponds to region (Northwest: dark pink; Central-west: light pink; Southwest^a: yellow; Southwest^b: olive; South: green; Southeast: teal; Northeast: light blue; North: indigo). Shape corresponds to decade between 1950-2019, and size corresponds to the sign and magnitude of the snowfall anomaly (smaller symbols represent drier conditions while larger symbols represent wetter conditions; snowfall anomaly values are between -100 and 100 mm w.e. and are split into four size bins).

References

1. Bjørk, A.A. et al. An aerial view of 80 years of climate-related glacier fluctuations in southeast Greenland. *Nat. Geosci.* **5**, 427–432 (2012).
2. Bjørk, A.A., et al. Changes in Greenland's peripheral glaciers linked to the North Atlantic Oscillation. *Nat. Clim. Change* **8**, 48-52 (2018).
3. Korsgaard, N.J. et al. Digital elevation model and orthophotographs of Greenland based on aerial photographs from 1978–1987. *Scientific Data* **3**, 1-15 (2016).
4. Lea, J.M. The Google Earth Engine Digitisation Tool (GEEDiT) and the Margin change Quantification Tool (MaQiT)—simple tools for the rapid mapping and quantification of changing Earth surface margins. *Earth Surface Dynamics* **6**, 551-561 (2018).
5. Urbanski, J.A. A GIS tool for two-dimensional glacier-terminus change tracking. *Computers & Geosciences* **111**, 97-104 (2018).
6. RGI Consortium. Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 6. [Region 05]. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center (2017).
7. Porter, C. et al. ArcticDEM, <https://doi.org/10.7910/DVN/OHHUKH>, Harvard Dataverse, V1, [2022] 2018.
8. Cappelen, J. Greenland—DMI Historical Climate Data Collection 1784-2020 DMI Report 21-04 (Danish Meteorological Institute, 2021).
9. Fettweis, X., et al. Reconstructions of the 1900–2015 Greenland ice sheet surface mass balance using the regional climate MAR model. *The Cryosphere* **11**, 1015–1033 (2017).