Dynamic changes in outlet glaciers in northern Greenland from 1948 to 2015

Emily A. Hill[1], J. Rachel Carr[1], Chris R. Stokes[2], G. Hilmar Gudmundsson[3]

[1]School of Geography, Politics, and Sociology, Newcastle University, Newcastle-upon-Tyne, NE1 7RU, UK
[2]Department of Geography, Durham University, Durham, DH1 3LE, UK
[3]Department of Geography and Environmental Sciences, Northumbria University, Newcastle-upon-Tyne, NE1 8ST, UK

Correspondence to: Emily A. Hill (e.hill3@newcastle.ac.uk)

Abstract

The Greenland Ice Sheet (GrIS) is losing mass in response to recent climatic and oceanic warming. Since the mid-1990s, tidewater outlet glaciers across the ice sheet have thinned, retreated, and accelerated, but recent changes in northern Greenland have been comparatively understudied. Consequently, the dynamic response (i.e. changes in surface elevation and velocity) of these outlet glaciers to changes at their termini, particularly calving from floating ice tongues, is poorly constrained. Here we use satellite imagery and historical maps to produce an unprecedented 68-year record of terminus change across 18 major outlet glaciers and combine this with previously published surface elevation and velocity datasets. Overall, recent (1995–2015) retreat rates were higher than at any time in the previous 47 years (since 1948). Despite increased retreat rates from the 1990s, there was distinct variability in dynamic glacier behaviour depending on whether the terminus is (or was) grounded or floating. Grounded glaciers accelerated and thinned in response to retreat over the last two decades, while most glaciers terminating in ice tongues appeared dynamically insensitive to recent ice tongue retreat and/or total collapse. We also identify glacier geometry (e.g. fjord width, basal topography, and ice tongue confinement) as an important influence on the dynamic re-adjustment of glaciers to changes at their termini. Recent grounded-outlet glacier retreat and ice tongue loss across northern Greenland, suggests that the region is undergoing rapid change and could soon contribute substantially to sea level rise via the loss of grounded ice.

1 Introduction

Mass loss from the Greenland Ice Sheet (GrIS) has accelerated since the early 2000s, compared to the 1970s and 80s (Kjeldsen et al., 2015; Rignot et al., 2008), and could contribute 0.45–0.82 m of sea level rise by the end of the 21st century (Church et al., 2013). Recent mass loss has been attributed to both a negative surface mass balance and increased ice discharge from marine-terminating glaciers (van den Broeke et al., 2016; Enderlin et al., 2014). The latter contributed ~40% of total mass loss across the GrIS since 1991 (van den Broeke et al., 2016), and increased mass loss was synchronous with widespread glacier acceleration from 1996 to 2010 (Carr et al., 2017b; Joughin et al., 2010; Moon et al., 2012; Rignot and Kanagaratnam, 2006).

Coincident with glacier acceleration, dynamic thinning has occurred at elevations <2000 m on fast flowing marine-terminating outlet glaciers (Abdalati et al., 2001; Krabill et al., 2000), particularly in the south-east and north-west of the GrIS (Csatho et al., 2014; Pritchard et al., 2009). Alongside thinning and acceleration, terminus retreat has been widespread since the 1990s (e.g. Box and Decker, 2011; Carr et al., 2017b; Jensen et al., 2016; Moon and Joughin, 2008), and several studies have identified terminus retreat as a key control on inland ice flow acceleration and dynamic surface thinning (Howat et al., 2005; Joughin et al., 2004, 2010; Nick et al., 2009; Thomas, 2004; Vieli and Nick, 2011).

Ice sheet wide dynamic changes have been linked to 21st century atmospheric/ocean warming, and the loss of sea-ice (e.g. Bevan et al., 2012; Cook et al., 2014; Holland et al., 2008; McFadden et al., 2011; Moon and Joughin, 2008). However, tidewater glaciers can also behave in a cyclic manner, which is not always directly related to climate forcing (Meier and Post, 1987; Pfeffer, 2007), but instead relates to their fjord geometry (Carr et al., 2013; Enderlin et al., 2013; Howat et al., 2007; Powell, 1990). These glacier cycles are characterised by slow long periods of advance (up to centuries) followed by rapid unstable retreat (Meier and Post, 1987; Post, 1975; Post et al., 2011). Once rapid retreat has begun, tidewater glaciers may behave independently of climate, and are instead controlled by basal and lateral resistance, which differs depending on local topography and whether the glacier terminus is floating or grounded. Calving at glaciers that are grounded at their termini are influenced by both basal and lateral drag, both of which reduce towards their termini. Initial retreat then causes longitudinal stretching, surface crevasse propagation and small magnitude calving events. Calving from floating ice tongues can either happen gradually, calving small icebergs continuously, or via slow rift propagation across the width of the ice tongue, leading to large tabular icebergs that calve episodically. Following these events, reduced lateral drag from the loss of ice contact with the fjord walls can decrease the buttressing forces acting on the grounded portions of the glacier, which increases driving stress, and accelerates ice flow (e.g. MacGregor et al., 2012). However, the response of inland ice to large calving events depends on the amount of lateral resistive stress provided by the tongue prior to calving: the loss of portions of ice tongues that are highly fractured and/or have limited contact with the fjord margins are unlikely to substantially influence inland ice dynamics. Differences in the calving nature and basal/lateral resistive stresses acting at tidewater glaciers with either grounded or floating ice tongues can therefore impact substantially on their dynamic behaviour.

Most previous work at tidewater glaciers in Greenland has concentrated on the central-west and south-east regions, and most notably at Jakobshavn Isbræ, Helheim, and Kangerdlugssuaq Glaciers (e.g. Howat et al., 2005, 2007; Joughin et al., 2004; Nick et al., 2009). Observations at all three glaciers showed acceleration and surface thinning following terminus retreat and, at Jakobshavn, this was in response to the gradual collapse of its floating ice tongue (Amundson et al., 2010; Joughin et al., 2008b; Krabill et al., 2004). In northern Greenland, several glaciers have thinned (Rignot et al., 1997), accelerated (Joughin et al., 2010), and retreated, losing large sections of their floating ice tongues between 1990 and 2010 (Box and Decker, 2011; Carr et al., 2017b; Jensen et al., 2016; Moon and Joughin, 2008; Murray et al., 2015). However, far fewer studies have focussed specifically on northern Greenland, with the exception of more detailed work at Petermann and the Northeast Greenland Ice

Stream (NEGIS) (e.g. Khan et al., 2015; Nick et al., 2012). Consequently, there are few records of longer-term changes in glacier frontal for the region and their potential impact on inland ice flow is unclear.

Here we present changes in frontal position, ice velocity and surface elevation over the last 68 years (1948 to 2015) in northern Greenland. We evaluate the dynamic response (i.e. acceleration and thinning) of glaciers in the region to observed changes in terminus position. We evaluate the differences in this response, depending on whether the glacier has a floating ice tongue or a grounded terminus. First, we provide a multi-decadal record of annual terminus positions between 1948 and 2015. We then combine terminus positions with recently published datasets of surface elevation and ice velocity to investigate the dynamic response of these glaciers to frontal position change. Finally, we assess the topographic setting and local glacier controls (i.e. fjord width and depth) on glacier behaviour.

2 Methods

2.1 Study region

We define Northern Greenland as the region of the Greenland Ice Sheet located north of 77°N (Figure 1). This region drains ~40% of the ice sheet by area (Hill et al., 2017; Rignot and Kanagaratnam, 2006) and includes 18 major marine-terminating outlet glaciers, which emanate from 14 major catchments (Figure 1). Early studies in Northern Greenland identified floating ice tongues up to 50 km long (Higgins, 1991; Koch, 1928) and it is now the last area of the GrIS with extant floating ice tongues. Studies from the 1950s and 1990s showed thinning and retreat of these large ice tongues (Davies and Krinsley, 1962; Rignot et al., 2001), and recent Greenland-wide studies suggest that terminus changes in northern Greenland are characterised by large iceberg calving events (e.g. Box and Decker, 2011; Moon and Joughin, 2008). Aside from at Petermann Glacier and the NEGIS, little work has focused on the other glaciers in northern Greenland, where the presence of floating ice tongues could alter the dynamic response of inland ice to calving events. Here, we use the ice-ocean mask from the Operation IceBridge BedMachine v3 product (nsidc.org/data/IDBMG4) to categorise glaciers in northern Greenland based on either grounded or floating termini (Howat et al., 2014; Morlighem et al., 2017). We also use the grounding line in this dataset to assess the location of past ice tongues. Currently, five glaciers in northern Greenland terminate in floating ice tongues (Figure 1), which range between 0.5 and 70 km long (Hill et al., 2017). An additional four glaciers have lost their ice tongues entirely over the last two decades (1995 to 2015). Our study region includes a further nine outlet glaciers, which are grounded at their termini. We note that Humboldt glacier is classified as grounded as the majority of the ~100 km long terminus is grounded, despite a small floating ice tongue in the northern section (Carr et al., 2015).

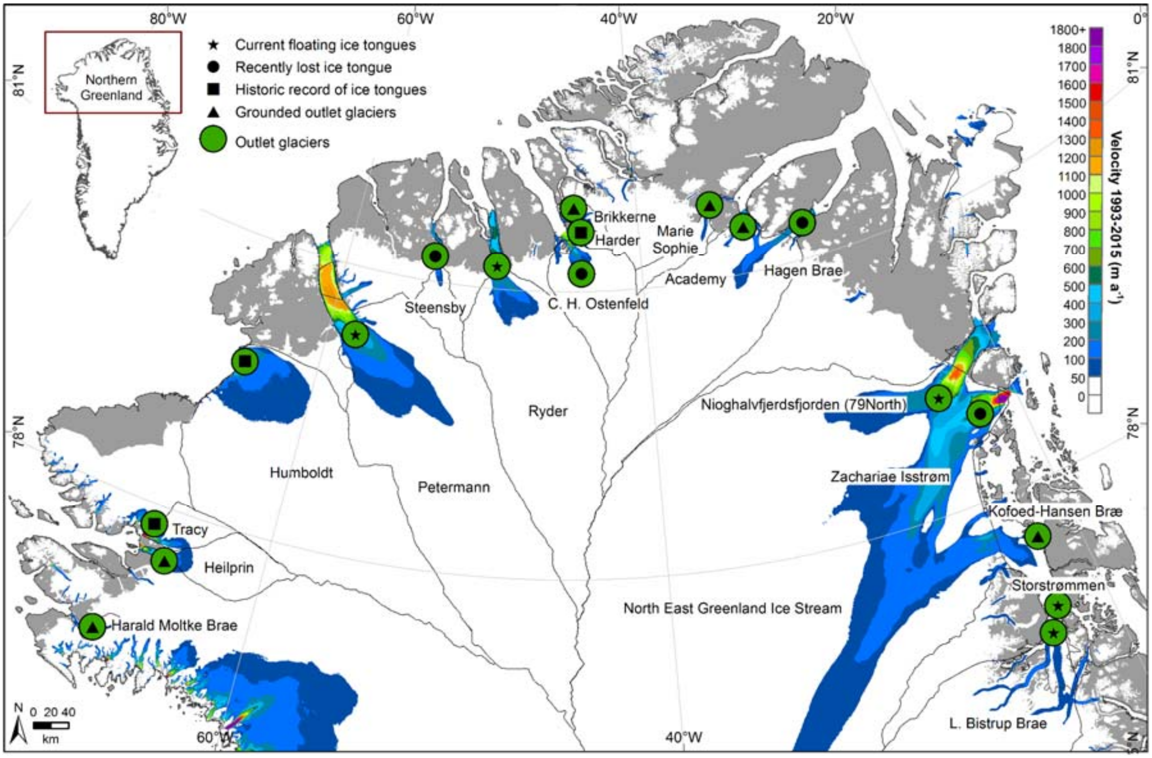


Figure 1: Study region of northern Greenland. Green circles show the location of each of 18 northern Greenland study outlet glaciers. Average glacier velocities (m a^{-1}) are shown between 1993 and 2015 derived from the multi-year mosaic dataset (Joughin et al., 2010). Black outlines show glacier drainage catchments. Symbols represents the state of the glacier terminus. Stars show glaciers which currently have floating ice tongues, circles represent glaciers which lost their ice tongues (during 1995 to 2015), squares denote glaciers which have some previous literature record of a floating ice tongue, and triangles are glaciers which are grounded at their termini and have been throughout the study record.

2.2 Terminus change

2.2.1 Data sources

The terminus positions of 18 study glaciers in northern Greenland (Figure 1) were manually digitised from a combination of satellite imagery and historical topographic navigational charts between 1948 and 2015 (Table S1). From 1975 to 2015 we used Landsat 1–5 MSS (1975–1994), Landsat 7 TM (2000–2013) and Landsat 8 (2013–2015). These scenes were acquired from the United States Geological Survey (USGS) Earth Explorer website (earthexplorer.usgs.gov). To reduce the influence of seasonal changes in terminus position, one scene per year was selected from late summer, and 70% were within one month of the 31st August. Several Landsat MSS images required additional georeferencing and were georeferenced to 2015 Landsat 8 images, as these have the most accurate georeferencing. Early Landsat scenes (1970–1980s) were supplemented with SPOT–1 imagery from the European Space Agency (ESA) (intelligence-airbusds.com). These scenes covered 8 of 18 study glaciers in 1986/87, and were also selected from late August. SPOT–1 scenes were also georeferenced to 2015 Landsat Imagery. Additionally, we used aerial photographs (2 m resolution), which were provided orthorectified by Korsgaard et al. (2016).

These covered all study glaciers between Humboldt east to L. Bistrup Bræ in 1978, and Harald Moltke Bræ, Heilprin and Tracy Glaciers in NW Greenland in 1985 (Korsgaard et al., 2016).

To extend the record of glacier terminus positions further back in time, declassified spy images from the Corona satellite were acquired from the USGS Earth Explorer website (Table S1), which covered 5 of 18 glaciers in 1962/63 and Petermann and Ryder Glaciers in 1966. These images were georeferenced to a Landsat 8 scene from 2015, with total RMSE errors of 105 to 360 m. Frontal position changes smaller than this error value were discounted from the assessment. To further assess the historical terminus positions of the glaciers we used navigational map charts from the United States Air Force 1:1,000,000 Operational Navigation Charts from 1968/69 (lib.utexas.edu/maps/onc/). These were made available through the Perry-Castañeda Library, courtesy of the University of Texas Libraries, Austin. Data from 1948 comes from AMS C501 Greenland 1: 250,000 Topographic Series maps distributed by the Polar Geospatial Centre (pgc.umn.edu/data/maps/). All maps were georeferenced to 2015 Landsat 8 imagery using a minimum of 10 ground control points (GCPs), which were tied to recognisable stationary features such as on nunataks and fjord walls. RMSE errors across all glaciers ranged between 150 and 510 m.

2.2.2 Front position mapping

Changes in glacier frontal positions were measured using the commonly adopted box method, which accounts for uneven calving front retreat (e.g. Carr et al., 2013; Howat and Eddy, 2012; Moon and Joughin, 2008). For each glacier, a rectilinear box was drawn parallel to the direction of glacier flow (Figure 2), and extending further inland than the minimum frontal position. Due to Steensby Glacier's sinuous fjord, a curvilinear box was used (see Lea et al., 2014). Glacier frontal positions were digitised in sequential images and the difference between successive terminus polygons give area changes over time within the box. Dividing these areas by the width of the reference box derives width-averaged relative glacier front positions.

Aside from georeferencing errors outlined in the previous section, the main source of error was attributed to manual digitisation (e.g. Carr et al., 2013; Howat and Eddy, 2012; Moon and Joughin, 2008). We quantified this by repeatedly digitising a ~3 km section of rock coastline 20 times for each image type or map source. The resultant total mean errors were: 3.6 m for Landsat 8, 19 m for Landsat 7 ETM, 17 m for Landsat MSS, 20 m for SPOT–1, 16 m for Orthophotographs, 21 m for Corona, and 27 m for historical maps. Overall, the mean total error associated with manual digitising was 19 m, which is below the pixel resolution of all imagery sources except the 15-m panchromatic Landsat band. The presence of sea ice and highly fractured glacier termini made terminus picking at Steensby, C. H. Ostenfeld and glaciers draining the NEGIS more difficult (Bevan et al., 2012; Howat and Eddy, 2012; Murray et al., 2015). Re-digitising all 1999-2015 Landsat terminus positions yielded additional errors of ± 13 % for these glaciers. At these glaciers, similar inaccuracies in identifying the true glacier terminus may have occurred by the authors of the earliest map charts (1948 and 1969), and we therefore consider these to be a broad estimate of the past location of glacier termini rather than exact frontal positions.

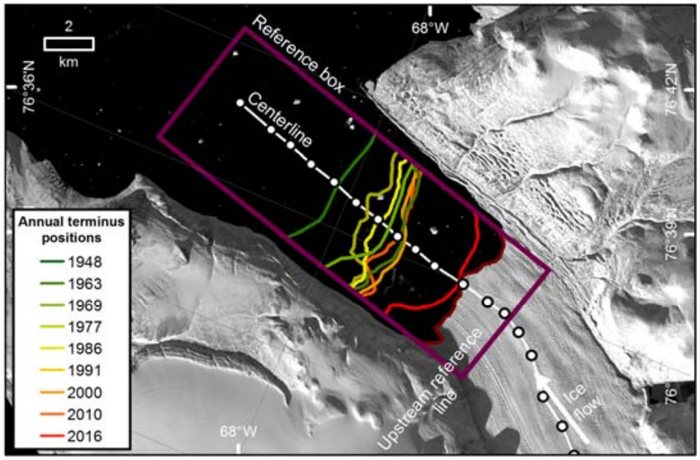


Figure 2: Rectilinear box method used to measure glacier terminus positions. An example at Harald Moltke Bræ, NW Greenland. This includes: reference box (pink), and roughly decadal terminus positions (green to red). The glacier centreline profile is shown in white and the location of 500 m sample points (white circles). Background image is Landsat 8 band 8 from the USGS Earth Explorer.

2.2.3 Changepoint analysis

We used 'changepoint' analysis to objectively test whether there were significant differences in the timing and duration of terminus position changes in northern Greenland, according to terminus type (grounded or floating). Changepoint analysis is used to identify significant breaks in time-series data, and has previously been used to identify changes in the terminus behaviour of outlet glaciers elsewhere in the Arctic (Bunce et al., 2018; Carr et al., 2017a). We employ a similar technique to detect statistically significant breaks in frontal position data across 18 outlet glaciers in northern Greenland. To do this we use the 'findchangepts' function in MATLAB software which employs the methodology of Killick et al. (2012) and Lavielle (2005). Linear regression was used to detect significant breaks in the frontal position time series: a change point was identified where there was a significant change in the mean and regression coefficients (slope and intercept) of the linear regression equation on either side of a data point. Similar to previous studies, we set the minimum distance between points to 4 (Carr et al., 2017a), to only allow breaks >4 years to occur. This number must be small enough to allow for breaks not to be missed, but also large enough so that breaks do not incorrectly occur between every data point. The results are highly insensitive to incrementing the number of breaks up and down within this range. We also include a minimum threshold penalty value which applies an additional penalty to each prospective changepoint. For this we use the mean terminus position for each glacier. This then allows for an automatic estimation of the number of changepoints, when the timeseries deviates significantly from the penalty value, rather than fixing the maximum number of changepoints ourselves. Changepoints therefore identify statistically significant changes in the rate of terminus position for each of our study glaciers in northern Greenland.

2.3 Ice velocity and surface elevation

Previously published datasets of annual ice velocity and surface elevation change were compiled to assess dynamic glacier changes in northern Greenland. Velocity and surface elevation change datasets are generally only available from 1990 onwards. The earliest velocity maps from winters 1991/92 and 1995/96 were acquired from the European Remote Sensing (ERS) satellites (1 and 2), as part of the ESA Greenland Ice Sheet CCI (Climate Change Initiative) project (Nagler et al., 2016). The earlier (1991/92) covers northern Greenland drainage basins from Humboldt and then east to Hagen Bræ, and the later (1995/96) covers all 18 study glaciers. Using dataset error maps we estimated average errors in velocity magnitude across all northern Greenland drainage basins, which were 2.5 m a^{-1} for 1991/92 and 10 m a^{-1} for 1995/96.

Subsequent velocity datasets were primarily acquired from the NASA MEaSUREs program (Joughin et al., 2010). These velocity maps were derived from 500 m resolution Interferometric Synthetic Aperture Radar (InSAR) pairs from the RADARSAT satellite in winter 2000/01, and then annually from winter 2005/06 to 2009/10 (Joughin et al., 2010). Using the dataset error values (Joughin et al., 2010), we estimate mean velocity errors across all years and study drainage catchments to be 6.3 m a^{-1}. For 7 study glaciers, additional annual velocity data, derived from ERS1, ERS2 and Envisat satellites, were available annually between 1991/92 to 1997/98 and between 2003/04 to 2009/10 from the ESA Greenland CCI project (Nagler et al., 2016). Winter velocities from these data were calculated from October to April.

For the winters of 2010/11, 2011/12 and 2012/13, glacier velocity maps were also acquired from InSAR (TerraSAR-X image pairs) for 11 of 18 study glaciers (Joughin et al., 2010). Despite higher spatial resolution (100 m), these maps are limited to the grounding line and extend 27–56 km inland. Mean error for these data is 23 m a^{-1} across all years (Joughin et al., 2010). Winter velocities for 2013/14 were derived from intensity tracking of RADARSAT-2 satellite data, and from offset tracking of Sentinel-1 radar data for 2014/15 and 2015/16, as part of the ESA CCI project (Nagler et al., 2016). The published mean error of these data from a central section of northern Greenland is 7.3 m a^{-1} (Nagler et al., 2015). Using the earliest full regional velocity map (1995/96) and the most recent record (2015/16), the rate of annual velocity change was calculated over this 20-year period.

We use surface elevation change data from ERS-1, ERS-2, Envisat, and Cryosat-2 radar altimetry for 1992 to 2015, which were made available by the ESA's Greenland Ice Sheet CCI project (Khvorostovsky, 2012; Simonsen and Sørensen, 2017; Sørensen et al., 2015). Data from 1992 to 2011 were acquired from the ERS-1, ERS-2 and Envisat satellites, using a combination of cross-over and repeat track analysis, which have then been merged to create a continuous dataset across satellites (Khvorostovsky, 2012). These data are provided in 5-year running means from 1992–1996 to 2007–2011 and at a resolution of 5 km. For the most recent elevation change (2011 to 2015), we used Crysosat-2 satellite elevation change which are provided in 2-year means (Simonsen and Sørensen, 2017). These data were generated using the Least Mean Squares method, where grid cells were subtracted from the Greenland Ice Mapping Project (GIMP) DEM (Howat et al., 2014) and corrected for backscatter and leading edge width (Simonsen and Sørensen, 2017). Calculations were made at a 1 km grid resolution and resampled to 5 km to conform with 1992–2011 datasets (Simonsen and Sørensen, 2017). Using error estimates (Simonsen and Sørensen, 2017), we calculated mean errors across all years and across all northern Greenland drainage basins to be ±0.14 m a^{-1}. Elevation changes from 1992–1996 were compared to elevation changes for 2014–2015 to assess how changes in surface elevation have evolved during the study period.

Velocity and surface elevation time series were extracted along each glacier centreline, which were drawn following Lea et al. (2014). The Euclidean distance was calculated between parallel fjord walls that were digitised in 2015 Landsat 8 imagery. The maximum distance line was then traced from the furthest terminus extent back to the ice divide. Annual average velocities were calculated within 5 km inland of the grounding line of each glacier, and elevation change rates were averaged across the entire centreline profile due to poorer/coarser data resolution (Figure 2).

2.4 Fjord width and basal topography

To assess the control of fjord geometry on outlet glacier behaviour we calculate fjord width and depth. Fjord width was measured perpendicular to glacier centrelines following Carr et al. (2014). Points were extracted at 500 m intervals along each fjord wall and joined by lines that crossed the fjord. The length of these lines is the width between the fjord walls, and changes along each fjord were fitted with a linear regression model to determine if the fjord widens or narrows with distance inland. To determine the fjord bathymetry of each study glacier in northern Greenland, regional basal topography was taken from the Operation IceBridge BedMachine v3 dataset which is derived from ice thickness and mass conservation (Morlighem et al., 2017). Basal topography was sampled at 500 m points along glacier centrelines. Using the error map from BedMachine v3 (Figure S1), we calculated errors along the grounded and non-grounded portions of each glacier centreline profile (Table S2). Mean grounded bed topography errors at 14 of 18 study glaciers range between 25 and 87 metres. These glaciers are well constrained by the mass conservation method, which works best for fast flowing areas near the glacier terminus (Morlighem et al., 2014, 2017). The remaining four glaciers (Storstrømmen, L. Bistrup Bræ, Kofoed-Hansen Bræ, and Brikkerne Glacier) have higher errors (from 112 to 215 m), owing to poor data coverage and kriging interpolation (Morlighem et al., 2017). Mean errors in bathymetry data are greater at all glaciers, averaging 156 metres and ranging from 15 to 283 m. To assess bed slope direction, we fit each glacier profile from the grounding line to 20 km inland with a linear regression model. These sections of each bed profile and model fit are presented in Figure S2, while entire bed profiles, and landward/seaward direction are presented in the results. Errors in basal topography do not significantly affect our assessment of bed slope direction, and we only use topography along the grounded portion of the glacier where errors are lowest. We treat basal profiles in the far east of the study region with caution due to their higher errors.

Finally, to estimate drainage catchment areas and the percentage of each catchment below present sea level for each study glacier, surface drainage catchments (Table 3) were delineated using the GIMP surface DEM (Howat et al., 2014) and topographic analysis functions within TopoToolbox in MATLAB (Schwanghart and Kuhn, 2010). The surface DEM was used to calculate flow direction, which was then used to affiliate raster cells with each surface drainage catchment.

3. Results

3.1 Changes in glacier frontal position (1948–2015)

Across northern Greenland, 13 of the 18 study glaciers underwent overall retreat between 1948 and 2015, while the remaining five advanced (Figure 3). Long-term glacier retreat rates (1948–2015) ranged between -15 m a^{-1} at Marie-Sophie Glacier, to twenty times greater at Petermann Glacier (-311 m a^{-1}). At Petermann Glacier, the high retreat rate resulted from two large calving events in 2010 and 2012, which together removed 27 km of its floating ice tongue (Falkner et al., 2011; Johannessen et al., 2013). Zachariae Isstrøm, which partially drains the NEGIS, had a similarly high retreat rate of -282 m a^{-1}, which resulted in the loss of its 21-km floating ice tongue between 2002 and 2012 (Table 1).

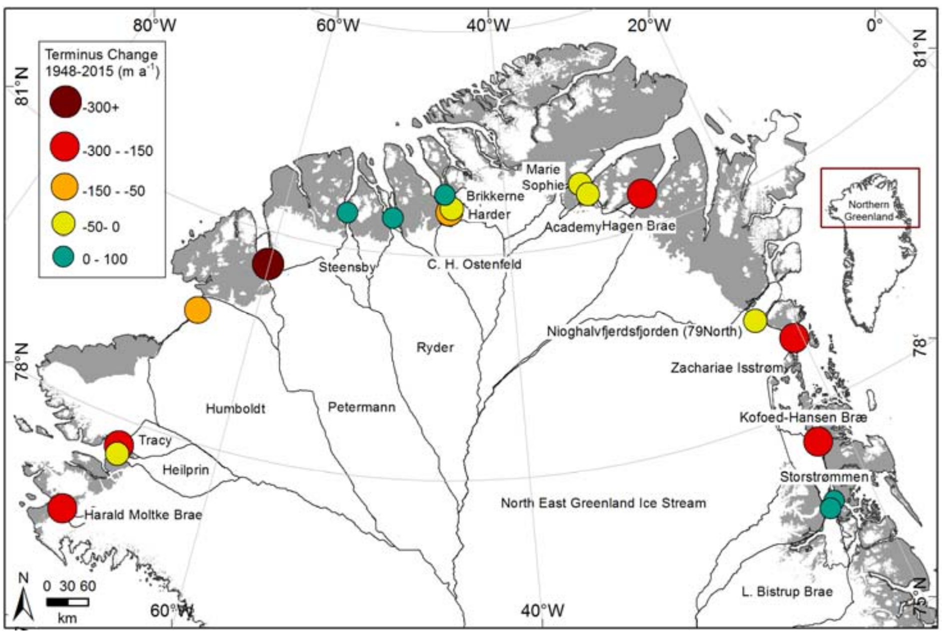


Figure 3: Overall rate of terminus change (m a^{-1}) at 18 outlet glaciers in northern Greenland from 1948 to 2015. Green circles represent glaciers which have undergone overall advance during the record, while yellow to red circles represent increasing retreat rates from 0 to larger than -300 m a^{-1}

There was variability in the long-term overall retreat rates across northern Greenland. A further five glaciers had retreat rates that exceeded -100 m a^{-1} (Table 1), and the remaining 6 glaciers that underwent retreat did so at rates of -15 to -58 m a^{-1}.

Between 1948 and 2015, Ryder, Storstrømmen and L. Bistrup Bræ Glaciers advanced at a similar mean rate (~40 m a^{-1}), while Brikkerne Glacier advanced at 82 m a^{-1} (Table 1). Steensby Glacier underwent minimal change during the study period (1 m a^{-1}: 1948–2015), but with a high rate of retreat from 1978 to 2015 (-366 m a^{-1}).

Table 1: Summary data for 18 northern Greenland outlet glaciers, ordered according to terminus type and by frontal position rate (from high retreat to high advance). Annual rates of terminus change are given for the entire record (1948 to 2015). Average velocity change along each glacier centreline from winter 1995/96 to 2015/2016. Average surface elevation change rates along each glacier centreline were differenced from the earliest record (1992-1996) and the most recent (2014/15).

	Northern Greenland Outlet Glaciers	**Terminus Change** (1948–2015) (m a^{-1})	**Velocity Change** (1995/96– 2015/16) (m a^{-1})	**Difference in surface elevation change rates** (1992-1996 and 2014-2015) (m a^{-1})
Category 1: Grounded terminus	Tracy	-173	36.8	-0.11
	Kofoed-Hansen Bræ	-169	-0.06	0.12
	Harald Moltke Bræ	-156	22.6	
	Humboldt	-111	0.32	-0.51
	Heilprin	-45	7.16	-0.15
	Academy	-31	-4.87	-0.97
	Harder	-25	0.58	-0.89
	Marie-Sophie	-15	1.03	-0.43
	Brikkerne	82	-2.56	
Category 2: Floating ice tongue	Petermann	-311	3.78	-1.34
	Zachariae Isstrøm	-282	20.3	-2.98
	Hagen Bræ	-162	6.45	-0.83
	C. H. Ostenfeld	-58	2.96	-1.26
	Nioghalvfjerdsfjorden	-28	1.62	-1.99
	Steensby	2	2.59	-0.33
	L. Bistrup Bræ	39	-3.89	0.57
	Storstrømmen	41	-1.11	-0.18
	Ryder	43	-0.08	0.47

While many glaciers retreated substantially, there were large differences in the timing and magnitude of retreat between glaciers (Table 1, Figure 3). To assess the variability of retreat rates across northern Greenland, we present mean retreat rates across five decadal time periods (1976–1985, 1986–1995, 1996–2005, 2006–2015) in Figure 4 (a-e), except for the earliest epoch (1948–1975) which spans 27 years due to image availability. During the first epoch (1948 to 1975) small advances and retreats took place across the region (< 500 m a^{-1} magnitude). This was followed by a decade (1976–85) dominated by glacier advance, and several glaciers with high retreat rates for the entire study period (e.g. Hagen Bræ, Zachariae Isstrøm, Petermann) underwent advance during this period. In the subsequent epoch (1986 to 1995), a mixture of advance and retreat occurred and the range of frontal position changes was great, from -780 m a^{-1} retreat at C. H. Ostenfeld to 750 m a^{-1} advance at Storstrømmen (Figure 4c). During the last two decades of the study period (1996 to 2015), retreat rates were substantially higher than in the previous three epochs, peaking at Petermann Glacier (-2200 m a^{-1}; Figure 4e, f). In particular, high magnitude retreat during this period at Hagen Bræ, Zachariae Isstrøm, and Petermann far outweighed earlier advances.

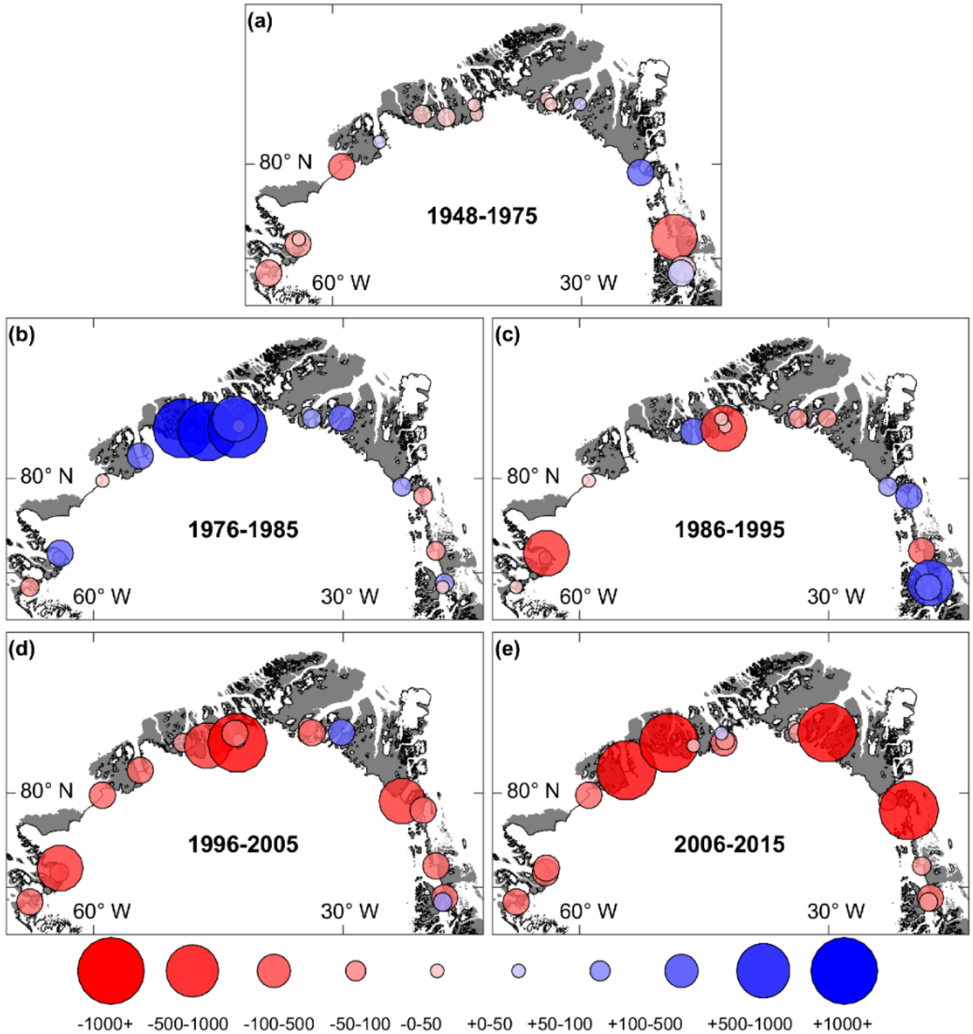


Figure 4: Mean decadal rates of terminus change across northern Greenland. These are shown for five epochs between 1948 and 2015. Increasing red circles represent glacier retreat rates between 0 and exceeding -1000 m a^{-1}. Increasing blue circles represent advance rates between 0 and exceeding 1000 m a^{-1}.

3.2 Frontal position change according to terminus type

Despite an increase in retreat rates from 1996 across the study region, the magnitude of frontal position change during the last two decades (1996 to 2015) varied considerably between glaciers and according to terminus type (i.e. grounded versus floating). Nine outlet glaciers were grounded at their terminus throughout the study period, while at the end of the study period another nine still had ice tongues or lost them during the last two decades (1996 to 2015). During this period, decadal mean retreat rates at glaciers with ice tongues (-745 to -835 m a^{-1}) were substantially higher than at grounded-outlet glaciers (-99 to 165 m a^{-1}: Table 2). We expect terminus changes and dynamic response to be different dependent on terminus type, and for this reason, throughout our analysis we treat these as separate categories. Additionally, we use statistical changepoint analysis to compare the duration and magnitude of frontal position changes at all study glaciers. This confirms that in general, there are two different types of frontal position behaviour and dynamic response to calving based on terminus type (grounded or floating: Figure 5), which we now describe throughout our results.

Table 2: Mean decadal frontal position change for all study outlet glaciers in northern Greenland, and split based on our two glacier categories of terminus type: grounded-terminus or terminating in a floating ice tongue

Mean terminus change (m a^{-1})	**1948-1975**	**1976-1985**	**1986-1995**	**1996-2005**	**2006-2015**
All (n =18)	-63.65	503.36	-7.83	-454.99	-467.06
Grounded-terminus (n =9)	-167.35	93.87	-112.07	-164.50	-99.23
Floating-terminus (n =9)	40.05	912.84	126.19	-745.49	-834.88

3.2.1 Grounded-terminus outlet glaciers

Nine of the major outlet glaciers considered in this study are grounded at their termini (Figure 5). For these glaciers, there was an initial period of minimal frontal position change averaging -26 m a^{-1} and ranging from 24 m a^{-1} advance at Kofoed-Hansen Bræ to -105 m a^{-1} retreat at Tracy Glacier. Frontal position change then switched to a period of higher magnitude retreat at eight glaciers (excluding Brikkerne), which lasted for an average of 26 years. During this period, frontal position change averaged -150 m a^{-1}, and net retreats ranged from -0.6 to 8 km. The greatest total terminus changes took place at Tracy Glacier (8 km retreat: 1981–2015), Harald Moltke Bræ (5 km retreat: 1988–2015), and Kofoed-Hansen Bræ (4.6 km: 1973–2015: Figure 6a-c). The timing of this switch from minimal change to steady retreat was not uniform, but most glaciers began steadily retreating from the 1990s to 2000s and continued at the same rate thereafter (Figure 5). The exception to this pattern of behaviour is Brikkerne glacier, which instead advanced by 9 km between 1968 and 1978 before returning to minimal terminus change (Figure 6i).

3.2.2 Glaciers with floating ice tongues

Nine glaciers terminated in floating ice tongues during the study period. Six of these glaciers showed minimal terminus change/advance at the beginning of the record (93 m a^{-1}), followed by short-lived rapid retreat, lasting less than 6 years on average (Figure 5). During the phases of rapid retreat, rates ranged between -700 m a^{-1} at Nioghalvfjerdsfjorden to -8997 m a^{-1} at Petermann Glacier (Figure 5), and were on average 40 times greater (-4536 m a^{-1}) than during the steady retreat phases at glaciers grounded at their terminus (-150 m a^{-1}). Rapid retreat was often followed by another period of relative minimal terminus change (-437 m a^{-1}) compared to order of magnitude earlier retreat (e.g. Petermann Glacier and Hagen Bræ: Figure

5). For five glaciers (Zachariae Isstrøm, Petermann and Steensby, C. H. Ostenfeld, and Hagen Bræ), rapid retreat removed substantial floating ice sections (11.6–26 km net retreat: Figure 7), through large episodic calving events. This led to complete ice tongue loss at Zachariae Isstrøm by 2011/12, and at C. H. Ostenfeld, Steensby and Hagen Bræ by 2016 (Figure 7). Similar to glaciers with grounded-termini, the timing of the switch to rapid retreat was not synchronous, but mainly occurred after 1990 (Figure 5). At most glaciers, the duration of rapid retreat was short-lived (< 5 years) in comparison to the duration of steady retreat (> 13 years) at grounded-glaciers.

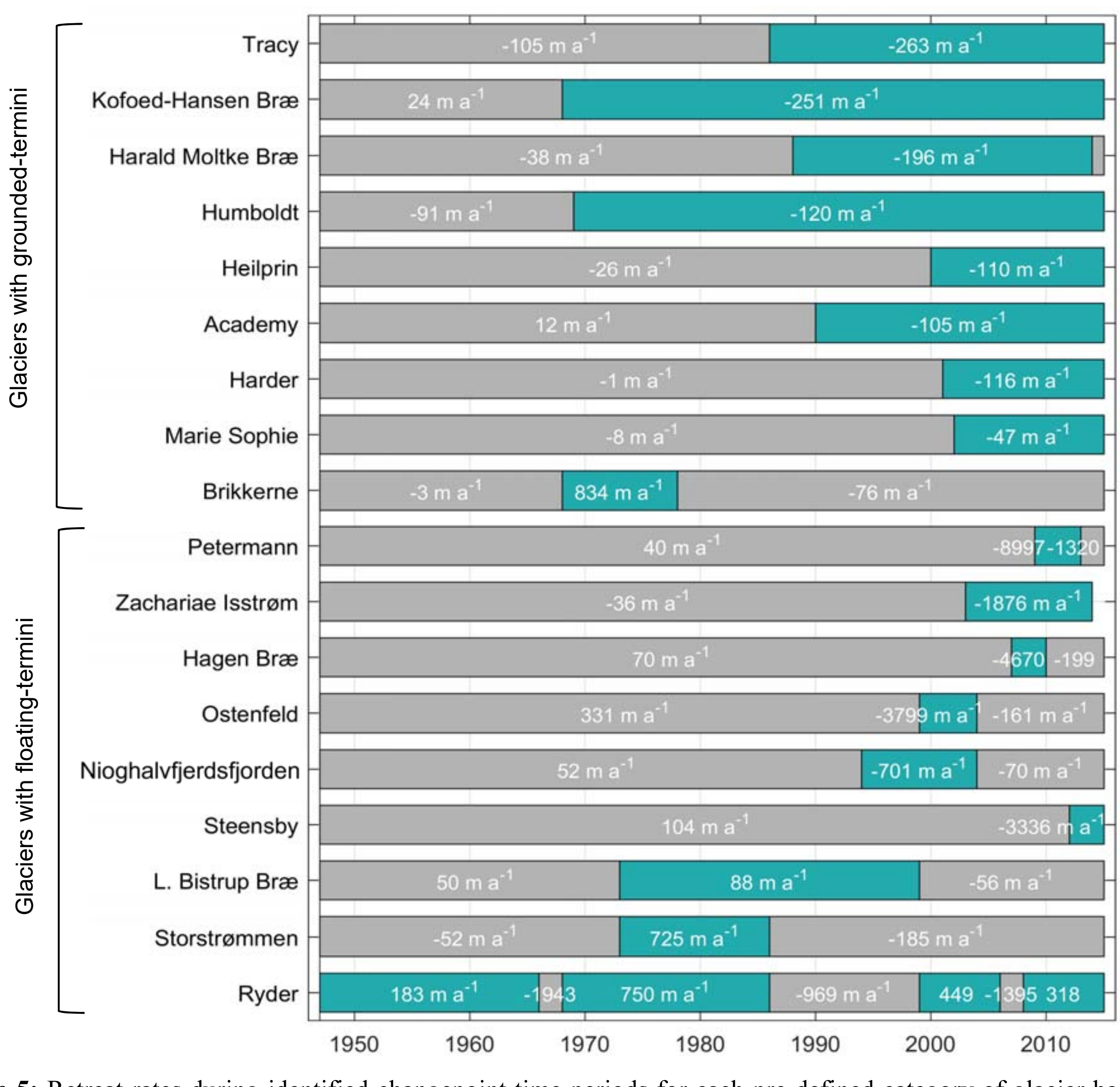


Figure 5: Retreat rates during identified changepoint time periods for each pre-defined category of glacier based on either grounded or floating termini. Glaciers are then ordered based on their overall (1948-2015: Table 1) frontal position change rates within each of these categories. Grey bars show their periods of minimal/variable terminus change (in some cases advance) and turquoise bars show the period of higher magnitude frontal position change.

Several glaciers with floating ice tongues (Storstrømmen, L. Bistrup Bræ, and Ryder) have shown cyclic periods of advance and retreat between 1948 and 2015 (Figure 7g-i). Periods of terminus advance at these glaciers averaged ~420 m a^{-1} and lasted for an average of 18 years (Figure 5). Adjacent glaciers Storstrømmen and L. Bistrup Bræ advanced during a similar period (from 1973 to 1990), and for ~13–17 years. After this, both glaciers underwent relatively limited terminus change from 2000 onwards (Figure 5). Despite synchronous advance, their advance rates differed by almost an order of magnitude (89 m a^{-1} at L. Bistrup Bræ, and 725 m a^{-1} at Storstrømmen, Figure 5). At Ryder Glacier, there were four main cycles of glacier advance and retreat during the record. These took place between 1948–1996, 1968–1986, 1999–2006, and 2008–2015 and advance rates ranged from 183 to 750 m a^{-1} (Figure 5). Periods of advance (7–48 years) were separated by shorter periods (2–13 years) of higher magnitude retreat (ranging from -960 to -1950 m a^{-1}) (Figures 5).

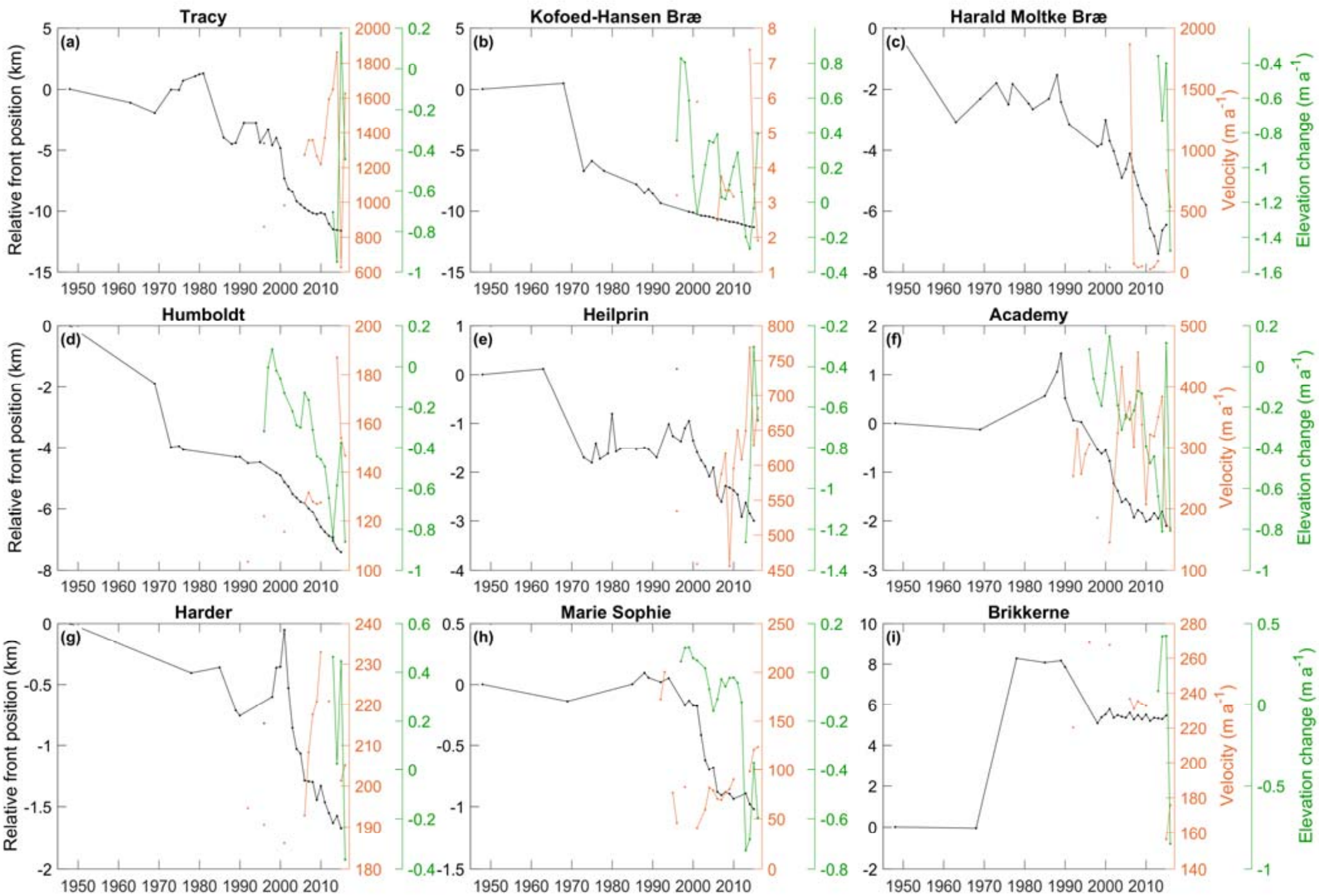


Figure 6: Front position, velocity and elevation change at nine outlet glaciers grounded at their terminus in northern Greenland. Left axes show relative front position (black line) between 1948 and 2015 relative to their initial position in 1948. Grounding line velocities (orange) on right axes one between 1996 and 2015. Surface elevation changes averaged across the glacier centreline profile (green) for 1996 to 2015.

3.3 Ice velocity change

3.3.1 Grounded-terminus outlet glaciers

Six of the nine outlet glaciers with grounded termini accelerated along their centreline profiles (ranging from 0.32 to 37 m a^{-1}) from 1996 to 2016 (Table 1). On average, these glaciers accelerated by 27%, following the onset of steady retreat at each glacier (Figure 5). For example, Tracy and Heilprin accelerated substantially during their steady retreat periods (Table 1). At Heilprin Glacier this resulted in a 49% increase (from 458 to 681 m a^{-1}) in grounding line velocity from 2001 to 2016 (Figure 6e), during which the glacier retreated at -110 m a^{-1} (Figure 5). Substantially greater acceleration (89%) took place at Tracy Glacier from 1996 to 2016 (Figure 6a), which was associated with higher magnitude retreat rates (-263 m a^{-1}: Figure 5). Humboldt, Harder, and Marie-Sophie Glaciers flowed more slowly than other grounded-terminus glaciers (< 400 m a^{-1}), but still showed large accelerations (27–108%) at their termini during steady retreat (Figure 6). Harald Moltke Bræ also accelerated between 1990 and 2016 (22 m a^{-1}: Table 1), and retreated at -196 m a^{-1} (Figure 5). However, it underwent two very large velocity increases (> 1000 m a^{-1}) between 2001 and 2006 and again during winter 2013/14, both of which coincided with short-lived glacier advance (0.5–0.8 km: Figure 6c). Some grounded-terminus outlet glaciers did not show substantial acceleration following retreat: Kofoed-Hansen Bræ and Academy Glacier had sustained periods of steady retreat, but showed no net trend in velocity and high variability (Figure 6b,f), which did not coincide with periods of increased retreat rates (Figure 5). Brikkerne Glacier decelerated from 1996 to 2016, while the terminus position changed little (Figure 6i).

3.3.2 Glaciers with floating ice tongues

All but one (Zachariae Isstrøm) of the glaciers with floating ice tongues showed minimal net velocity change between 1996 and 2016, despite major retreat episodes and tongue disintegration on certain glaciers (Table 1). Within this period there was more variability, and two main patterns in velocity change which followed periods of rapid: 1) short-lived, minimal glacier acceleration, followed by some deceleration, 2) continuous acceleration following initial terminus retreat. Four outlet glaciers with floating ice tongues (C. H. Ostenfeld, Hagen Bræ, Petermann Glacier and Steensby Glacier) showed short-lived (< 3 year) low magnitude grounding-line acceleration following rapid ice tongue retreat. At the former three, there was <8% increase in speed, while Steensby Glacier accelerated by ~25%. At all four glaciers, after retreat and acceleration, ice flow decelerated, ranging from 2% at Petermann to 28% at Hagen Bræ. In the year preceding rapid retreat (2005 to 2006), Hagen Brae showed higher magnitude acceleration (~52%) alongside some glacier advance. This was also the case at Ryder Glacier, which showed cyclic behaviour, of grounding line acceleration (~8%: 4.7–5.5 m a^{-1}) during both 7-year periods of terminus advance, followed by more dramatic deceleration (11%) during periods of high magnitude retreat (~2 years) in-between periods of advance. Storstrømmen and l. Bistrup Bræ also show evidence of some acceleration immediately following retreat, later followed by deceleration (Figure 7h.i) from 2010 to 2016. However, in contrast to most glaciers which flow fastest at their terminus, velocities at both glaciers are fastest inland, and decrease with distance towards the terminus (Figure 8). Grounding line terminus velocities accelerated by 350% and 150% at Storstrømmen and L. Bistrup Bræ throughout the record (1996 to 2016: Figure 7); and velocities ~20–40 km inland decelerated by 10–15 m a^{-1} (> 54%).

Despite minimal velocity change over the entire study period (Table 1) at most glaciers with floating ice tongues, during this period, ice tongue retreat at both glaciers draining the NEGIS, were followed by gradual glacier acceleration in the subsequent decade (2006 to 2016: 43% at Zachariae Isstrøm and 10% at Nioghalvfjerdsfjorden). This prolonged glacier acceleration following retreat, is more similar to patterns observed on grounded termini, rather than the other floating tongues. Further, the removal of the entire ice tongue at Zachariae Isstrøm in 2011/12 was followed by glacier acceleration (125 m a^{-2}: 2012 to 2016, Figure 7g), whereas other glaciers (e.g. C. H. Ostenfeld and Hagen Bræ) underwent a similar collapse, but changes in velocities were limited. Despite this behaviour in the northeast of the study region, the majority of glaciers in northern Greenland showed negligible acceleration in response to retreat and/or collapse of their floating ice tongues.

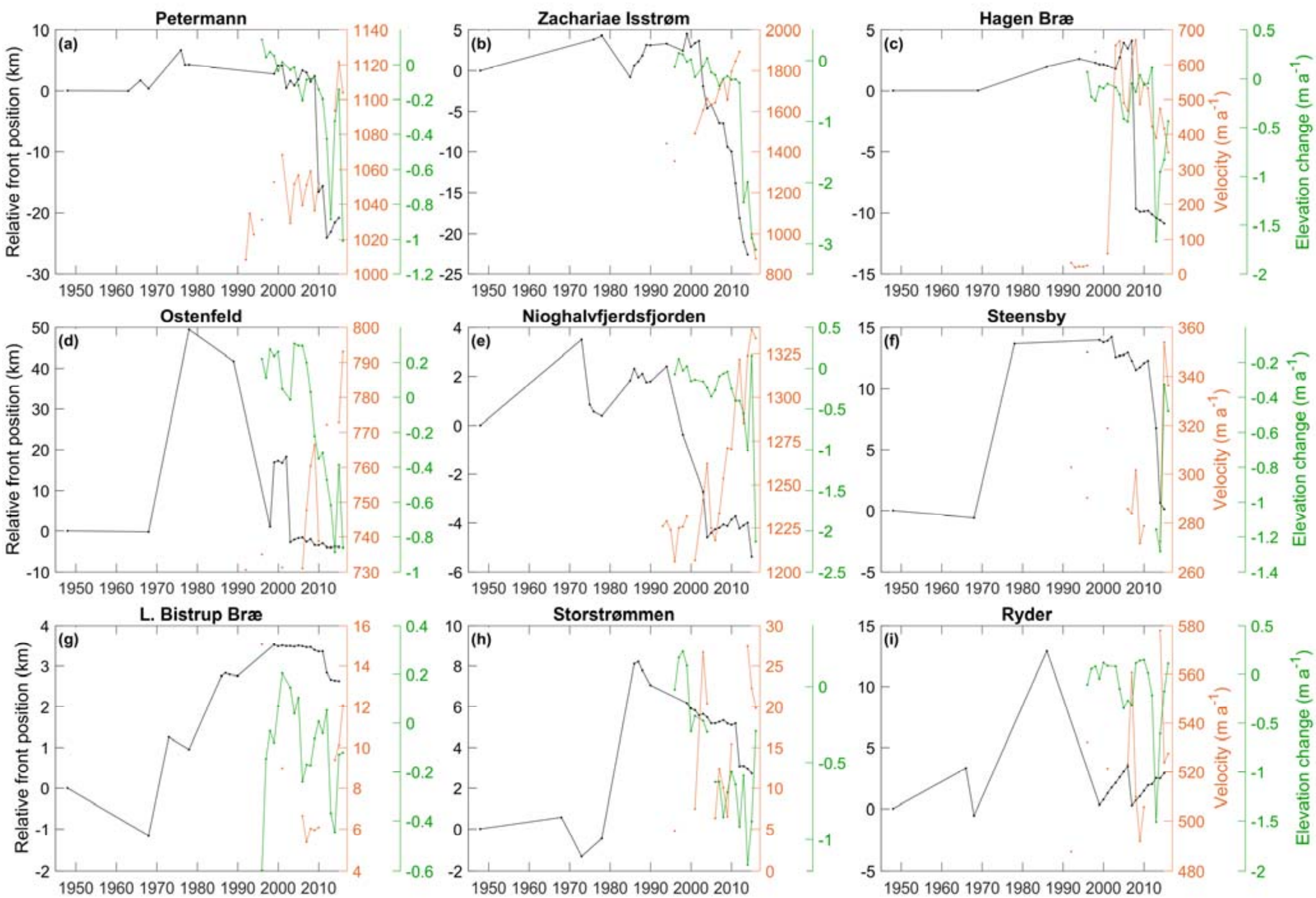


Figure 7: Front position, velocity and elevation change at nine outlet glaciers which terminate in floating ice tongues in northern Greenland. Left axes show relative front position (black line) between 1948 and 2015 relative to their initial position in 1948. Grounding line velocities (orange) on right axes one between 1996 and 2015. Surface elevation changes averaged across the glacier centreline profile (green) for 1996 to 2015.

3.4 Surface elevation change

3.4.1 Grounded-terminus outlet glaciers

Thinning rates on all outlet glaciers with grounded-termini (except Kofoed-Hansen Bræ) increased between 1992–1996 and 2014–2015 (Table 1). Short-term surface lowering was synchronous with the start of their steady retreat and examples of this were at Marie-Sophie and Academy Glaciers. Small increased thinning or reduced thickening rates at Academy and Marie-Sophie Glaciers (1999 to 2000: Figure 6f,h), were followed by high retreat rates in the following years at both Marie-Sophie (-130 m a^{-1}: 2001 to 2004) and Academy Glacier (-205 m a^{-1}: 2001 to 2003). Periods of greater retreat (2001 to 2003/04) were followed by dramatically increased thinning rates at both glaciers to -0.3 m a^{-1} (Academy) and -0.16 m a^{-1} (Marie-Sophie: Figure 6f,h). Thinning rates similarly increased strongly from -0.19 m a^{-1} to -0.78 m a^{-1} at Humboldt Glacier from 1996–2005 to 2005–2012, which coincided with increased retreat rates (-98 to -160 m a^{-1}: Figure 6d). Limited data prevent us from commenting in depth on elevation changes at glaciers in NW Greenland. However, the few years of data available at Harald Moltke Bræ show increased thinning between 2012 and 2015, coincident with retreat (Figure 6c). Within this record lies an anomalous year of reduced thinning rates (2013 to 2014), which were coincident with an order of magnitude increase in velocity (~1000 m a^{-1}) and 0.8 km terminus advance.

3.4.2 Glaciers with floating ice tongues

Several glaciers with floating ice tongues experienced even higher thinning rates from 1992–1996 to 2014–2015 (Table 1), and were characterised by short-lived increases in thinning rates following ice tongue retreat. This occurred at Petermann, Hagen Bræ, and Zachariae Isstrøm, which all showed a slight thickening before ice tongue retreat/collapse, followed by a switch to thinning immediately before large calving events (Figure 7). For example, rates of elevation change at Petermann Glacier switched from negligible thickening in 2008 (0.03 m a^{-1}) to thinning (-0.22 m a^{-1}) in 2009, before the removal of 27 km of floating ice in the following three years (2010 to 2013: Figure 7a). At Zachariae Isstrøm a switch to thinning was synchronous with the onset of rapid retreat in 2003 (Figure 7b), although thinning rates were greater once the entire ice tongue was lost between 2011 and 2012. Thinning rates during and immediately after floating ice tongue retreat increased from minimal change (< -0.2 m a^{-1} thinning) to -0.8 m a^{-1} at Petermann Glacier (2010 to 2013), -1.7 m a^{-1} at Hagen Bræ (2007/11 to 2012/13), and -2 m a^{-1} at Zachariae Isstrøm (2011/12 to 2012/13: Figure 7). At these three glaciers, increased thinning was also coincident with acceleration during the years following ice tongue removal (Figure 7). Other glaciers showed more gradual and smaller increases in thinning rates (Figure 7). For example, at C. H. Ostenfeld the removal of 21 km of floating ice between 2002 and 2003 was followed by a steady and low magnitude increased thinning rates at a rate of -0.15 m a^{-1} from 2006 to 2014 (Figure 7d). In this case, velocity increases alongside increased thinning rates were also gradual, but minimal in comparison to other glaciers. Ryder Glacier also showed increased thinning rates prior to retreat (2005–2006) but was followed by a rapid switch to thickening as ice flow accelerated, and the calving front advanced (Figure 7i).

Two glaciers with floating ice tongues in northeast Greenland showed a different pattern of elevation change to the rest of the region. Storstrømmen and L. Bistrup Bræ thinned at the glacier terminus and thickened inland from 1996 to 2015 (Figure 8). Periods of glacier advance (~1970s–80s) at both Storstrømmen and L. Bistrup Bræ preceded the earliest record of elevation change and, following this, their terminus positions underwent minimal change (Figure 5). Between 1996 and 2015, inland elevation change was minimal (Figure 8), whereas greater thinning took place at the terminus. Large retreat events of 2.1 km at Storstrømmen and 0.7 km at L. Bistrup Bræ between 2011 and 2013 coincided with increased terminus thinning rates of -0.8 m a^{-1} at Storstrømmen (2011 to 2012) and -1.76 m a^{-1} at L. Bistrup Bræ (2011 to 2013: Figure 8). These spatial patterns of elevation change were synchronous with velocity variations: deceleration and thickening occurred inland, while acceleration, thinning, and retreat were synchronous at the terminus (Figure 8).

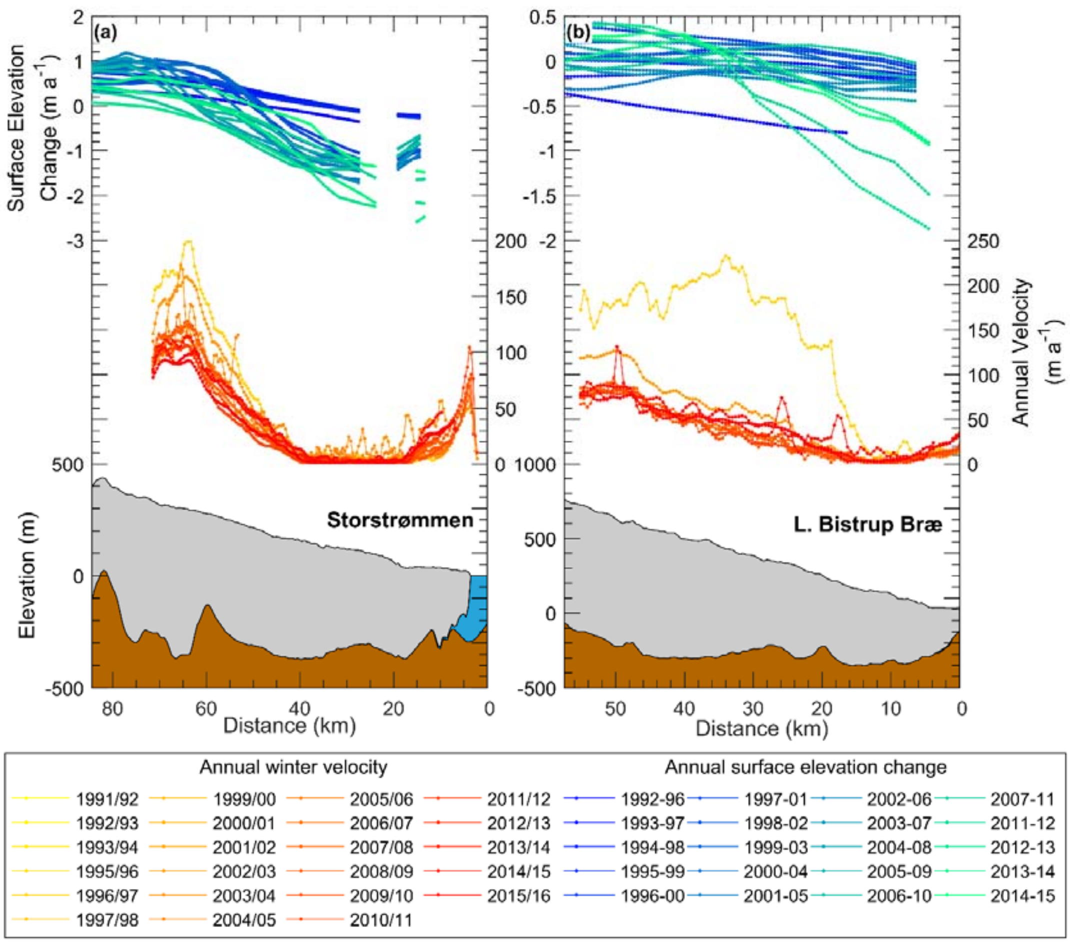
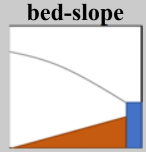
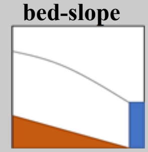
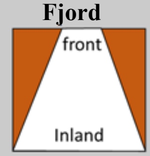
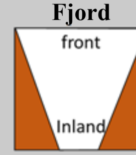


Figure 8: Annual surface elevation change, annual velocity and surface/bed topography for two outlet glaciers in northeast Greenland: Storstrømmen (a) and L. Bistrup Bræ (b). Blue to green coloured lines represent annual surface elevation through time (1992–96 to 2014–15) and yellow through to red lines represent annual winter velocity from 1991/92 to 2015/16.

3.6 Topographic factors

Distinct variability in glacier geometry exists between individual outlet glaciers in northern Greenland. Glaciers that are grounded at their termini, tend to be characterised by deep beds, that in all but two cases (Harder and Brikkerne) rest below sea level (-33 to -370 m below sea level: Figure 9). There is a split between glaciers which rest on inland sloping bed topography and seaward sloping topography (Table 3, Figure 9). Harald Moltke Bræ, Tracy, Heilprin and Humboldt Glaciers have the steepest inland sloping bed profiles 20 km inland of their grounding line (Figure S2), and currently appear to have retreated downslope away from topographic ridges (Figure 9). In contrast, Harder, Brikkerne, Academy and Marie-Sophie Glaciers all slope seaward (Table 3), and have retreated into shallower water (Figure 9). Deeper, inland sloping bed topography is associated with higher mean retreat rates (-121 m a^{-1}) and greater velocity increases (Table 1). Retreat rates at glaciers with seaward sloping beds average -24 m a^{-1} (Table 1), excluding Brikkerne which advanced. Grounded-terminus glaciers in northern Greenland are mainly confined within long narrow fjords (5–16 km wide), but there is no apparent correspondence between widening/narrowing fjords (Table 3), and higher retreat rates (Table 1).

Table 3: Glacier-specific factors at 18 northern Greenland study glaciers. This includes: the size and percentage of each surface drainage basin below sea level, the direction of the bed slope 20 km inland of the grounding line (inland or seaward), and whether the fjord widens or narrows with distance inland. Red and blue shading for bed-slope and fjord width represent expected instability, and stability respectively for each parameter.

	Northern Greenland Outlet Glaciers	**Drainage Basin Size (km^2)**	**% of drainage basin below sea level**	**Inland bed-slope** 	**Seaward bed-slope** 	**Widening Fjord** 	**Narrowing Fjord** 
Category 1: Grounded terminus	Tracy	3,176	3.6	X			X
	Kofoed-Hansen Bræ	[b]	[b]	X		X	
	Harald Moltke Bræ	666	17	X			X
	Humboldt	51,815	27	X		*Does not terminate in fjord*	
	Heilprin	6,593	2.9	X		X	
	Academy	[a]	[a]		X	X	
	Harder	792	0.2		X		X
	Marie-Sophie	2,567	6.8		X	X	
	Brikkerne	929	2.3		X		X
Category 2: Floating ice tongue	Petermann	60,093	67	X		X	
	Zachariae Isstrøm	257,542[b]	54	X		X	
	Hagen Bræ	30,250[a]	20		X	X	
	C. H. Ostenfeld	11,013	1.5	X			X
	Nioghalvfjerdsfjorden	[b]	[b]	X			X
	Steensby	3,356	4.2	X			X
	L. Bistrup Bræ	26,660	4.4	X		X	
	Storstrømmen	[b]	[b]	X		X	
	Ryder	36,384	40		X	X	

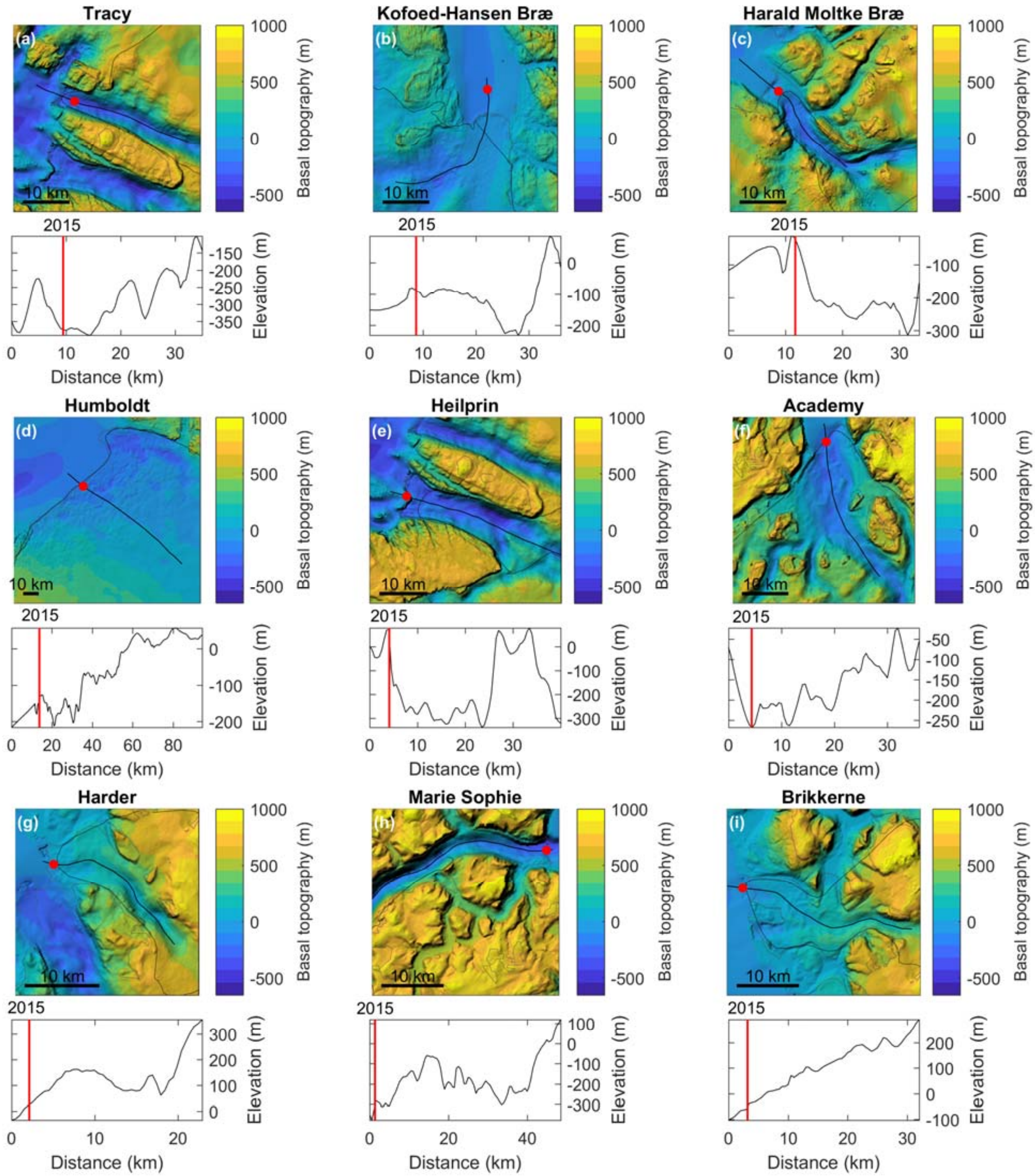


Figure 9: Basal topography from Operation IceBridge BedMachine v3 (Morlighem et al., 2017) beneath nine study glaciers with grounded termini in northern Greenland. Red points represent the position of the terminus/grounding line at each glacier from our most recent record of their terminus position (2015). Black lines are glacier centreline profiles. Profile plots show basal elevations along each glacier centreline profile and solid red lines nearest to zero show the terminus location.

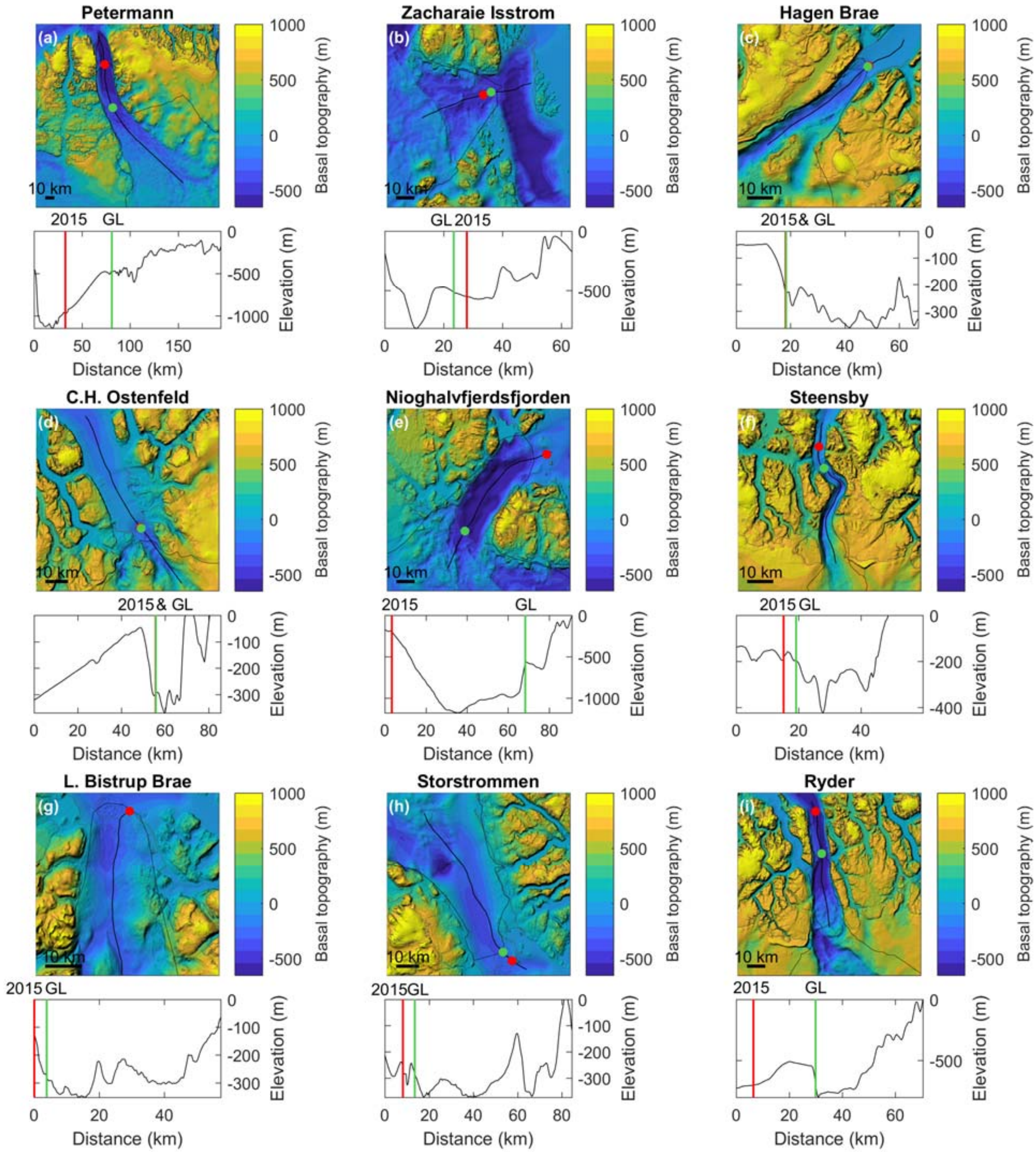


Figure 10: Basal topography from Operation IceBridge BedMachine v3 (Morlighem et al., 2017) beneath nine study glaciers which terminate in floating ice tongues in northern Greenland. Red points represent the most recent recorded terminus position (2015) from this study. Green points represent the location of the grounding line along the centreline profile from the GIMP DEM mask (Howat et al., 2014). Profile plots show basal elevations along each glacier centreline profile, where closest to zero red lines show the terminus locations, and further inland green lines shown the grounding line.

In contrast to grounded-terminus glaciers, those which terminate in floating ice tongues have deeper bed topography (-73 to -1000 m below sea level: Figure 10) and greater proportions of their glacier catchments below sea level (Table 3). Fjords widths are also on average (19 km) wider than grounded-terminus glaciers (9 km) and the majority widen with distance inland (Table 3). Basal topographic profiles beneath seven of nine glaciers with floating tongues show inland sloping bed topography within 20 km of the grounding line (Table 3). At the remaining two glaciers (Hagen Bræ and Ryder) their bed topography slopes seaward (Table 3). While bed profiles at Petermann, C. H. Ostenfeld, and Steensby have retrograde bed slopes close to the grounding line (Figure S2), further inland they show steeper seaward sloping topography (Figure 10). Additionally, current grounding line positions at Petermann, C. H. Ostenfeld and Hagen Bræ, rest on relatively flat topography (Figure 10a,c,d), rather than retrograde slopes. Like most other floating ice tongue glaciers, Ryder Glacier also has a deep basal trough (~800 m below sea level) 20 km inland of the grounding line, but further inland (~50 km from the terminus) it has a steep seaward sloping bed, and a large topographic ridge immediately seaward of the current grounding line position (Figure 10c). Glaciers draining the NEGIS (Nioghalvfjerdsfjorden and Zachariae Isstrøm), have even steeper inland sloping bed profiles immediately inland of their grounding line positions than most other glaciers with floating ice tongues (Figure 10). Both Nioghalvfjerdsfjorden and Zachariae Isstrøm experienced gradual ice tongue retreat and prolonged glacier acceleration, dissimilar to the dynamic behaviour of most other glaciers with floating ice tongues. Since losing its ice tongue in 2011/12, Zachariae Isstrøm retreated down its steep basal trough, past the recorded (nominal date of 2007 in BedMachine dataset) grounding line position (Figure 10b). Further south-east in the study region, Storstrømmen and L. Bistrup Bræ also have deep basal troughs, particularly close to their current grounding lines, but high errors in this region mean we do not consider their bed topography further.

4. Discussion

4.1 Timing of glacier change between 1948 and 2016

Decadal terminus changes at all 18 study glaciers (Figure 4), showed a transition from slow low magnitude advance and retreat (averaging +72 m a^{-1}) between 1948 and 1995 to rapid high magnitude retreat (averaging -445 m a^{-1}) between 1996 and 2015. The latter period included the onset of steady retreat at most grounded outlet glaciers in northern Greenland, and the occurrence of large, rapid retreat events at floating ice tongue glaciers (Figure 5). While this switch from minimal terminus change/advance to more rapid retreat is perhaps similar to the cyclic behaviour of tidewater glaciers (Meier and Post, 1987; Pfeffer, 2007), it is unlikely that this pattern of widespread retreat is driven by internal factors alone (e.g. Nick et al., 2007). Importantly, the switch to terminus retreat the 1990s was coincident with increased air and ocean temperatures across the GrIS (e.g. Box et al., 2009; Hanna et al., 2008; Luckman et al., 2006) and with Arctic-wide increased retreat rates (Carr et al., 2017b; Moon and Joughin, 2008; Jensen et al., 2016), acceleration and retreat in south-east Greenland. Thinning rates also increased in the GrIS ablation area (< 2000 m elevation) since the 1990s (Abdalati et al., 2001; van den Broeke et al., 2016; Krabill et al., 2000). At several glaciers, e.g. Jakobshavn (Thomas et al., 2011), and Helheim and Kangerdlugssuaq in the south-east (Howat et al., 2008; Luckman et al., 2006), increasing temperatures after the 1990s increased thinning in the ablation zone, which reduced basal/lateral drag and instigated a period of rapid terminus retreat. Indeed, increased thinning occurred at many of the study glaciers in northern Greenland, prior to rapid retreat. Thus, it is likely that similar increased ice marginal thinning due to negative mass balance (van den Broeke et al., 2016; Khan et al., 2015; Pritchard et al., 2009), may have been the initial condition for increased glacier retreat rates and feedbacks between thinning, retreat, acceleration and further dynamic thinning in northern Greenland.

Climatic and oceanic changes may have been the initial trigger of retreat in northern Greenland, with subsequent retreat being sustained by the fjord topography (i.e. basal topography and fjord width: Section 4.3). Previous studies in northern Greenland have identified a number of potential triggers for glacier retreat in the region: 1) the loss of sea ice buttressing, particularly in the NEGIS (Khan et al., 2014; Reeh et al., 2001) and 2) increased basal melt rates beneath floating ice tongues due to ocean warming (Reeh et al., 2001; Rignot et al., 2001; Rignot and Steffen, 2008; Wilson et al., 2017). However, in line with tidewater glacier cyclic behaviour, it is likely that after an initial change in dynamics at the terminus triggered by climate forcing, fjord width and depth become more important controls on the duration and magnitude of retreat at individual glaciers (Benn et al., 2007; MacGregor et al., 2012). Here, we do not assess in detail the climate-ocean forcing mechanisms that may have influenced recent terminus change behaviour in northern Greenland, partly due to lack of data and partly as the main focus of this paper is on glacier dynamics and their interaction with topography. Instead we focus on the patterns of terminus change, dynamic glacier behaviour, and geometric controls. We highlight ascertaining the climate-ocean drivers on recent outlet glacier behaviour as an important area of future work in northern Greenland.

4.2 Dynamic glacier response to terminus change

Our analysis of terminus behaviour shows that the dynamic response to a frontal position change is highly dependent on whether the terminus is grounded or the glacier terminates in a floating ice tongue (Benn et al., 2007). Across northern Greenland we observe two dominant calving behaviours based on terminus type: 1) low magnitude continuous calving events/terminus retreat at grounded outlet glaciers, 2) large episodic tabular calving events at glaciers with floating ice tongues. Our changepoint analysis also revealed significant differences in the duration and magnitude of rapid retreat based on terminus type. Different calving styles at these two categories of glacier correspond to variances in their dynamic glacier response (acceleration and thinning) to terminus change.

Independent of style (continuous vs episodic), calving at both categories of terminus type is influenced by the velocity structure of the glacier, and ice velocity itself is sensitive to changes in terminus position and alterations to the force balance, i.e. decreased basal/lateral resistance and increased driving stress (Benn et al., 2007). Increased thinning at the glacier terminus, causes downstream increases in velocity, which stretches the ice, promotes crevasse propagation induced calving, and accelerates flow inland. As such, thinning is thought to have initiated enhanced retreat and accelerated terminus velocities, similar to other regions of the ice sheet (e.g. Luckman et al., 2006; McFadden et al., 2011; Moon and Joughin, 2008). Indeed, across northern Greenland our results suggest that terminus thinning (~1990s) could have been the initial criterion for instigating enhanced calving and terminus retreat in the following two decades (1996 to 2015).

Following an initial change in terminus conditions (~1990s), outlet glaciers in northern Greenland that are grounded at their terminus, underwent prolonged periods of steady terminus retreat (on average -150 m a^{-1}), that usually lasted for two to three decades (Figure 5). Like grounded-outlet glaciers elsewhere, e.g. Helheim and Kangerdlugssuaq (Howat et al., 2008, 2005, 2007) and in west Greenland (McFadden et al., 2011), periods of steady and continuous retreat at grounded-terminus outlet glaciers in northern Greenland were accompanied by increased annual ice velocities (27-110%), and dynamic thinning (Figure 6). Thus, continuous calving and retreat, and the associated reduction in resistive stresses at the terminus, substantially altered the force balance by increasing longitudinal stretching and driving stress. This prolonged stress perturbation at the terminus of most grounded outlet glaciers in northern Greenland, allowed acceleration and thinning to propagate inland and continue for a longer period as most glaciers may have not reached a stable geometry (McFadden et al., 2011; Nick et al., 2009: Section 4.3).

In contrast, terminus changes at most glaciers with floating ice tongues were characterised by short-lived (<6 years), significantly higher magnitude retreat events that averaged -4536 m a^{-1} (after ~1990s). These high magnitude retreat events were often due to the calving large tabular icebergs, initiated by rift propagation (e.g. MacGregor et al., 2012). However, in most cases large calving events, appeared not to perturb the force balance by neither increasing longitudinal stretching, nor driving stresses on inland grounded ice (Figure 7). Instead, terminus retreat was followed by minimal/and or short-lived increases in annual velocity, and short-term increases in ice surface thinning rates (Figure 7). This was particularly the case at Petermann, Hagen Bræ and C. H. Ostenfeld, in response to ice tongue collapse or large calving events. This contrasts with the behaviour of ice-tongue terminating glaciers elsewhere in Greenland (e.g. Joughin et al., 2008, 2004) and glaciers draining into Antarctic ice shelves (e.g. Scambos et al., 2004), which instead showed prolonged acceleration and dynamic thinning following the loss of substantial floating ice. At some glaciers short-lived acceleration was followed by reduced retreat, and deceleration (e.g. Hagen Bræ), which represents a rapid re-adjustment at the terminus, and that calving at floating ice tongue glaciers in northern Greenland, appear to limit the dynamic glacier response to large calving events. This could be due to limited lateral resistance provided by floating ice tongues (Section 4.3).

However, Zachariae Isstrøm was a notable exception to this pattern. At Zachariae Isstrøm, sustained annual calving was accompanied by a longer period of glacier acceleration and thinning (Figure 7b). This is comparable to the behaviour of grounded outlet glaciers in northern Greenland, and ice-tongue terminating glaciers elsewhere (e.g. Jakobshavn Isbræ: Joughin et al., 2004, 2008). In this case, continuous retreat is likely to have gradually reduced resistive forces (i.e. backstress) acting on inland grounded ice, causing higher magnitude and prolonged flow acceleration. Apart from Zachariae Isstrøm, our data show outlet glaciers in northern Greenland have been largely insensitive to either entire ice tongue loss (C. H. Ostenfeld, Steensby and Hagen Bræ), or large iceberg calving events (Petermann, Nioghalvfjerdsfjorden). Thus, despite some similarities (e.g. Zachariae Isstrøm to grounded-behaviour), region wide glacier behaviour in northern Greenland appears dependent on whether the terminus is grounded or floating, due to their calving nature and dynamic response to perturbations of their termini. This highlights the need to consider terminus type when assessing the long-term response of outlet glaciers to changes at their terminus.

4.3 Influence of glacier geometry

While climate-ocean forcing may have triggered a change in glacier dynamics at the terminus of outlet glaciers in northern Greenland (e.g. Khan et al., 2014; Reeh et al., 2001), glacier geometry (e.g. width and depth of fjords) may have determined the duration and extent of the resultant retreat. Indeed, variations in basal topography and fjord width have been previously identified as an important control on the dynamic response of glaciers in many regions of the GrIS (e.g. Carr et al., 2013, 2017b; Howat and Eddy, 2011; McFadden et al., 2011; Millan et al., 2018; Thomas et al., 2009). Collectively these factors could explain differences between grounded-terminus and floating ice-tongue glaciers (McFadden et al., 2011), as well as individual glacier variability.

Calving from grounded outlet margins is controlled by both basal and lateral drag, and both reduce as a glacier retreats into a deeper and wider fjord (Benn et al., 2007). At grounded outlet glaciers in northern Greenland, prolonged acceleration and thinning following retreat suggests that these glaciers were still adjusting to terminus change by the end of the study period in 2015. This is likely due to deep basal topography (> 200 m below sea level), and retrograde bed slopes (~20 km of their grounding zones) beneath most grounded-terminus glaciers (Figure 9). We suggest grounded-terminus retreat into deeper water contributed to: (i) buoyancy driven feedbacks, as the ice thinned to flotation (van der Veen, 1996), (ii) the penetration of basal crevasses through the full ice thickness (van der Veen, 1998, 2007), and (iii) subsequent enhanced rates of calving and continued retreat (e.g. Joughin et al., 2008). Our results showed grounded-outlet glaciers which retreated into deeper fjords, had higher retreat rates (e.g. Tracy, Harald Moltke Bræ, and Heilprin), than those with shallower basal troughs (e.g. Academy and Marie-Sophie). The former three glaciers also appear to be retreating downslope from topographic highs at the edge of their fjords (Figure 9a,c,e).

Unlike grounded-termini, floating ice tongues predominantly provide resistive stresses through their contact with the lateral fjord margins. Consequently, lateral resistive stresses are the main control on the glacier force balance and driving stresses, and hence the impact of terminus retreat on inland ice dynamics. Our data have shown variability in glacier response to ice tongues loss (Figure 7), and we suggest that this could be due to differences in the lateral resistive the floating ice tongue provides when it is in place. Once the ice tongue has entirely collapsed, the terminus becomes grounded, at which point basal drag becomes an important control, and basal topography at and immediately inland of the grounding line becomes more significant.

At most glaciers with floating ice tongues in northern Greenland, the minimal dynamic response to ice tongue retreat and/or collapse (Figure 7), may be due to limited lateral resistance provided by their floating ice tongues. In particular, C. H. Ostenfeld and Hagen Bræ, have heavy rifting along their shear margins, appear relatively un-confined by their fjord walls, and weakly attached to the grounded terminus (Figure 11b,c). Indeed, both glaciers showed no significant increase in flow speeds following large calving events. This suggests that, in both cases, the buttressing provide by the tongues was minimal, and large ice tongue retreats caused a limited change in the inland force balance. Alternatively, Steensby Glacier showed some acceleration (~25%) following ice tongue retreat, which could be due to both a greater loss of lateral resistive stresses from a well-confined ice tongue, and retreat past a narrower sinuous section of the fjord (Figure 11a).

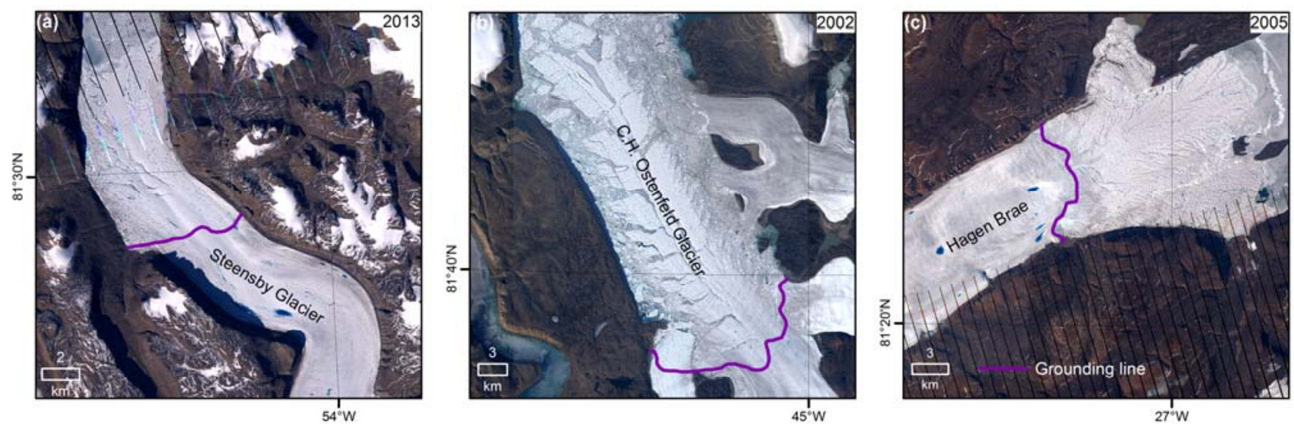


Figure 11: Landsat imagery of three glaciers which terminate in floating ice tongues in northern Greenland before their ice tongue collapse. (a) Steensby Glacier in 2013, (b) C. H. Ostenfeld Glacier in 2002, (c) Hagen Bræ in 2005. Purple lines denote the location of the grounding line.

As well as the lack of resistive stress provided by their ice tongues, the limited response of Hagen Bræ and C. H. Ostenfeld to terminus retreat (Figure 7) may result from their basal topography: following retreat, both grounding lines retreated into shallow water (Figure 10). This may have supressed retreat rates, as it reduces grounding line thickness and therefore discharge. In turn, this would reduce the impact on inland ice velocities and surface thinning rates (Vieli and Nick, 2011). The flat sections of basal topography beneath the grounding lines of Petermann Glacier and Nioghalvfjerdsfjorden may also control their future response to ice tongue collapse, as their grounding lines would need to retreat ~20 km inland to sit on a retrograde slope (Figure 8b, g). In contrast, ice tongue collapse at Zachariae Isstrøm, was followed by continued acceleration, retreat, and more dramatic thinning (Figure 7b). Here, the deep retrograde bed-slope that extends ~20 km inland of the grounding line, is likely responsible for continued retreat (Khan et al., 2014; Mouginot et al., 2015). Retreat into deeper water, gradually reduced buttressing forces, and caused continuous glacier acceleration and surface thinning following ice tongue collapse, similar to Jakobshavn Isbræ (Vieli and Nick, 2011).

4.4 Glacier surging

Surge-type behaviour has been previously documented at several outlet glaciers in northern Greenland (e.g. Hill et al., 2017; Rignot et al., 2001; Weidick et al., 1994), but detailed evidence for surging is rare. Our results provide substantial evidence for the presence of three surge-type glaciers in northern Greenland (Storstrømmen, L. Bistrup Bræ, and Harald Moltke Bræ). This is based on the following characteristics: 1) substantial periods of glacier advance (> 90 m a^{-1}) followed by retreat during the study period, 2) accelerated ice flow coincident with periods of advance, and 3) surface thickening inland and thinning at the terminus position indicative of a quiescent surge-phase. We also provide a long-term record for Ryder Glacier, which suggests its previously recorded surge-behaviour (Joughin et al., 1996, 1999), may instead by related to cyclic tidewater glacier behaviour and basal topographic controls.

Two glaciers in northeast Greenland show strong evidence of being surge-type: Storstrømmen and L. Bistrup Bræ. Interestingly both glaciers began to advance at a similar time, despite separate drainage catchments, and advance continued until 1985 at Storstrømmen, and 1998 at L. Bistrup Bræ (Figure 5). Unfortunately, velocity and surface elevation change datasets do not cover this period. However, dynamic changes at both glaciers between 1992 and 2016 were indicative of periods of quiescence. Both glaciers show inland thickening, which coincides with slower glacier flow, and a terminus region of greater thinning, coincident with acceleration and retreat (Figure 8). Terminus and dynamic glacier changes recorded in this study at Storstrømmen and L. Bistrup Bræ (Figure 7g,h) provide firmer evidence to support previous work that identified a surge event at 1970s (Reeh et al., 1999), and highlighted evidence of quiescence since (Abdalati et al., 2001; Csatho et al., 2014; Thomas et al., 2009).

In northwest Greenland, Harald Moltke Bræ has been previously considered surge-type (Moon et al., 2012; Rignot and Kanagaratnam, 2006), and we record an additional surge event from 2013 to 2014, based on high magnitude acceleration (~1000 m a^{-1}) and glacier advance (0.8 km: Figure 6c). This is similar in duration to a previous period of advance and acceleration from 2004 to 2006. This glacier fits the conventional definition of surging, i.e. a short active phase, which included an order of magnitude increase in velocity (e.g. Meier and Post, 1969). However, it has a short surge-cycle (< 10 years) compared to most other glaciers in the Arctic (Carr et al., 2017a; Dowdeswell et al., 1991; Kamb et al., 1985), and underwent overall retreat from the late 1980s to 2015 (Figure 5), suggesting that climate-ocean forcing may be altering its cyclical behaviour.

Several other glaciers in northern Greenland have also been identified as potentially surge type (Academy and Hagen Bræ: Rignot and Kanagaratnam, 2006; Thomas et al., 2009). These observations were based on limited elevation records which suggested thickening at the terminus of Hagen Brae (Thomas et al., 2009), and some speed up recorded at Academy Glacier in 2005 (Rignot and Kanagaratnam, 2006). However, our detailed, long-term (1948 to 2015) analysis of terminus positions, acceleration and thinning, show no substantial evidence (i.e. cycles of advance/retreat or order of magnitude increases in velocity) to suggest these glaciers are surge-type. Another previously documented surge-glacier is Brikkerne, due to its fast movement and advance seen in early aerial photographs (Higgins, 1991; Higgins and Weidick, 1990). Indeed, terminus changes recorded here confirm a period of advance between 1969 and 1978, followed by a period of apparent terminus stability (Figure 6i). However, due to the lack of detailed elevation and surface velocity observations during this period of advance, we are unable to provide more substantial evidence to classify it as surge-type.

Finally, Ryder Glacier is an exception to most outlet glaciers in the region and appears to be behaving non-linearly to climate-forcing (Figure 7i). Ryder has been referred to as surge-type in the past (Joughin et al., 1996, 1999; Rignot et al., 2001), largely due to a 'mini-surge' event in 1996 (Joughin et al., 1996). Indeed, it has shown some surge-like behaviour: several cycles of advance (~7-years) and retreat (2-years) during the study period (1948–2015), and some acceleration during advance. Additionally, previous studies also identified near-terminus thinning (2–4 m a^{-1}: 1997 to 1999) and, at ~50 km inland, a similar magnitude of thickening (Abdalati et al., 2001), which is indicative of the quiescent phase of surge-type glaciers (e.g. Kamb et al., 1985; Meier and Post, 1969; Sharp, 1988). Despite this, the short surge-cycle (9 years), minimal glacier acceleration (~8%) during advance, and a cyclic pattern of slow advance followed by rapid retreat, is more characteristic of cyclic tidewater glacier behaviour. We instead suggest that Ryder Glacier cyclic behaviour may be controlled by basal topography. The glacier rests in a deep basal trough (~1000 m below sea level), that slopes seaward, and has a large basal ridge in front of the glacier grounding line (Figure 10i). We suggest this could be a terminal moraine, or moraine shoal, which may have promoted periods of glacier advance (Alley, 1991; Powell, 1990). Similar to Columbia Glacier (Alley, 1991; Nick et al., 2007), the deep basal depression just inland of the grounding line (Figure 10i), and steep seaward bed slope further inland, could have allowed relative terminus stability. As the same time, this could have promoted the build-up of a large moraine seaward of the grounding line, and the decrease in water depth then promoted glacier advance (Alley, 1991; Nick et al., 2007). Shoal advance may have allowed slow terminus advance through this deep basal trough (~7 years), and minimal retreat away from this moraine caused rapid retreat (~2 years) back into the trough. We therefore suggest that instead of surging, Ryder Glacier is controlled by internally driven tidewater glacier cycles, and re-advance may be promoted by the presence of a moraine shoal.

5. Conclusions

Outlet glaciers in northern Greenland drain ~40% of the ice sheet by area but remain understudied compared to other regions of the ice sheet. We have analysed the dynamics of 18 major marine-terminating outlet glaciers in northern Greenland between 1948 and 2015. Overall, glacier retreat rates ranged from -15 to -311 m a^{-1} over the entire study period. Between 1948 and 1995 glaciers exhibited generally low magnitude advance and retreat, with an average frontal position change of +72 m a^{-1}

(advance) across the 18 study glaciers. Following this, there was a regional transition to more rapid and widespread retreat, when average frontal position change was -445 m a^{-1} (1995 to 2015). This was coincident with accelerated retreat in other regions of the ice sheet (e.g. Carr et al., 2013; Howat et al., 2008; Howat and Eddy, 2011). From 1996 to 2015, most glaciers also experienced accelerated ice flow and increased dynamic thinning.

While increased retreat rates from the mid-1990s were near-ubiquitous, we observe distinct differences in glacier behaviour depending on whether the terminus is grounded or floating. Three factors play a role in the dynamic behaviour of these two types of glacier i) different methods of calving, continuous small magnitude calving vs large episodic calving ii) differences in resistive stresses at the terminus, iii) glacier geometry. Continuous retreat into deep, widening fjords at grounded-terminus glaciers led to a greater reduction in basal/lateral resistive stresses, and caused high magnitude acceleration and dynamic thinning. In contrast, large episodic calving events, from unconfined ice tongues that provided little lateral resistance meant that most glaciers with floating ice tongues appear dynamically insensitive to the retreat of their terminus. We note there are exceptions; continuous ice tongue retreat at Zachariae Isstrøm caused prolonged acceleration and thinning, and several glaciers with ice tongues went through cycles of advance and retreat during the study record. This can be explained by the method of glacier calving (continuous rather than episodic), and a deep wide fjord that promoted unstable retreat. Glacier advance can be explained by surging, or topographic controls which allow cyclic advance and retreat. We provide further evidence for surging at three glaciers (Harald Moltke Bræ, Storstrømmen and L. Bistrup Bræ) in northern Greenland, and an explanation for the cyclic behaviour of Ryder Glacier, which is likely related to topographic controls (e.g. moraine shoal), that allowed the re-advance of the terminus. While we have shown that northern Greenland has begun to undergo rapid dynamic change over the last two decades (1996 to 2015), we highlight variability between individual glaciers and the importance of considering terminus type and glacier geometry (basal topography, fjord width and ice tongue confinement) when considering future glacier response to climate change across this region of the ice sheet. Currently, ice tongue retreat does not appear to substantially affect inland ice dynamics, however, once these glaciers become grounded, they may accelerate, thin, and increase the volume of grounded ice discharge into the ocean.

Data availability

Shapefiles of frontal positions for all 18 outlet glaciers in this study between 1948 and 2015 are freely available on request to the corresponding author. All other data sources, including: satellite imagery, historical maps, surface elevation change, annual velocity, climate and ocean, and topographic data, are already available online. The sources of each of these datasets are given in the text and the supplementary information.

Author contribution

The initial project was designed by all authors, and E. A. Hill led the data analysis and interpretation, with comments throughout from all authors. E. A. Hill led the manuscript writing, and all authors contributed towards the editing of the manuscript and figures.

Competing interests

The authors declare that they have no conflict of interest.

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