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Exceptional retreat of Kangerdlugssuaq Glacier, east Greenland, between 2016 and 2018

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Abstract

Kangerdlugssuaq Glacier is one of Greenland's largest tidewater outlet glaciers, accounting for approximately 5 % of all ice discharge from the Greenland Ice Sheet. In 2018 the Kangerlussuaq ice front reached its most retreated position, since observations began in 1932. We determine the relationship between retreat and: (i) ice velocity; and (ii) surface elevation change, to assess the impact of the retreat on the glacier trunk. Between 2016 and 2018 the glacier retreated ~5 km and brought the Kangerlussuaq ice front into a major (~15 km long) overdeepening. Coincident with this retreat, the glacier thinned as a result of near-terminus acceleration in ice flow. The subglacial topography means that 2016-18 terminus recession is likely to trigger a series of feedbacks between retreat, thinning and glacier acceleration, leading to a rapid and high-magnitude increase in discharge and sea level rise contribution. Dynamic thinning may continue until the glacier reaches the upward sloping bed ~10 km inland of its current position. Given the complexity and scale of the processes involved, such changes will not be represented in prognostic models of the Greenland Ice Sheet to 2100 and beyond.

1 Introduction

The Greenland Ice Sheet (GrIS) is a major source of global sea level rise (SLR) and contributed 171 Gt a^{-1} (~0.47 ± 0.23 mm a^{-1}) to SLR between 1991 and 2015 (van den Broeke et al., 2016). Mass loss has accelerated since the mid-1990s and coincided with both elevated atmospheric temperatures (e.g. Hanna et al., 2012) and warmer oceanic waters reaching marine-terminating glacier margins (e.g. Straneo and Heimbach, 2013). Approximately 40% of Greenland's mass loss since 1991 was due to increased ice discharge from marine-terminating outlet glaciers and it accounted for ~60% of ice loss during the phase of rapid outlet glacier retreat observed between 2000 and 2005 (Rignot and Kanagaratnam, 2006; Enderlin et al., 2014; Anderson et al., 2015; van den Broeke et al., 2016). As such, predictions of ice discharge from Greenland's marine-terminating outlet glaciers are critical for forecasting near-future sea level rise. Despite their importance, substantial uncertainty remains over the response of Greenland's outlet glacier to climatic and oceanic warming (e.g. Carr et al., 2013; Enderlin et al., 2013; Stocker et al., 2013). This response is complicated by glacier-specific factors, particularly the bed and fjord geometry, which can strongly enhance/suppress glacier response to forcing (e.g. Moon et al., 2012; Carr et al., 2015).

Kangerdlugssuaq Glacier (68.5ºN, 33.0ºW; Kangerdlugssuaq herein), East Greenland, is one of Greenland's largest tidewater glaciers, draining approximately 3 % of the total area of the ice sheet (Bevan et al., 2012) and accounting for 5% of ice sheet discharge (Enderlin et al., 2014). Following a period of sustained low-elevation thinning during the mid to late 1990s (Thomas et al., 2000; Khan et al., 2014), Kangerdlugssuaq retreated abruptly by 5 km between April 2004 and April 2005 (Luckman et al., 2006; Howat et al., 2007). Coincident with this retreat, the glacier accelerated from ~7,500 m a^{-1} (~20 m d^{-1}) to ~13,000 m a^{-1} (~35 m d^{-1}) (Luckman et al., 2006). Following the 2005 retreat, Kangerdlugssuaq decelerated and re-advanced by ~2 km between 2006 and 2010 (Howat et al., 2007; Bevan et al., 2012). Ice losses returned to pre-retreat values by the summer of 2008 (Howat et al., 2011). However, these changes in speed, frontal position, and subsequent diffusive thinning (Stearns and Hamilton, 2007) resulted in mass loss of 80 Gt of ice between September 2004 and January 2008; a three-fold increase on pre-retreat rates of ice loss (Howat et al., 2011). Between 2000 and 2012, Kangerdlugssuaq accounted for ~14 % (~105 Gt) of the total cumulative discharge anomaly of the entire GrIS (~750 Gt; Enderlin et al., 2014) and was second only to Jakobshavn Isbræ (~21 %; 158 Gt).

The most recent published records of Kangerdlugssuaq's variations in frontal-position and speed end by 2012 (Bevan et al., 2012; Khan et al., 2014; Murray et al., 2015). Since then, Kangerlugssuaq has entered a new phase of rapid retreat. Here we present an intra-annual time-series of ice frontal position between March 2013 and September 2018 from Landsat 8 satellite imagery. We couple this time-series of ice frontal positions with ice velocity and surface elevation datasets to evaluate the dynamic response of Kangerdlugssuaq to recent changes in terminus position. Finally, we discuss local topographic setting as a control on recent and future glacier behaviour.

2 Methods

2.1 Glacier frontal position

Terminus positions of Kangerdlugssuaq were manually digitised from all available Level 1T pansharpened (15 m) Landsat 8 Operational Land Imager (OLI) satellite imagery between 2013 and 2018 using the Google Earth Digitisation Tool (GEEDiT) (Lea, 2018). We visualised (within a web-browser) every Landsat 8 image available between 20 March 2013 (first available Landsat 8 image for Kangerdlugssuaq) and 03 September 2018 (end of study period), and manually digitised the glacier termini for each image where an ice front was visible. The presence of year round mélange precluded the mapping of part or all of the glacier terminus for some images. In such scenarios, only the contiguous portion of the terminus that could be differentiated from the mélange was mapped. Due to overlap in satellite tracks, where multiple images were available for the same day we measured the ice front using the first image acquired unless there was any discernible change. Mapped glacier termini were subsequently exported from GEEDiT in vector format as GeoJSON files and were converted to ESRI Shapefiles using the Margin change Quantification Tool (MaQiT) (Lea, 2018). As each terminus trace has metadata automatically appended within GEEDiT, including the unique path identifier, it is possible to directly and easily identify the original image used in the mapping; for example using GEEDiT Reviewer (Lea, 2018).

Changes in frontal position were assessed using the curvilinear box method in MaQiT (Lea, 2018). This method is an extension of the commonly used 'box method' (e.g. Moon and Joughin, 2008), and used a reference box of fixed width (3 km here) and upstream extent spanning the centre line that intersects with contiguously mapped glacier termini. Any termini that did not fully cover the width of the reference box were excluded from the analysis. Here we defined the centre line as the line representing the midpoint between the 0 m elevation contour from the BedMachinev3 dataset (see Section 2.4; Morlighem et al., 2017). The centre line was extracted by tracing the line following the maximum Euclidean distance between the 0 m contour, from its furthest point up-glacier to an arbitrary point beyond the glacier's maximum extent (Figure 1; e.g. Lea et al., 2014). Mean retreat was subsequently calculated by normalising the change in reference box area by its width. This method therefore captured spatially asymmetric retreat and advance of a calving margin (Moon and Joughin, 2008). Based on the above method, from a possible 199 images, we obtained 124 terminus traces between 2013 and 2018 (Figure S1 in the Supporting Material). Cloud and/or mélange obscured imagery precluded a constant temporal sampling frequency. However, an average of ~20 (~σ 8) terminus traces were obtained per year, with an average sampling frequency of ~15 days (σ ~32). We coupled these newly-derived terminus positions with the datasets of Khan et al. (2014) (annual 1932, 1966, 1972, 1981, 1985, 1991 and 1999 - 2012) and Murray et al. (2015) (seasonal 2000 - 2010) to provide historical (back to 1932) context to the ice front evolution of Kangerdlugssuaq (Figure 1).

Uncertainty in ice front positions is attributed to error in both geolocational accuracy of imagery and precision in manual digitisation of the ice fronts (e.g. Carr et al., 2015). The former was assessed by digitising a section of rock coastline adjacent to the terminus of Kangerdlugssuaq for a sub-sample of 30 Landsat 8 images that covered the whole time-period and path/row combinations, using the curvilinear box method, where there should be no discernible change between images (e.g. Bevan et al., 2012; Carr et al., 2013). The mean error was ± 3.6 m. The latter was assessed by repeatedly digitising the termini of the glacier 30 times in a single Landsat 8 image (e.g. Moon et al., 2015), using the curvilinear box method, again there should be no discernible change. The mean error was ± 2.5 m. Propagating these errors gives an overall mapping uncertainty of ± 4.4 m, which is less than the pixel resolution (15 m) of our imagery.

2.2 Ice velocity

Datasets on ice velocity, basal topography and surface elevation change were compiled from publicly available sources. Ice surface velocities for Kangerdlugssuaq were acquired from the MEaSUREs (https://nsidc.org/data/NSIDC-0481) programme (Joughin et al., 2010; 2011). These velocity maps were produced from 11 to 33 day Interferometric Synthetic Aperture Radar (InSAR) image pairs measured by TerraSAR-X / TanDEM-X, and have a resolution of 100 m (Joughin et al., 2011). 172 velocity maps were available between February 2009 and November 2017 (Figures S2 and S3), with an average of ~19 (σ ~7) velocity maps available per year. Velocity time-series were extracted from fixed points along the ice flow centre line (Figure 1) at 100 m intervals (Figure 2). Velocity errors were calculated using the dataset error values for each velocity maps (Joughin et al., 2011), and resulted in a mean error of ± 11.5 m a-1 for our centre line.

2.3 Surface elevation change

The rate of surface elevation change was determined using Operation IceBridge ATM L4 Surface Elevation Rate of Change data (Studinger, 2014; https://nsidc.org/data/IDHDT4). Measurements were made at all points where coincident Airborne Topographic Mapper (ATM) widescan ILATM1B elevation data existed from two different campaigns, and were provided as average rate of change (dH/dT) of the surface elevation between the two measurement times. Data availability varied spatially and temporally, so values that exactly followed our centreline could not be extracted. To overcome this, we assessed surface elevation change along the profiles where data were available for each time step (Figure 3 and S4). We determined annual change for all available years (n = 11) between 2017 and 2001, and cumulative change to a 2001 baseline (n = 14). The latter were converted from average rate of change to cumulative elevation change using the time difference information provided in the dataset's metadata. Using the dataset errors (Studinger, 2014) for all points in our selected time periods, resulted in a mean error of ± 1.43 m for the annual change datasets and ± 1.89 m for the cumulative change datasets.

2.4 Basal topography

Basal topography was acquired from the Operation IceBridge BedMachine v3 dataset (https://nsidc.org/data/IDBMG4), which is derived from ice thickness and mass conservation, and is coupled with ocean bathymetry to provide a 150 m resolution bed map of Greenland (Morlighem et al., 2017). Bed topography was sampled at 150 m intervals along the centre line (Figure 4). Errors were calculated using the dataset error values (Morlighem et al., 2017), and resulted in a mean error of ± 84 m.

3 Results

Between 2013 and 2016 Kangerdlugssuaq's frontal position followed a typical seasonal progression: before our first available position in late February the ice front advanced with limited calving reaching a maximum position towards the middle of the year (~July; Figures 2c and S5). After this, the ice front retreated, often via a series of large calving episodes, and retreat continued until at least our last available frontal position in October/November (Figures 2c and S5). During each winter (December to February), the ice front would re-advance so that the early spring terminus position was seaward of the previous autumn position. This 2-3 km seasonal oscillation has been typical of Kangerdlugssuaq since at least 1985 (Figure 2c; e.g. Luckman et al., 2006; Bevan et al., 2012; Murray et al., 2015). However, the behaviour of the glacier changed markedly in winter 2016/2017, when the ice front retreated by 2.5 km, rather than the usual winter advance (Figures 2c and S4). As a result, the spring 2017 ice front was ~2.5 km behind the spring 2016 position (Figures 2c and S5). In 2017, the early season advance was interrupted by a series of calving events, limiting the seasonal advance (Figures 2c and S5). During winter 2017, Kangerdlugssuaq's ice front underwent a second phase of extended retreat through to May 2018, with total retreat of 3 km (Figures 2c and S5). This brought the spring 2018 ice front ~2.5 km behind its position in spring 2017, and ~5 km behind its location in spring 2016 (Figures 2c and S5). As in 2017, early seasonal advance in 2018 was punctuated by further calving events. Kangerdlugssuag has therefore entered a new phase of retreat, which occurred through extended winter retreat and limited spring readvance in 2017 and 2018. This retreat has brought Kangerdlugssuaq's ice front to its most retreated position since at least 1932 (Figure 1).

Our data demonstrate that Kangerdlugssuaq decelerated between 2011 and 2017, with peak summer velocity reducing by ~1,500 m a^{-1} from ~10,000 m a^{-1} in 2011 to ~8,500 m a^{-1} in 2017. The glacier then accelerated throughout 2017, such that early spring velocities (~8,500 m a^{-1}) equalled the previous year's summer velocities, reaching a peak velocity of ~10,000 m a^{-1} in November (Figure 2). This near-terminus (V0.5) November velocity was ~2,500 m a^{-1} above the previous year's November velocity of ~7,500 m a^{-1} (Figure 2), representing a 33% increase. This velocity increase is far greater than annual velocity cycles of the preceding years (~1,000 m; Figure 2). Changes in velocity were apparent at least 20 km inland of the terminus but were of highest amplitude nearer to the ice front (Figure 2). Coincident with velocity change, near-terminus thinning of up to 10 m a^{-1}

occurred between 2017 and 2016, following three years of thickening for the periods of 2016-2015, 2015-2014 and 2014-2013 (Figure 3 and S4).

Given the influence of basal topography on the rate and extent of glacier retreat (e.g. Weertman, 1974; Thomas, 1979; Schoof, 2007) we investigated the position of the ice front with respect to basal topography over time (Figure 4). Kangerlussauq currently terminates within an overdeepening. Between 2013 and 2016 the ice front occupied a zone of flat-lying bed topography within this overdeepening, ~850 m below sea level. Retreat during the winter of 2016 removed the ice front from this flat-lying bed into the deepest parts of the overdeepening and onto a reverse bed slope. Apart from one bedrock ridge across the fjord (~50 m in height; located at ~45 km in Figure 4) this reverse slope continues to over 1,100 m below sea level, with the overdeepening extending ~15 km inland before the bed slopes upward again (Figure 4). Retreat during 2017 also brought the glacier front into the widest section of its fjord (~8.5 km wide; Figure 1).

4 Discussion

Our observations demonstrate that between 2016 and 2017 Kangerdlugssuaq's dynamics changed substantially (Figures 2 and 3). Following a period of terminus advance between summer 2011 and summer 2016, Kangerdlugssuaq's ice front rapidly retreated by 5 km between 2017 and 2018 (Figure 2). Although comparable rates of retreat have occurred at least twice since 1932 (Luckman et al., 2006; Khan et al., 2014), this current phase retreated the terminus to the most inland position since the earliest known observations in 1932 (Figure 1; Bevan et al., 2012; Khan et al., 2014). Following late 2016/early 2017 retreat, Kangerdlugssuaq accelerated throughout 2017 (Figure 2) and began to thin close to the terminus (Figure 3). This dynamic response has been observed on other Greenland outlet glaciers, and stems from a loss of resistive stress at the glacier front, leading to ice acceleration, thinning and further retreat (e.g. Howat et al., 2007; Stearns and Hamilton. 2007; Joughin et al., 2010; Moon et al., 2012). As such, it can lead to feedbacks developing and major ice loss (Thomas et al., 2011; Joughin et al., 2012).

Kangerdlugssuaq experienced similar retreat and acceleration to those observed in 2016/17 between 2004 and 2005 (e.g. Luckman et al., 2006). During 2004/2005, increases in speed, retreating frontal position and subsequent diffusive thinning caused Kangerdlugssuaq to lose 80 Gt of ice before returning to the pre-event balance rate (~6.5 Gt a^{-1}) in the summer of 2008. This enhanced period of mass loss represented a three-fold increase in ice discharge when compared to pre-retreat rates of ice loss (Howat et al., 2011). Other short-lived episodes of retreat have led to Kangerdlugssuaq monthly loss rates exceeding 100 Gt a^{-1} (Howat et al., 2011). Variations in ice discharge from Kangerdlugssuaq therefore have substantial implications for total GrIS mass loss (e.g. Stearns and Hamilton, 2007). The observed dynamical changes at Kangerdlugssuaq since 2016 are likely to lead to an increase in discharge and contribution to global SLR over the next 1-5 years. Unlike the 2004/2005 event, where the glacier acceleration and retreat was short lived, and the glacier started to decelerate and advance the following year (Howat et al., 2007; Bevan et al., 2012), recent retreat at Kangerdlugssuaq has occurred over multiple years. If the associated acceleration in speed is maintained, or increases, beyond 2018 then enhanced ice discharge and mass loss from Kangerdlugssuaq could be sustainable for 5-20 years. At present, Jakobshavn Isbræ is the only glacier on the GrIS that has experienced comparable sustained acceleration over multiple years (e.g. Van der Veen et al., 2011; Joughin et al., 2012).

Fjord geometry (bed and width) is a very important control on recent fluctuations of Kangerdlugssuaq's ice front and will continue to influence the glacier's near future behaviour. The last major retreat event in 2005 left the terminus on the edge of a ~15 km long bedrock high (yellow bar in Figure 4b). In contrast, the recent phase of retreat (from 2017) moved the terminus from this bedrock high into an ~3 km long region of reverse bed slope that falls by ~150 m of elevation, and into a wider section of the fjord (Figure 1 and red bar in Figure 4). Retreat down a reverse bedrock slope can cause large increases in ice discharge, due to feedbacks between grounding line thickness, terminus retreat, acceleration and dynamic thinning (Meier and Post, 1987; Schoof, 2007; Gudmundsson et al., 2012). Theoretically, these feedbacks will only stop once the terminus reaches an area of horizontal or forward-sloping bed (Weertman, 1974; Schoof, 2007; Gudmundsson et al., 2012). Similarly, a terminus moving into a widening fjord can also promote enhanced ice discharge, as the ice must thin to conserve mass and because lateral resistive stresses is inversely proportional to width, meaning that the fjord walls will offer less resistance to flow in wider sections of the fjord (Raymond, 1996; Jamieson et al., 2012; Carr et al., 2013). At present, the ice front appears to be resting on a ~750 m wide, ~50 m high bedrock ridge, which may inhibit immediate rapid retreat into the overdeepened trough (Figure 3) (e.g. Jamieson et al., 2012). However, bed elevation immediately beyond this bump decreases for ~10 km inland from ~950 m to ~1,150 m below sea level. Although upstream narrowing in fjord width could also modulate the rate of flow (e.g. Jamieson et al., 2012), Kangerdlugssuaq's ice front is likely primed for further retreat to the head of this trough (Khan et al., 2014). Unlike the 2005 retreat event where the glacier rapidly (1-2 years) re-adjusted to near-balance following a perturbation in geometry (Howat et al., 2007), our observation of multi-year retreat, coupled with a topographic profile that deepens significantly inland suggests that Kangerdlugssuaq is likely to experience prolonged rapid retreat and accelerated ice flow, and thus enter an extended phase of enhanced mass loss. Near-future change (retreat) in ice front position may therefore largely be governed by changes in ice dynamics, with only a weak dependence on atmospheric or oceanographic forcings.

Recent changes in Kangerdlugssuaq's dynamics are likely to have a number of implications for regional and ice sheet-wide mass loss. At the basin scale, Kangerdlugssuaq dominates mass loss from the eastern sector of the GrIS (basin 3 of Andersen et al., 2015). Unlike the majority of the GrIS, it is ice dynamics and not surface mass balance that contributes the largest fractional proportion to mass loss in this sector (Andersen et al., 2015). We expect this trend to continue in the near future. At the ice sheet-scale, 80 % of total ice discharge is from glaciers in the south-east and north-west of Greenland (Enderlin et al., 2014). These regions also accounted for 86 % of ice sheet wide increases in ice discharge as it increased from 462 ± 6 Gt in 2000 to 546 ± 7 Gt in 2012 (Enderlin, et al., 2014). Since 2006 discharge has stabilised in south-east Greenland following the slowdown of Kangerdlugssuaq and Helheim Glaciers (e.g. Howat et al., 2007), and recent (2008-2012) increases in GrIS discharge have been attributed to glaciers from the north-west (Enderlin et al., 2014). Given Kangerdlugssuaq's impacts on both the magnitude and pattern of ice sheet wide mass loss (Rignot and Kanagaratnam, 2006; Stearns and Hamilton, 2007; Enderlin et al., 2014), its new phase of retreat, acceleration and thinning (Figures 2-4) is likely to markedly increase discharge form south-east Greenland, and may result in the south-east region dominating future increases in discharge from the GrIS.

5 Conclusions

We have shown that within the last two years, Kangerdlugssuaq has entered a new phase of rapid retreat and acceleration, the second time this has occurred within the last two decades, and its ice front is now at its most retreated position since at least the early 20th-century. This retreat has brought Kangerlussuaq's ice front into a major (~15 km long) overdeepening. Coincident with retreat, Kangerdlugssuaq accelerated and thinned near the terminus, and is likely to result in substantial dynamic draw down and loss of ice to the oceans. Glacier geometry strongly modulates Kangerdlugssuaq's behaviour. The phase of rapid 5 km retreat between 2016 and 2018 coincided with the ice front moving from the edge of a bedrock high, to a region of reverse bed slope. Given the proximity of the ice front to further reverse bed slope, further retreat would very likely result in ~10 km retreat to the head of this trough. Due to these uncertainties, high temporal resolution monitoring of geometric, frontal position and velocity change, coupled with accurate bed topography, will be critical for accurately predicting and quantifying future patterns of ice loss at Kangerdlugssuaq. Given Kangerdlugssuaq's previous impacts on both the magnitude and pattern of ice sheet wide mass loss, we predict that its new phase of retreat, acceleration and thinning will result in a switch back to the south-east being the largest contributing region to increasing discharge from the GrIS. More broadly, accurate forecasting of the GrIS's contribution to SLR will require a deeper understanding of, and responses to, these non-linear ice dynamic processes.

6 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

7 Author Contributions

SB, RC, NR designed the study. JL wrote and provided the code for GEEDiT and MaQiT. SB conducted all data analysis and led the writing of the manuscript. RC, NR and JL gave conceptual and technical advice, and edited the manuscript.

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10 Data Availability Statement

A shapefile of frontal positions for Kangerdlugssuaq between 2013 and 2018 is included in the supporting material to this article. All other data sources – including satellite imagery, InSAR velocity maps, surface elevation, surface elevation change and bed topography – are freely available online. The sources for these datasets are provided in text and subsequent reference list.

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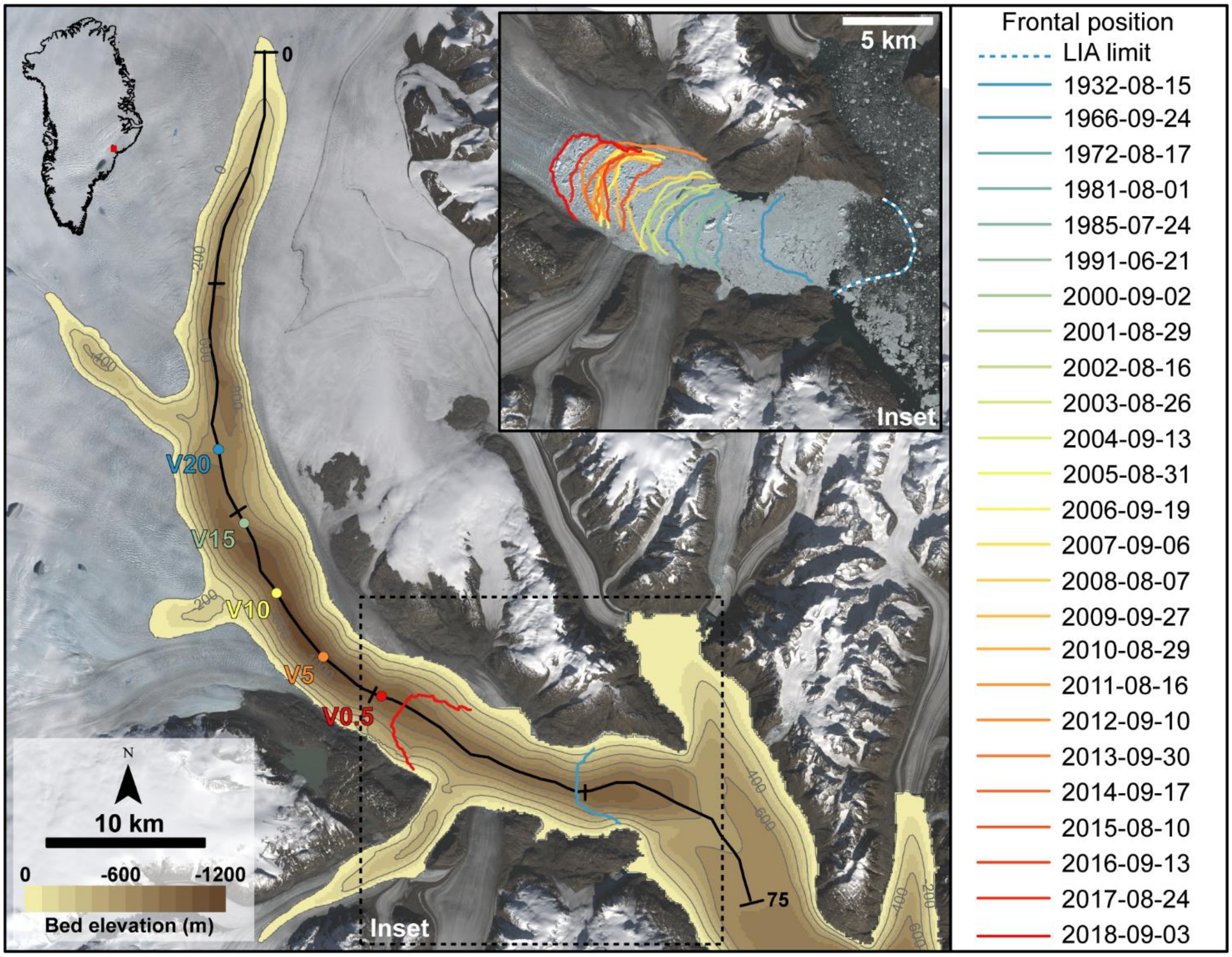

Figure 1: Overview of Kangerdlugssuaq Glacier and mapped historical terminus positions (inset). Black line indicated the centre line profile plotted in Figures 2 and 3. Points V0.5 – V20 mark the locations for the velocity series shown in Figure 2d and indicate the distance (in km) from the most retreated ice front (16 May 2018). Annual ice fronts combine data from this study between 2013 and 2018 and Khan et al. (2014) between 1932 and 2012. Background image is Landsat 8 scene from 03 November 2018 (path 231 and row 012).

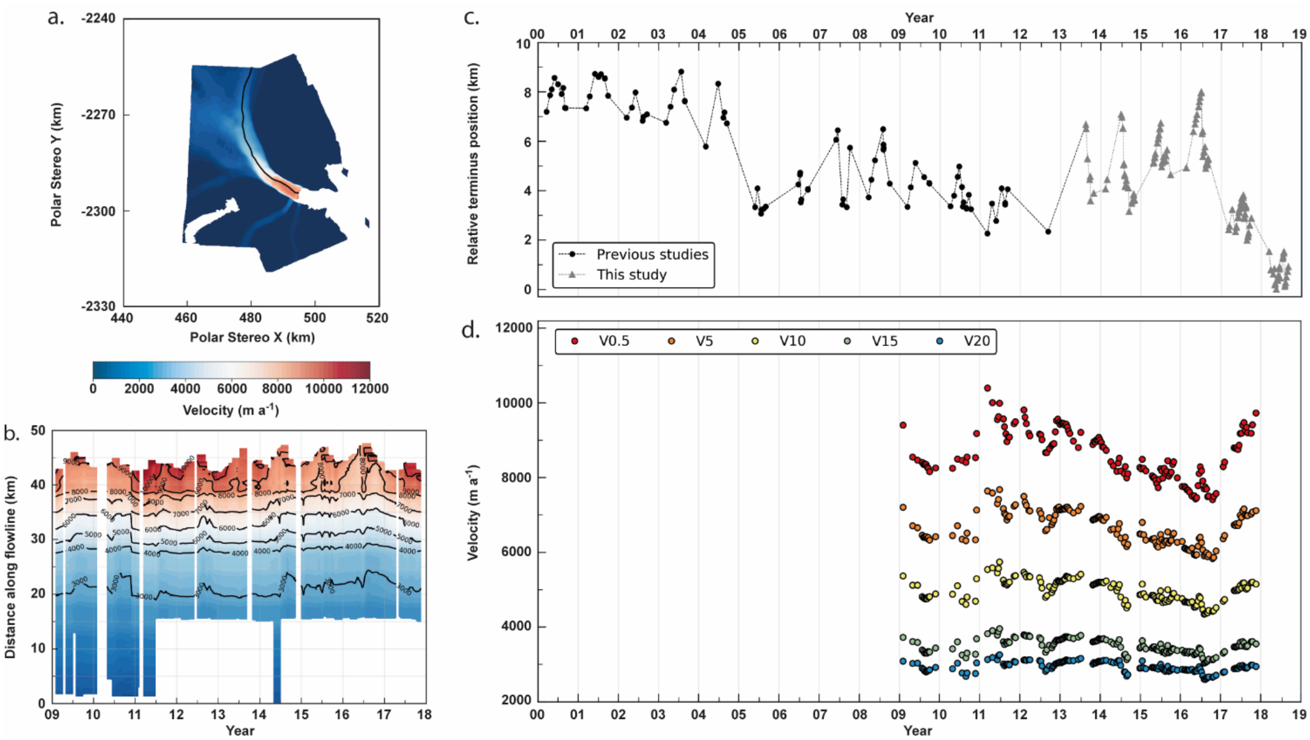

Figure 2: Terminus and velocity change for Kangerdlugssuaq. (a) Mean glacier velocity between 2009 and 2017. (b) Contour plot of along glacier velocity profile for centre line shown in (a). For visualisation purposes, and to obtain a more complete velocity record that accounts for unequal sampling periods between observations, the later were linearly interpolated if there were fewer than 66 days between observations (i.e. six repeat pass cycles). (c) Change in terminus position between 2000 and 2018. (d) Plots of velocity for selected points along the centre line as shown in Figure 1. Points were coded such that the numerical designation (e.g. V5) indicates the distance in kilometres from the most retreated ice front (16 May 2018).

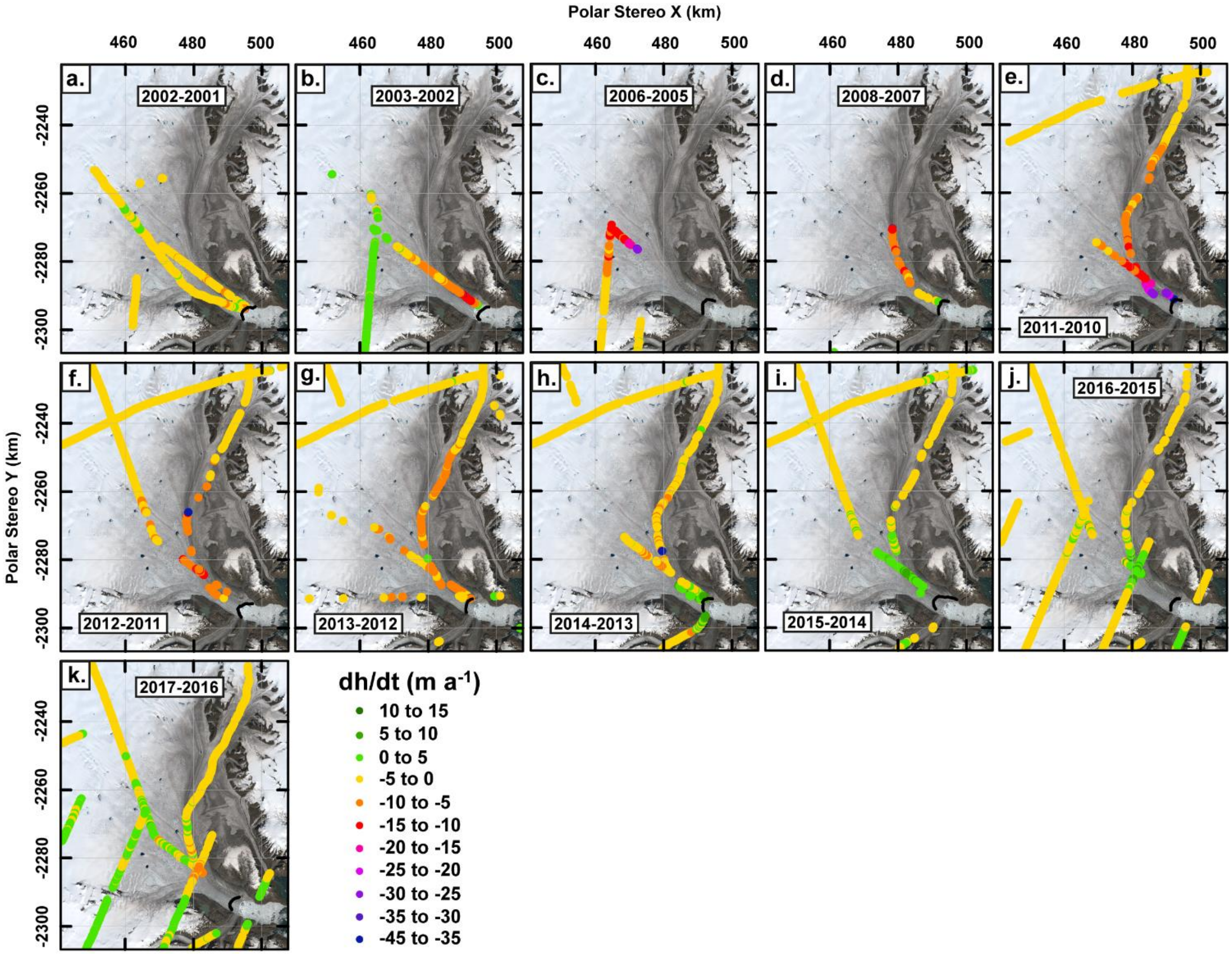

Figure 3: Annual elevation change for Kangerdlugssuaq between 2001 and 2017. Panels relate to surface elevation change for the time periods 2002-2001 (a), 2003-2002 (b) 2006-2005 (c), 2008-2007 (d), 2011-2010 (e), 2012-2011 (f), 2013-2012 (g), 2014-2013 (h), 2015-2014 (i), 2016-2015 (j), 2017-2016 (k). The most retreated terminus position for the given time period is demarcated in black.

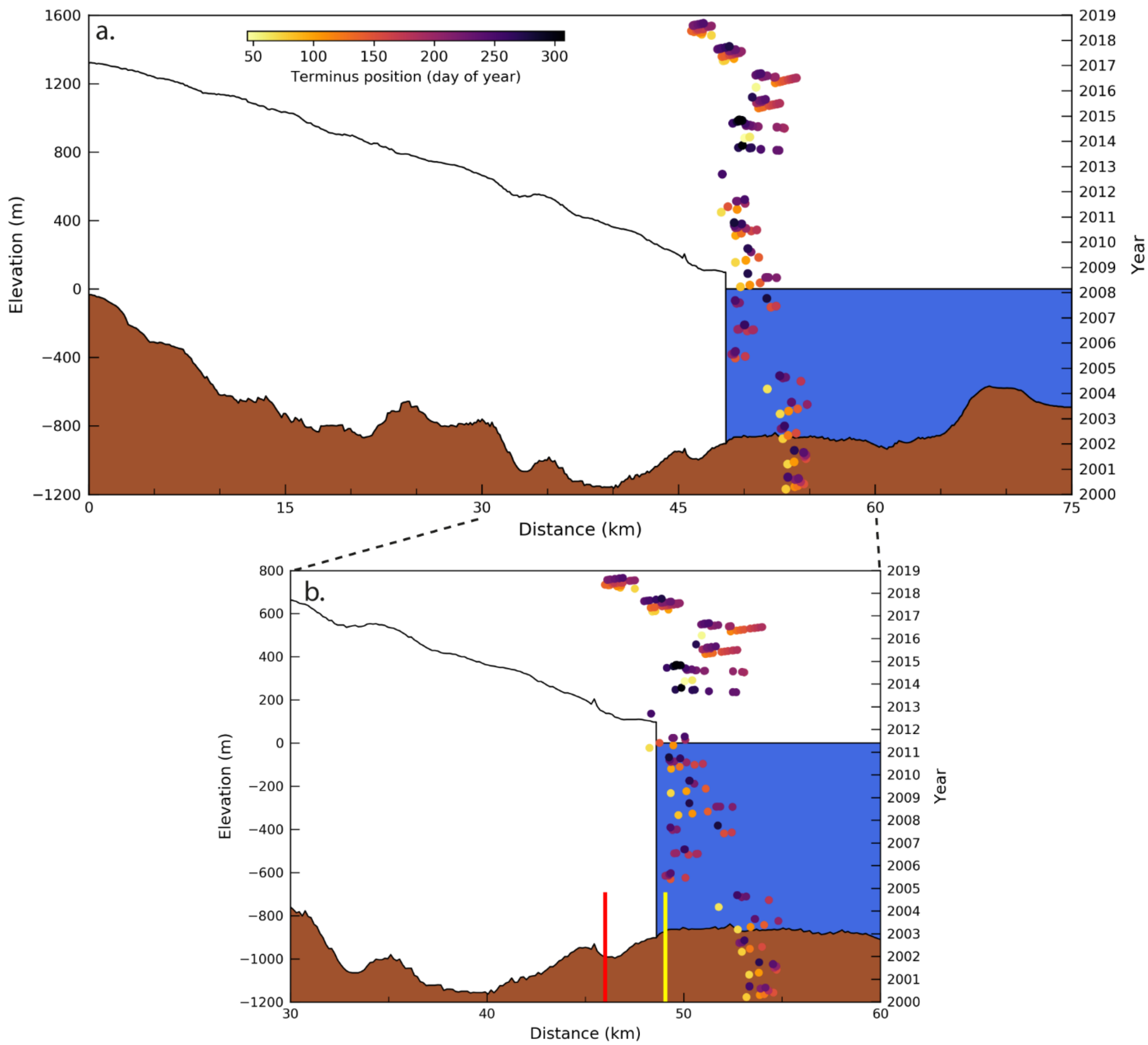

Figure 4: Bed and surface profiles of Kangerdlugssuaq along the centre line shown in Figure 1. (a) Bed and surface profiles overlain with terminus positions between 2000 and 2018. Terminus positions are coloured by day of year. (b) Near-terminus view of (a). The maximum retreat for the years 2005 (yellow) and 2018 (red) are indicated by vertical lines. Surface elevation data is obtained from the Greenland Ice Mapping Project (GIMP) surface digital elevation model, and has a nominal date of 2007 (Howat et al., 2014).