Warming of SE Greenland shelf waters in 2016 primes large glacier for runaway retreat

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Abstract. Kangerdluqssuaq Glacier in south-east Greenland has now retreated further inland than at any time in the past 33 years and is fast approaching a region of retrograde bedslope, meaning that continued rapid retreat is likely. Here we show that the current retreat was driven by anomalously warm surface water on the continental shelf during 2016. The warm surface water likely penetrated the fjord and weakened the mixture of sea ice and icebergs known as mélange, which is normally rigid

5   enough to inhibit calving in winter. As Kangerdlugssuaq Glacier continued to calve almost continuously throughout 2017 and 2018 it accelerated by 35% and thinned by 35 m.

1 Introduction

Since the early 1990s the Greenland Ice Sheet (GrIS) has been a major contributor to sea-level rise, losing a total of 2700±930 Gt of ice between 1992 and 2011 (Shepherd et al., 2012). About 40% of the 0.47±0.23 mm/year mean 1991–2015 sea-level rise

10   originating from Greenland was caused by increases in the rate at which glaciers calve ice into the oceans, and the remainder by increases in surface melt and run-off (van den Broeke et al., 2016). Kangerdlugssuaq Glacier (KG) is a large tidewater-terminating glacier in south-east Greenland (Fig. 1) which delivers around 24 Gt/year of ice to the ocean, equivalent to about 5% of GrIS total discharge (Enderlin et al., 2014). In 2004 the calving front of KG suddenly retreated by over 6 km, its surface flow speeds doubled (Luckman et al., 2006; Howat et al., 2005), and between 2003 and 2007 the glacier thinned by over 100 m

15   (Khan et al., 2014). The rapid retreat of KG was accompanied by a similar pattern of change in tens of other SE Greenland outlet glaciers and accounted for ∼16% of the total 2000–2005 net mass loss of the GrIS (Rignot and Kanagaratnam, 2006). KG thus typifies the response of Greenland outlet glaciers to climate forcing whilst being a significant specific source of sea level rise. After 2006, KG slowed down, although speeds remained at least 20% greater than pre-retreat values, and the ice front oscillated around a similar mean annual position, with seasonal advances and retreats of up to 6 km (Kehrl et al., 2017).

20   The synchronous retreat of south-east Greenland glaciers in the early 2000s suggested that atmospheric and/or ocean warming were responsible for initiating the rapid retreat, thinning and subsequent dynamic response (Howat et al., 2008; Hanna et al., 2009; Murray et al., 2010; Howat and Eddy, 2011; Christoffersen et al., 2011; Inall et al., 2014). Nevertheless, local differences in glacier geometry, fjord and shape, and connection to the ocean normally determine individual responses to changing environmental conditions (Moon et al., 2012; Enderlin et al., 2013; Millan et al., 2018). When KG retreated in 2004 it did so

into deeper water (Khan et al., 2014) — such a reverse or retrograde bed slope can set up a positive feedback between frontal retreat, ice discharge and dynamic thinning (Schoof, 2007). KG's retreat was halted in mid 2011 only when its grounding line once again reached shallower water. At that stage thinning had slowed, the final few km of the glacier was afloat (Khan et al., 2014; Kehrl et al., 2017), and there was a balance between advance of the calving front in winter and its retreat in summer.

5   KG calves into the head of a 75 km long, 5–10 km wide, fjord (Murray et al., 2010) (KF); the fjord has a wide mouth and is connected to the shelf break by a straight, deep, 300 km long trough (Dowdeswell et al., 2010; Inall et al., 2014). Much of the passage from ocean to glacier is 600–900 m deep with sills shallowing to 400–550 m at the fjord mouth and within the shelf trough (Fig. 1). The increase in mass loss from the SE GrIS ice to the ocean that began in the mid 1990s coincided with a warming of the North Atlantic Ocean (Straneo and Heimbach, 2013) and the relatively unimpeded connection of KG with

10   the ocean was shown to have allowed increasing ocean temperatures to trigger retreat in 2004 (Christoffersen et al., 2011; Inall et al., 2014; Jackson et al., 2014; Millan et al., 2018).

Here we show that Kangerdlugssuaq Glacier is currently retreated further upstream than at any point in the satellite record (33 years). We present direct evidence that recent retreat was triggered by the weakening of ice mélange in the fjord, a mechanism only previously shown by association (Moon et al., 2015). We demonstrate that the mélange weakening can be explained

15   by exceptionally warm surface waters originating from outside the fjord. The observed contemporaneous interannual thinning superimposed on the seasonal cycle of surface elevation change will leave the glacier vulnerable to basal melt and further rapid retreat.

2   Methodology and Data

2.1   Frontal positions

20   Glacier fronts were manually digitised on a variety of optical and synthetic aperture radar (SAR) satellite images. We located the intersection points of the digitised fronts with a series of parallel linear flowlines at 160 m spacing, and the frontal change was calculated by taking the mean of the changes in these intersection points (Luckman et al., 2015). From 1985–2012 the images include Landsat-5 (TM Band 4) and Landsat-7 (ETM+ Band 8), European Remote Sensing satellites (ERS-1 and ERS-2), and Envisat Advanced Synthetic Aperture Radar (ASAR) Image (IM) and Wideswath mode (WSM) data (Bevan et al.,

25   2012). From 2011–2018 we use TerraSAR-X SAR data, and additionally, from 2015–2018, Sentinel 1A and 1B Ground Range Detected High-resolution Interferometric Wideswath (GRDH, IW) images. Image spatial resolution ranges from 30 m for Landsat-5 to 8 m for the multi-looked TerraSAR-X data. All images were reprojected to the Polar Stereographic co-ordinate system before the fronts were digitised. Appendix Fig. A1 shows which observations derived from which satellite missions.

2.2   Surface velocities

30   Surface velocities were derived using feature tracking, see Bevan et al. (2012) for details of the early (1985–2012) part of the time series. After 2011 velocities are based on TerraSAR-X SAR and Sentinel 1A and 1B single-look complex (SLC) data
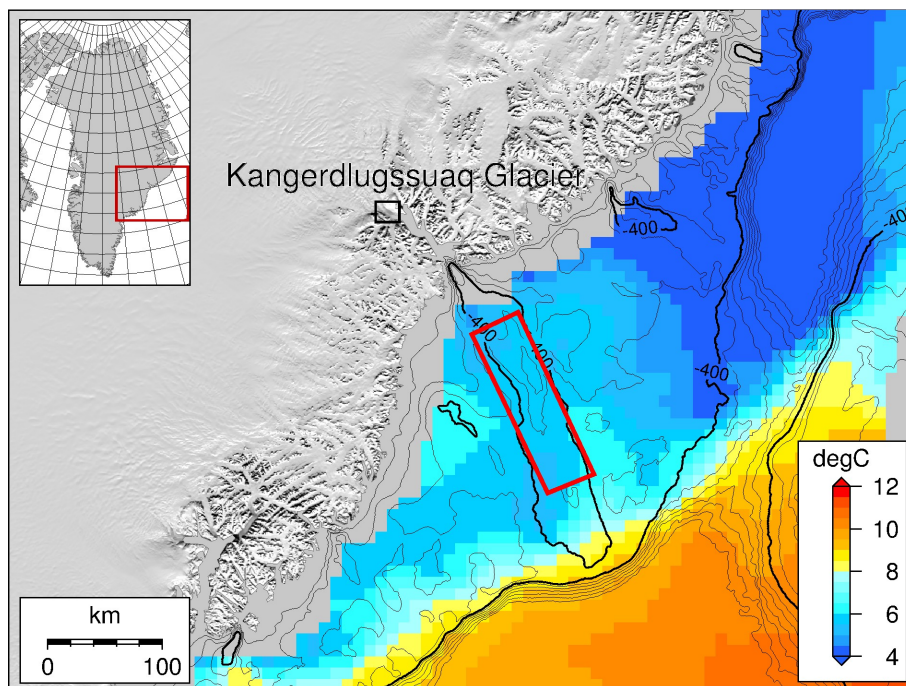
Figure 1. South-east Greenland with re-analysis 5 m ocean temperatures for July 2016. The bathymetric contours are in metres and are based on the International Bathymetric Chart of the Arctic Ocean Version 3 (Jakobsson et al., 2012). The small black box shows the Kangerdlugssuaq Glacier area covered by Fig. 6. The red box shows the area over which ocean temperatures were averaged for Figs 2 and 3.

using Gamma Remote Sensing software. Pairs of TerraSAR-X SLCs with 11 day time separation were tracked using a window spacing of 40 m and the results converted to ground range and geocoded using coincident interferometric DEMs (Section 2.4). Sentinel-1 pairs were tracked with pair delays of either 6 or 12 days, with a window spacing of 100 m and geocoded using the 90 m Greenland Icesheet Mapping Project (GIMP) DEM (Howat et al., 2014). Appendix Fig. A1 shows which velocity
5   measurements derived from which satellite missions.

2.3 Ocean temperatures

Ocean temperatures for 1991–2016 were extracted from Arctic Ocean Physics Reanalysis monthly mean data supplied by the Copernicus Marine Environment Monitoring Service (CMEMS). Temperatures for 2017–2018 were based on monthly means of the Arctic Ocean Analysis and Forecast Product (also supplied by CMEMS) which are available at daily intervals. Both the
10   reanalysis and the analysis/forecast products are based on a 3D physical ocean and sea-ice model that assimilates remotely sensed and in-situ data, and have a spatial resolution of 12.5 km, and 12 levels distributed unevenly between depths of 5 and 3000 m. We plot mean 5 m temperatures over the Kangerdlugssuaq Trough area. Temperatures from published Conductivity Temperature Depth (CTD) profiles are used to compare fjord temperatures in 2017 with earlier years.

2.4 Surface elevation

A time series of 150 digital Elevation Models (DEMs) from June 2011 to July 2018 were created using experimental SAR data from the TanDEM-X satellite system which comprises the TerraSAR-X and TerraSAR-X add on for Digital Elevation Measurement (TanDEM-X) satellites. We used Gamma Remote Sensing software to interfere, unwrap and geocode the bistatic
5   stripmap mode Co-registered Single look Slant range Complex images (CoSSCs). The images have a spatial resolution of ∼2 m; after the interferometry stage the DEMs were geocoded with a horizontal resolution of 8 m. We used the provided orbital vector data and the 30 m Greenland Icesheet Mapping Project (GIMP) DEM (Howat et al., 2014) to initially geolocate and phase scale the images; geolocation was iteratively improved using the interferometrically generated DEMs. The interferograms were unwrapped from a bare-rock location on the south side of the glacier (33.0365°W,68.5939°N), and the DEMs tied in the vertical
10 to this point using the GIMP DEM height (730 m). Only CoSSCs with satellite separations perpendicular to the look direction of less than 500 m were used; long baselines result in too many interference fringes which lead to unwrapping errors. This restriction meant that there were few DEMs created for 2015. Elevations are given relative to the WGS 84 reference ellipsoid. Orbit uncertainties (Krieger et al., 2013) mean that we cannot expect relative elevation accuracies better than 2 m. The standard deviation of DEM heights at a point on the opposite side of the fjord to the unwrapping start point was 2.3 m, indicating that
15 unwrapping errors were minimised even across the glacier. The accuracy of absolute height values depends on the accuracy of, and geolocation with respect to the GIMP DEM. The GIMP DEM in turn is quoted as having a vertical precision of between ±1.0 m over most ice areas and ±30 m over areas of high relief (Howat et al., 2014). We therefore estimate absolute errors of the order of ±10 m which is the root mean squared validation error of the GIMP DEM with respect to ICESat.

We used IceBridge BedMachine Greenland, Version 3 data (Morlighem et al., 2017) together with the hydrostatic assumption
20 to determine where the DEM is above flotation height. We used an ice density of 917 kg/m^3, and a sea-water density of 1023 kg/m^3. At the location of KG WGS84 datum is 55 m below the Geoid.

3 Results and Discussion

3.1 Interruption of normal winter advance in 2017 and 2018

Our long and detailed record of ice-front position shows that before the 2004 retreat and from 2005 to the end of 2016,
25 KG maintained a relatively stable mean-annual frontal position (Fig. 2). The clear seasonal variation in ice-front position is characterised by an advance of 2 to 6 km from January until July or August (which we will refer to simply as winter), with almost no calving events. During the second half of the year (summer) the front normally retreats in a similar steady manner. By contrast, in 2017 and 2018, the glacier continued to calve throughout both summer and winter, only advancing a fraction of the normal distance between the beginning of January and the end of July in 2017, and not at all in 2018 (Fig. 3a). This
30 lack of sustained winter advance has only occurred twice before in the observed record; in 1996, and in 2005 which marked the previous episode of retreat and thinning (Fig. 2). By the start of summer 2018 the ice front had retreated by 8 km relative to the start of summer 2016 and the anomalous winter calving continued into the summer months.
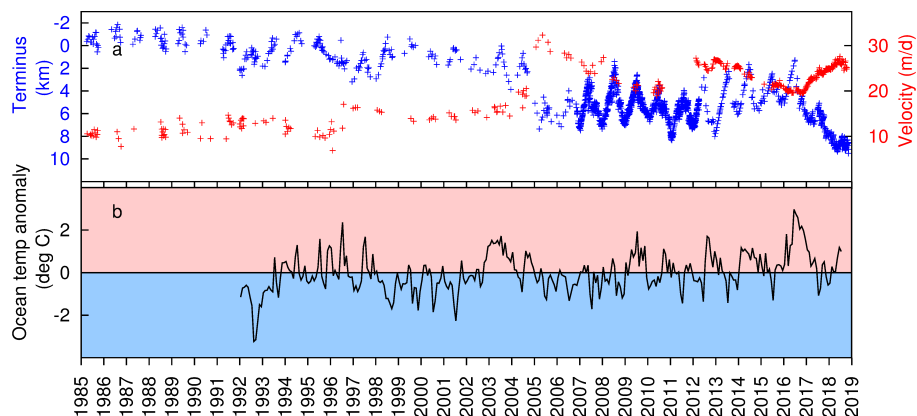
Figure 2. Time series of a) Kangerdlugssuaq Glacier front position and surface velocity. The y-axis distance scale for the front position matches the profile drawn in Fig. 6. Front positions and velocities are based on a variety of satellite images and the velocities were measured at the star marked in Fig. 6. See Appendix Fig. A1 for the key describing which instruments contributed which observations. b) Kangerdlugssuaq trough ocean potential temperature anomaly at 5 m averaged over the red box shown in Fig. 1.
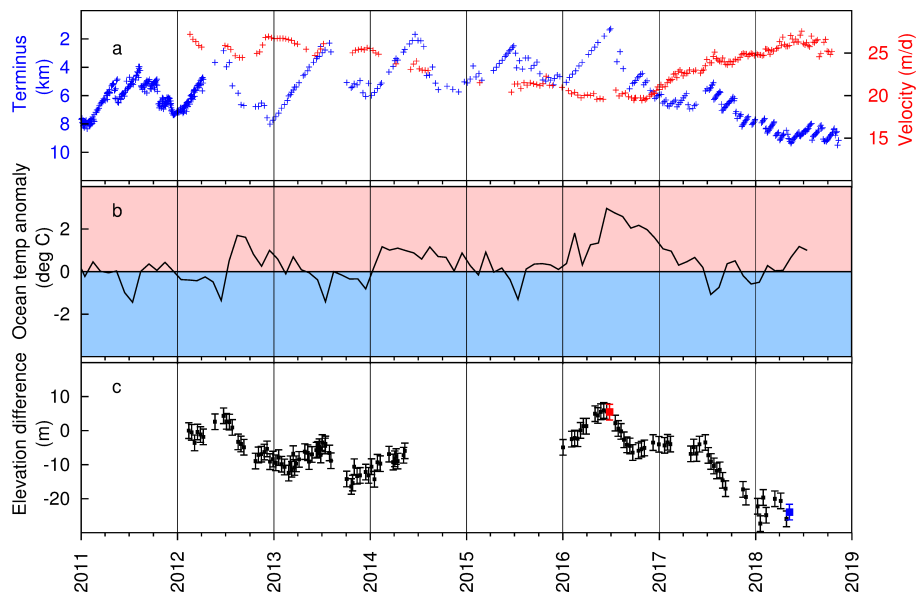
Figure 3. Time series of a) front position and surface velocity (note the change in front position and velocity scales compared with Fig. 2a), b) Kangerdlugssuaq trough ocean potential temperature anomaly at 5 m averaged over the red box shown in Fig. 1, and c) cross-glacier mean surface elevation difference taken from the TanDEM-X DEMs, the error bars represent the relative accuracy of ±2.3 m. The elevations are an average across the transect marked in Fig. 6, and the differences are relative to the first DEM.

The winter advance of KG coincides with the formation of a rigid mélange consisting of icebergs bound together with sea ice (Fig. 4, and Video 1). Although interstitial sea ice likely contributes little to mélange strength, it prevents iceberg dispersal

and thus encourages the transfer of backstress from the fjord sides to the glacier front via compressional stress bridges between adjacent icebergs (Burton et al., 2018). The mélange normally inhibits detachment of icebergs from the glacier front until sea ice melts and the mélange disperses with the onset of summer.

In contrast to previous years, in early 2017 and 2018, formation of a rigid mélange was repeatedly interrupted by episodes of break-up and dispersal. Close examination of a series of synthetic aperture radar (SAR) images from Sentinel 1 reveals that each mélange breakup episode commenced at the down-fjord end and propagated towards the glacier front, culminating in large calving events (Fig. 4, and Video 1). In consequence, the normal sustained advance during winter was punctuated by several periods of calving. This behaviour is similar to that usually experienced in the autumn and early winter, when rigid mélange repeatedly forms and breaks up. The failure of KG to advance in the winters of 2017 and 2018 thus reflects weakly bonded mélange and indicates that conditions in the fjord were not conducive to the formation of mélange at this time.

3.2 The role of ocean warming

The stability of ocean-terminating glaciers in Greenland has been linked to coastal sea surface temperatures (SSTs) (Howat et al., 2008; Bevan et al., 2012; Inall et al., 2014) and with changes in the seasonal formation of sea ice or fjord mélange (Joughin et al., 2008; Moon et al., 2015). The break-up of mélange is also directly correlated with coastal SSTs (Howat et al., 2010). In 2016 the surface waters on the SE Greenland continental shelf were exceptionally warm: by July and August 2016 potential temperatures at a depth of 5 m were up to 4°C warmer than the 1992–2018 mean (Appendix, Fig. A2) and the anomalies persisted into the first half of 2017 (Fig. 3b). The warming is linked to sea-ice retreat, regional air temperature and advection of water from the Atlantic Ocean (Derksen et al., 2016).

Observations from KF show that these seasonally heated surface waters (termed Polar Surface Water warm, PSWw) penetrate deep in to KF as a shallow tongue of warm water, becoming capped by a surface layer of cooler, fresher glacially modified waters towards the fjord head (Inall et al., 2014). This PSWw constitutes the warmest of the fjord water masses during the summer months, and accounts for ∼25% of ice melt within the fjord system (Inall et al., 2014). Critically, PSWw exists primarily at depths of <100 m, meaning that it is well situated to interfere with mélange formation. We therefore propose that the exceptionally warm surface waters on the shelf adjacent to KF during 2016 and early 2017 resulted in the presence of anomalously warm PSWw well within the fjord, sufficient to hinder rigid mélange formation and thus allow winter calving of KG. Although there were previously no direct observations, the possibility that anomalously warm PSWw could be responsible for episodes of retreat at KG has been hypothesised (Christoffersen et al., 2011): the authors noted that CTD data from inner KF showed PSWw at >2°C shortly prior to the major retreat of 2004, compared to <-1°C during a previous survey during the stable year of 1993. Similarly, warm anomalies were reported in PSWw (based on SSTs at the fjord mouth) in 2004 and 2010 (Inall et al., 2014), both years with unusual winter calving of KG. With the improved resolution and frequency of available remote sensing imagery, we are able to demonstrate that weakness in the mélange, following a year of exceptional SSTs, caused the reduced winter advance of KG.

A question remains as to the cause of the continued retreat during 2017/18, a year during which shelf surface waters were not observed to be anomalously warm. It is likely that the ongoing retreat is a dynamical consequence of the retreat commencing
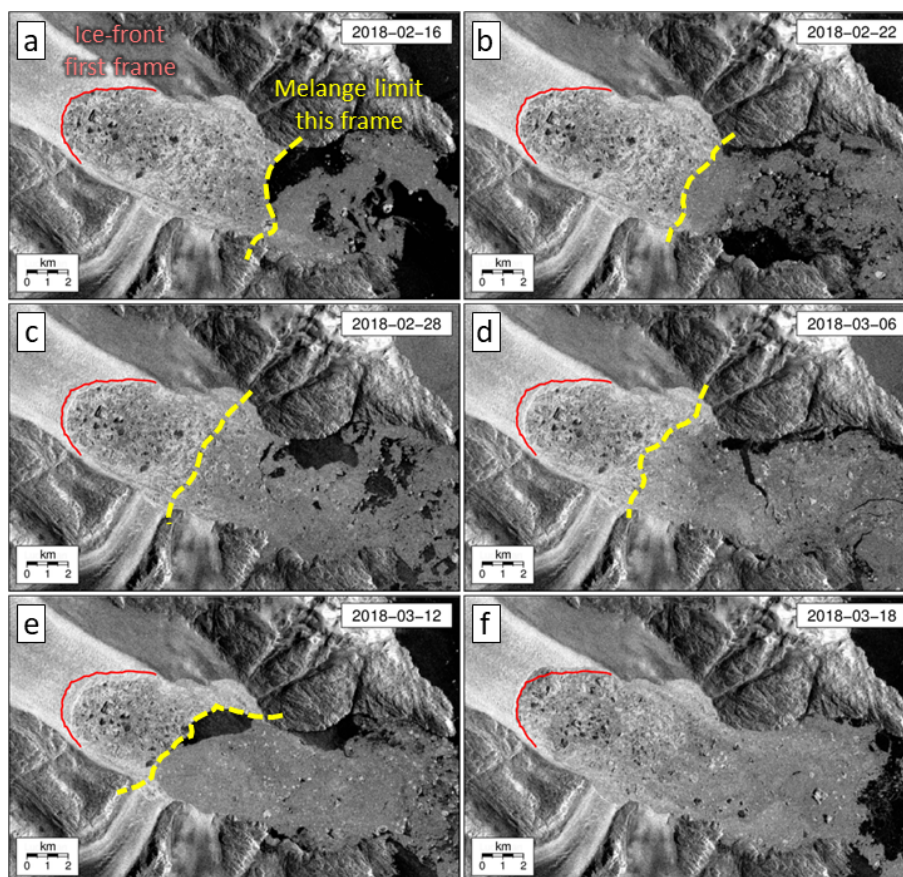
Figure 4. Sequence of Sentinel-1 SAR images of the Kangerdlugssuaq ice-front and fjord showing how the ice advances when mélange inhibits calving (panels a) to e)), then retreats again by calving because of loss or weakening of the mélange. The red line in each panel marks the ice-front position at the start of the sequence, and the yellow line marks the approximate extent of coherent mélange at each step. This behaviour is commonly seen in summer, but has recently also occurred in winter leading to ongoing glacier retreat.

in 2016/17, with the glacier entering a phase of self-sustaining instability (Joughin et al., 2008). Additional evidence may lie in CTD data from October 2017 (Fig. 5). Compared with all previous data from the inner fjord (representing 5 different years), these show unusually warm waters remaining in the upper part of the water column (particularly ∼50–100 m depth) in the early winter. Thus, while summer 2017 was not characterised by the same exceptional shelf SSTs as 2016, there may be sufficient latency in the system to allow water temperatures in the inner fjord to remain warmer than usual, and thus continue to interfere with mélange formation, in the winter of 2017/18.

a

b
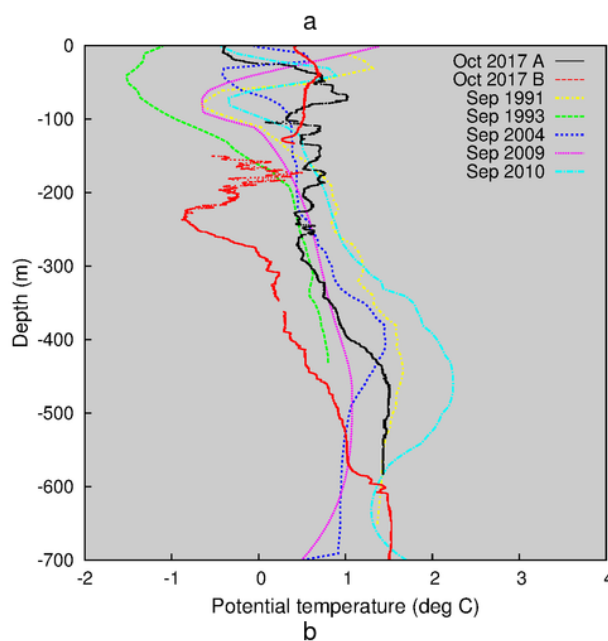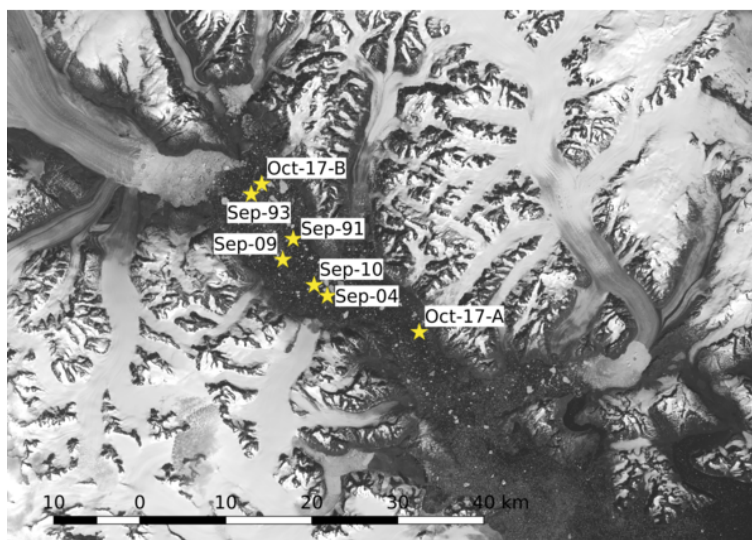
Figure 5. a) Location map (background Landsat Image 18/06/2016) and b) temperature profiles from published Conductivity Temperature Depth (CTD) data. September 1991 (Station K9, Andrews et al., 1994); September 1993 (Station KF3, Azetsu-Scott and Syvitski, 1999); September 2004 (Dowdeswell, 2004); September 2009 (Straneo et al., 2012); September 2010 (Inall et al., 2014); October 2017 A and B (OMG Mission, 2016).

3.3 Implications of further retreat

A decrease in surface elevations of outlet glaciers in the early 1990s was one of the first indications that the GrIS was losing mass via increased surface melt and dynamic thinning (Krabill et al., 2000; Krabill, 2004). Dynamic thinning is the result of acceleration when retreat and melt-driven thinning reduce resistive stresses at the glacier front. Seasonal cycles of dynamic

5 thinning have recently been observed on Helheim, another large tidewater glacier 300 km to the south of KG (Bevan et al., 2015), where they are associated with fluctuations in ice-front position (Kehrl et al., 2017).

We also see dynamic thinning on KG. The high temporal resolution time series of velocities for KG (Fig. 3a) shows a summer acceleration as the ice-front retreats and winter slowdown as it advances. Associated with this seasonal velocity pattern is a seasonal dynamic change in KG surface elevations; the glacier thins as it retreats and accelerates, and thickens as it advances

10 and slows (Figs. 3a and c).

At the start of 2017, when the normal winter advance faltered, velocities increased and the acceleration was sustained through to summer 2018, by which time KG was flowing 35% faster than two years earlier (Fig. 3a). During this period (June 2016 to May 2018) a thinning of 35 m, caused by the increase in velocity, is superimposed on the seasonal thinning (Figs. 3c and Fig. 7). Surface elevations relative to sea-level and an assumption of hydrostatic equilibrium indicate that in summer 2016 the

15 final 5 km of the glacier was floating; the velocity profile (Fig. 7, for 04/06/2014, when the glacier thickness and front location were similar to summer 2016) confirms this. The reduction in down-flow acceleration between kilometers 11 and 4 is consistent with transition to a floating tongue and loss of basal drag. By May 2018 (the last available DEM) most of this floating tongue has been lost and the ice front is left only 1 km ahead of the start of a section of reverse bed slope (Figs. 6 and 7).

The two-year retreat of KG to a point only a kilometre or so ahead of the reverse bedrock slope, and further up fjord than at

20 any point in the observation record, has placed the glacier in a precarious position. Continued dynamic thinning as it retreats and accelerates is likely to result in the ice front refloating when it will then be susceptible to basal melt and further thinning. KG may only stabilise where the prograde bed slope is reached some 6 km upstream.

4 Conclusions

We conclude that the retreat of KG in 2017 and 2018 was driven by anomalously warm water on the shelf in the latter half of

25 2016 which likely penetrated the fjord. Our observations reveal a weakened winter ice mélange in 2017 and 2018 that allowed sustained calving when the glacier would normally be advancing. KG is about to retreat into an upstream over-deepening which could result in further retreat and thinning via dynamics and basal melt.

Our research emphasises the importance of accounting for the delivery of heat into the fjords of Greenland by surface as well as deep water. Heat delivered by surface water can weaken the stabilizing influence of ice mélange proximal to ocean-

30 terminating glaciers, disrupting the seasonal calving pattern and triggering terminus retreat.
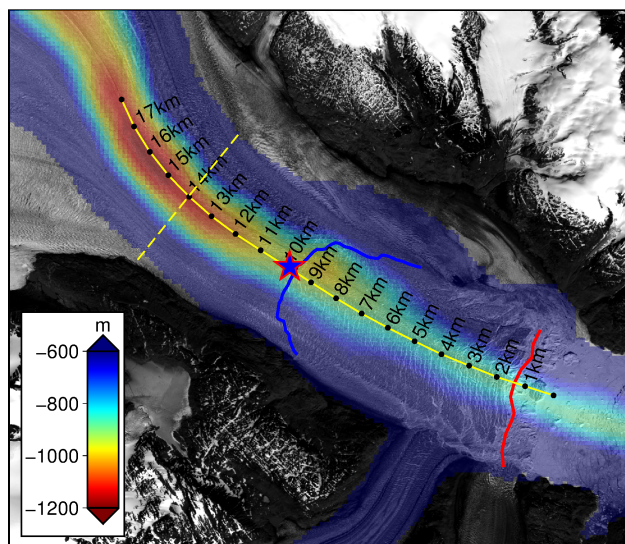
Figure 6. Glacier bed mapped using IceBridge BedMachine Greenland, Version 3 (Morlighem et al., 2017). The yellow profile and red and blue front positions relate to those drawn in Fig. 7. The dashed yellow transect marks indicates the line along which surface elevations were averaged for Fig. 3c. The star marks the velocity extraction location.
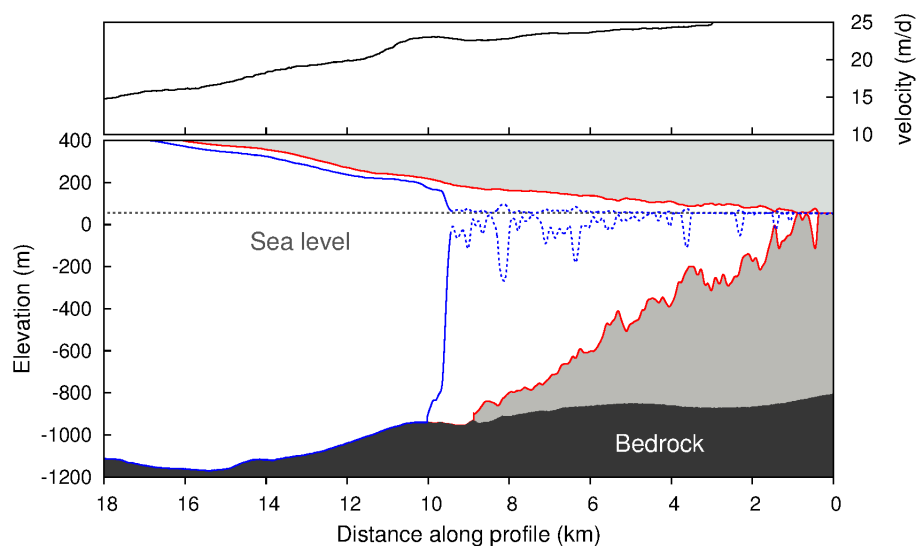
Figure 7. Surface elevation profiles for advanced (red, 26/06/2016) and retreated (blue, 09/05/2018) front positions, corresponding to the same colour points plotted in Fig. 3c. The surface velocity profile is the result of feature tracking TanDEM-X data from 29/05/2014 to 09/06/2014

Data availability. Timeseries data on frontal positions and surface velocities, surface DEMs and Video 1 will be made available at the Polar Data Centre.

Video supplement. Video 1 is an animation of Kangerdlugssuaq Glacier front and adjacent fjord composed of images from 14/06/2015 to 01/11/2018 based on Sentinel 1 synthetic aperture radar (SAR) data. The video may be found at:

geography.swan.ac.uk/luckman/kanger/kanger_movie.gif

Username: guest

5   Password: sw@nsea2018

Author contributions. The study was led and the manuscript drafted by Suzanne Bevan. Expert advice, data and contributions to the text and figures were supplied by Adrian Luckman (SAR imagery and glacier velocities), Douglas Benn and Joe Todd (interpretation of glacier calving and interaction with mélange), Tom Cowton (fjord processes). TanDEM-X DEMs were processed by Suzanne Bevan.

Competing interests. The authors declare that they have no competing interests.

10   *Acknowledgements.* The research under project CALISMO (Calving Laws for Ice Sheet Models) was funded by the Natural Environment Research Council (NERC) grants NE/P011365/1. TanDEM-X data used for generating the DEMs and for ice-front positions and glacier velocities were supplied by DLR, as part of NERC project NE/I00714811. Satellite imagery for front positions were supplied by European Space Agency (ERS-1 and -2, Envisat, Sentinel), the U.S. Geological Survey (Landsat). BedMachine data were obtained from NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: https://doi.org/10.5067/2CIX82HUV88Y. [16/01/2018].

15   **Appendix A**
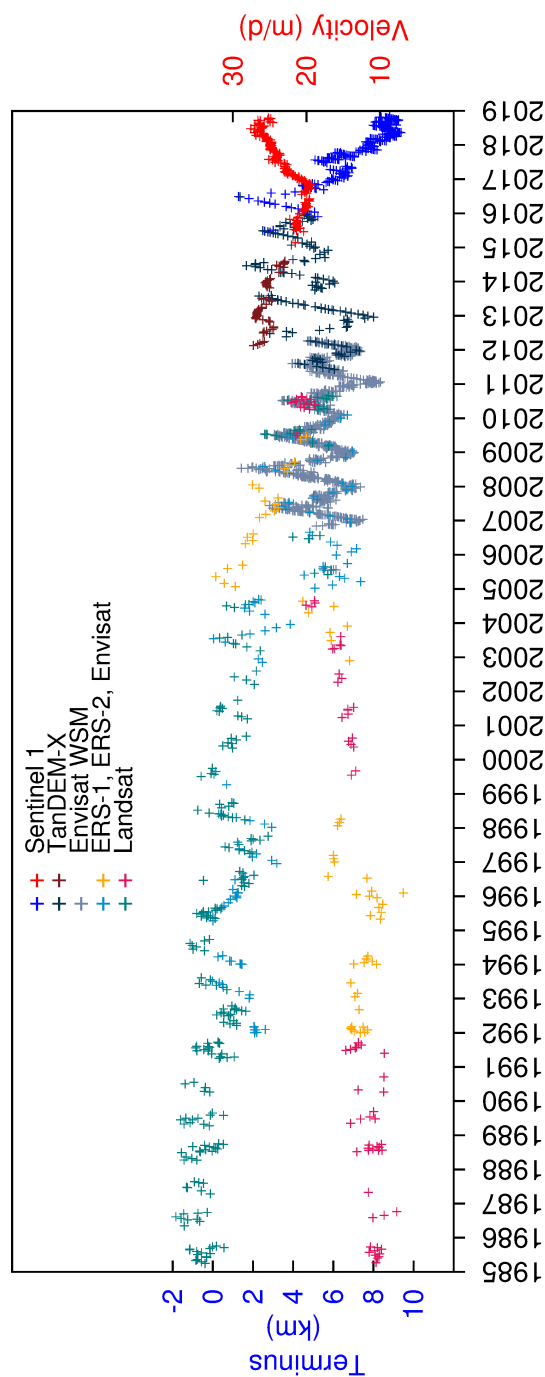
Figure A1. Time series of ice-front positions and velocity, with observations colour coded according to data source. Sentinel 1 includes 1A and 1B, TerraSAR-X refers to a single image from the TanDEM-X pair. Envisat WSM is Wideswath Mode data, European Remote Sensing satellites ERS-1 and ERS-2, and Envisat are Image Mode data, Landsat includes data from satellites 5, 7 and 8.
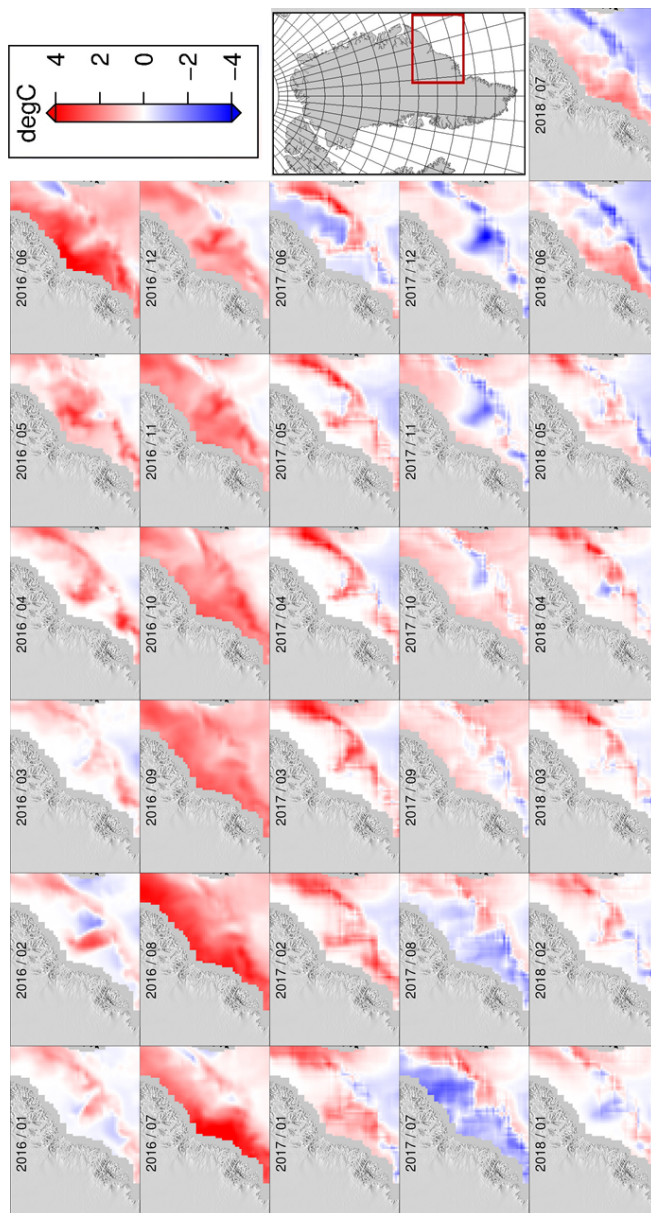
Figure A2. Anomalies in re-analysis 5 m ocean potential temperatures. Temperatures are monthly means of daily data and are from the Arctic Ocean Analysis and Forecast Product supplied by the Copernicus Marine Environment Monitoring Service. Anomalies are relative to the period 1992–2018.

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