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Glacier dynamics over the last quarter of a century at Helheim, Kangerdlugssuaq and 14 other major Greenland outlet glaciers

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Abstract

The Greenland ice sheet is experiencing increasing rates of mass loss, the majority of which results from changes in discharge from tidewater glaciers. Both atmospheric and ocean drivers have been implicated in these dynamic changes but understanding the nature of the response has been hampered by the lack of measurements of glacier flow rates predating the recent period of warming. Here, using Landsat-5 data from 1985 onwards, we extend back in time the record of surface velocities and ice-front position for 16 of Greenland's most significant glaciers, and compare these to more recent data from Landsat-7 and SAR. Climate re-analysis and sea-surface temperatures from 1982 show that since 1995 most of Greenland and its surrounding oceans have experienced significant overall warming, and a switch to a warming trend. During the earlier period of climate consistency, major tidewater outlet glaciers around Greenland, including Kangerdlugssuaq and Helheim, were dynamically stable. Since the mid-1990s, glacier discharge has consistently been both greater and more variable, adding weight to the hypothesis that dynamic change is a rapid response to climate forcing. Both air and ocean temperatures in this region are predicted to continue to warm, and will undoubtedly drive further change in outlet glacier discharge.

1 Introduction

Ice losses from the Greenland ice sheet (GrIS) have been detected from the early 1990s onwards in studies based on altimetry, gravity-field observations, and flux-balance comparisons (e.g., Pritchard et al., 2009; Schrama et al., 2011; van den Broeke et al., 2011). Low-elevation thinning (below 2000 m) has been observed since 1993/94 (Krabill et al., 1999, 2000; Thomas et al., 2006) and is now reaching all latitudes in Greenland, particularly along the southeast and northwest margins (Pritchard et al., 2009) with the percentage of thinning attributable to changing dynamics being far more significant for marine-terminating glaciers (Sole et al., 2008). Observations

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of gravity-field anomalies by the GRACE satellite system from 2002 confirm that the GrIS is losing mass (Velicogna and Wahr, 2005) and at an increasing rate (Chen et al., 2006; Wouters et al., 2008; Velicogna, 2009). Mass losses were greatest at low elevations (Luthcke et al., 2006) and appeared first in the southeast and later also in the northwest (Luthcke et al., 2006; Khan et al., 2010; Schrama and Wouters, 2011; Schrama et al., 2011).

Mass balance estimates based on flux-balance agree to within 15 % of most GRACE-based estimates for the period from 2003 to 2008 (van den Broeke et al., 2009). The balance has been consistently negative since 1999 (van den Broeke et al., 2011) owing to negative trends in surface mass balance (SMB) (Wake et al., 2009; Hanna et al., 2011) combined with increases in discharge (Rignot et al., 2011). Three major tidewater glaciers experienced large and rapid increases in flow speed: first, Jakobshavn Isbrae in the west, beginning in 1998 (Joughin et al., 2004; Luckman and Murray, 2005), and then in the southeast Helheim in 2002, and Kangerdlugssuaq in 2004 (Howat et al., 2005; Luckman et al., 2006). The latter pair have since decelerated (Howat et al., 2007; Murray et al., 2010) but their behaviour meant that in the southeast discharge dominated the balance signal, whereas in the northwest the losses were equally distributed between surface processes and ice discharge (van den Broeke et al., 2009).

This range of studies has pointed to ice loss concentrated on the marine-terminating outlet glaciers of the southeast and west margins of the ice sheet with changing glacier dynamics playing a key role. The precise mechanisms controlling the response of the outlet glaciers have yet to be fully identified but all emerging hypotheses invoke a response to increasing atmospheric and/or ocean temperatures resulting in a break-up and retreat of a floating tongue or grounded ice front. The various hypotheses include increased hydrofracturing and calving due to surface meltwater (Benn et al., 2007; Nick et al., 2009; Andersen et al., 2010), reductions in the strength and extent of ice mélange in the fjord (Amundson et al., 2010; Seale et al., 2011), weakening of the ice in the lateral shear margins of the floating tongue (van der Veen et al., 2011), and increased submarine melt rates (Holland et al., 2008; Nick et al., 2009; Rignot et al., 2010; Straneo et al., 2011). Any increased submarine melt rates are likely to be the result of fjord-water circulation changes controlled by meltwater plumes (Motyka et al., 2003; Rignot et al., 2010; Motyka et al., 2011), the degree of fjord-water stratification, or external factors such as offshore wind events and changes in coastal currents (Murray et al., 2010; Straneo et al., 2010, 2011; Christoffersen et al., 2011). Once thinning and retreat are underway, changing force-balance conditions at the terminus allow upstream glacier acceleration and thinning (Joughin et al., 2004; Howat et al., 2005; Nick et al., 2009).

The proposed connection between thinning, retreat and acceleration allows changing tidewater glacier frontal positions to be used as an indicator or predictor of glacier instability. Surveys based on satellite images show that glaciers in the southeast and west were generally stable between 1972 and 1985 (Howat and Eddy, 2011) with regionally consistent patterns of retreat beginning in 1992 (Moon and Joughin, 2008; Murray et al., 2010; McFadden et al., 2011; Seale et al., 2011). In the southeast the glaciers retreated at an increasing rate until 2005/06 when a general advance was established (Moon and Joughin, 2008; Murray et al., 2010; Seale et al., 2011). In the northwest nearly all marine-terminating outlet glaciers showed retreat and thinning at some point between 2000 and 2009 (McFadden et al., 2011); tidewater glaciers north of 69° N in the east showed no retreat from 2000 (Seale et al., 2011). In contrast, land-terminating glaciers have remained stable since 1992 (Moon and Joughin, 2008).

Throughout this period of observed changes in the mass balance of the GrIS, air temperatures for Greenland have been increasing (Hanna et al., 2008; Box et al., 2009) with mean summer temperatures now being positively correlated with Northern Hemisphere warming (Hanna et al., 2008), although they have yet to "catch up" (Box et al., 2009). Prior to the early 1990s, from 1961 onwards, Southern Greenland summer air temperatures were significantly inversely correlated with the North Atlantic Oscillation (NAO) which was then in a positive mode (Hanna and Cappelen, 2003) implying regional atmospheric circulation patterns were insulating Greenland from northern hemispheric warming.

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As well as being coincident with increases in air temperature, the acceleration and retreats of major tidewater glaciers in the east and west show a strong correspondence with warming of adjacent sea-surface temperatures (SSTs) (Hanna et al., 2009) and the subsequent deceleration of the Kangerdlugssuaq and Helheim glaciers with cooling of coastal surface water (Murray et al., 2010). The mechanisms underlying the correlation between SSTs and ice loss are likely to include the effect on surface melt of warm air advected from the over the ocean. This process is dependent on atmospheric circulation patterns and SSTs, and was thought to have been significant particularly for West Greenland during the high melt year of 2007 when anomalously high SSTs coincided with strong southerly airflow (Hanna et al., 2009). In certain locations SSTs may also be considered a reasonable proxy for ocean temperatures down to sill depths and hence relevant to submarine melting; Hanna et al. (2009) found this to be the case for SSTs off the coast of Western Greenland away from the marginal ice zone by comparison with two 1950–2007 ocean-depth sections. Andresen et al. (2012) also used SSTs as a proxy for subsurface Atlantic Water for a region south of Iceland where they claim Atlantic Water extends to the surface.

Like air temperatures, sea surface, subsurface and deeper ocean temperatures around Greenland are also modulated by oscillations in regional atmospheric circulation patterns such as the NAO (Holland et al., 2008) and teleconnections with SSTs as indexed by the Atlantic Multi-decadal Oscillation (AMO) (Sutton and Hodson, 2005). For example, since 1995–1996 the NAO has moved into a phase that allows warm subpolar waters to move westward around the southern tip of Greenland to the West Greenland continental shelf (Holland et al., 2008). Similarly, the AMO began a warm phase in the mid 1990s meaning that warm SSTs were more likely off the southeast and west coasts of Greenland (Sutton and Hodson, 2005).

The evidence discussed above supports theories that the tidewater-terminating outlet glaciers of the GrIS are responsible for a major part of the recent mass loss and that they respond rapidly and dynamically to changes in air and surrounding ocean temperatures. Constructing a record of changes in glacier dynamics with sufficient spatial extent and temporal resolution to reveal this type of rapid and region-wide response to atmosphere and ocean conditions relies on air- or satellite-borne instrument systems. To date, most glacier surface velocity measurements have been based only on data collected since the launch of ERS-1 in 1992. By coincidence this limitation barely predates the start of the recent period of increasing air and ocean temperatures around Greenland.

In this paper we investigate the extent and magnitude of the air and ocean temperature changes leading up to and during the period of ice loss and test the evidence for a response by extending observations of flow speeds and terminus positions back to 1985 for 16 major glaciers around Greenland (Fig. 1), including Kangerdlugssuaq, Helheim and Jakobshavn Isbrae. In total, these glaciers drain about 25 % of the GrIS and the measurements extend the time series back 7 yr before most published measurements, to a period when both air temperatures and SSTs were more stable.

2 Data and methods

Tidewater glaciers are now believed to respond rapidly to climate change in ways not dominated by SMB therefore we expect to see a contrast in their behaviour as Greenland climate moved from a relatively stable period during the 1980s and early 1990s to the more recent years of temperature increases. We test this hypothesis by first examining the spatial and temporal characteristics of the climate over a 30 yr time span using re-analysis air and remotely sensed sea surface temperatures. We then use feature-tracking techniques and manual digitisation of frontal positions on over 2000 satellite images covering the period from 1985 to 2011 to thoroughly sample outlet glacier behaviour around the ice sheet over the same time period.

Using both air and sea temperatures and a good spatial distribution of glaciers around the ice sheet we aim to gain some insight as to whether air or ocean temperatures are the dominant control on outlet glacier dynamics. A high number of coincident retrievals of speed and ice-front position also allows us to determine the strength of

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the relationship between retreat and acceleration by calculating for each glacier the statistical correlation between the two parameters.

2.1 Air and sea surface temperatures

Gridded time series of monthly- and summer-mean air and sea surface temperatures covering Greenland and surrounding ocean were analysed for the period 1982–2010. ERA-Interim monthly mean 2 m air temperature data, at a spatial resolution of 1.5°, were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF). The SSTs are based on Optimum Interpolation 1/4 Degree Daily Sea Surface Temperature Analysis (OISST), AVHRR-only data from the US National Climatic Data Center (Reynolds et al., 2007). Both sets of data were reprojected to a Polar Stereographic co-ordinate system.

Following suggestions that the switching of the NAO from a positive to a neutral state in the mid 1990s allowed Greenland temperatures to reflect Northern Hemisphere warming (Hanna et al., 2008), trend lines were fitted to the summer-mean temperature grids, using a linear least squares regression, for the two periods 1982 to 1995, and 1995 to 2010. In addition, total period summer means were calculated and the earlier period subtracted from the later.

2.2 Flow speeds and frontal positions

Time series of surface velocities and frontal positions were measured for 16 tidewater outlet glaciers in total. The sample avoided known surge-type glaciers and, where possible, included the largest glaciers discharging all sectors of the ice sheet. For the chosen glaciers as many pairs as possible of high spatial resolution satellite images of all types were analysed within the restrictions imposed by archive contents and cloud cover.

The velocities were measured by applying intensity feature tracking between pairs of optical (Landsat-5 TM Band 4 and Landsat-7 ETM+ Band 8) and Synthetic Aperture

Radar (ERS-1, ERS-2 and Envisat (Advanced) SAR (ASAR)) images (Scambos et al., 1992; Lucchitta et al., 1995; Strozzi et al., 2002; Luckman et al., 2003; Pritchard et al., 2005). The optical pairs were separated by either 16 or 32 d and, before tracking, were resampled from 30 m to 20 m (TM) and from 15 m to 10 m (ETM+) and reprojected to the Polar Stereographic co-ordinate system. The SAR pairs were multi-looked at 1 × 5 to a ground pixel size of approximately 20 m and tracked in slant-range and azimuth geometry over 35 d. A spatial sampling for tracking was selected such that velocity fields were produced at a pixel spacing of 40 m for all image types. Geocoding of Landsat-5 velocity fields was improved by coregistering the first image of the pair to a Landsat-7 image from the same track, and SAR image displacements were converted from slant-range and azimuth to surface-parallel using orbit data and the ASTER global DEM. The final velocity fields were then filtered with respect to expected downslope flow direction (Luckman et al., 2006).

The errors associated with determination of surface velocity using feature tracking include random errors associated with measuring the two-dimensional displacement of surface features, and systematic errors associated with reprojection and geolocation. Coregistration of patches with a precision of 1/10th (Gray et al., 2001) to 1/20th (Strozzi et al., 2002) of a pixel is possible, hence the errors associated with determining the displacements are, in the worst case, $\approx 0.2\,\mathrm{m\,d^{-1}}$ for tracking of Landsat 5 images over 16 d, and less for the other image pairs. Errors introduced during subsequent processing can be estimated by measuring the mean displacement over a stationary point close to the front of the glacier being tracked. Bevan et al. (2012) found the mean displacement at such points was $0.28\,\mathrm{m\,d^{-1}}$ for Landsat-5 images, $0.09\,\mathrm{m\,d^{-1}}$ for Landsat-7 images, and $0.22\,\mathrm{m\,d^{-1}}$ for SAR images. Combining the above errors as independent error sources results in a maximum estimated error of $0.34\,\mathrm{m\,d^{-1}}$.

Ice-front positions were manually digitised on each Landsat and SAR image including those unsuitable for feature tracking. The intersection points of the digitised fronts with a centreline profile were used as single-point indicators of ice-front position. Errors in ice-front location can arise as a result of geolocation error and also depend on the

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precision with which the fronts are digitised, which depends on image type and resolution. Bevan et al. (2012) found accuracies of ± 49 m for SAR images, and ± 76 m for Landsat-5 images, Landsat-7 images are likely to be more accurate.

2.3 Basin outlines

Catchment boundaries were delineated by tracing flowlines upstream from the glacier terminus following the method of Costa-Cabral and Burges (1994) (see Fig. 1). Flow directions were derived from smoothed fields of gravitational driving stress (GDS) (Le Brocq et al., 2006). The gravitational driving stresses were based on a digital elevation model and an ice thickness grid of 5 km resolution (Bamber et al., 2001). The GDS fields were computed at 1 km resolution and linearly smoothed over a distance equivalent to 20 times the ice thickness. The selection of start points at the glacier terminus was restricted to locations covered by the DEM and guided by visual inspection of the ice margins and velocity distribution.

3 Results

3.1 Air and sea surface temperatures

The analyses of SSTs and re-analysis air temperatures show that the mean summer temperatures during the 1996–2010 period were warmer everywhere than in 1985–1995, apart from in the far north (Fig. 2). Over land, southern and coastal temperatures showed the greatest warming. Coastal SSTs showed little warming except in the northwest even though offshore SSTs were significantly higher in the later period.

Between 1985 and 1995 no significant trends in air or sea surface temperatures were detected other than increases over a small patch of ocean between Southeast Greenland and Iceland, and over the far northwest of Greenland (Fig. 3a). Between 1995 and 2010, however, linear increases in summer SST and air temperatures were widespread and significant (Fig. 3b). Trends in SST of up to 0.5 °C yr^{-1} occur off the

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west coast between 70 and 75° N. The northwestern limit of SST warming is the northern tip of the Nares Strait (Fig. 1), where water at 300 m depth was also found to have warmed significantly during the period 2003–2009 (Münchow et al., 2011).

An exception to the widespread increases in SST is over the southeast and southern coastal shelf where there is either cooling or no significant warming (Fig. 2). This region coincides with the location of the East Greenland Current (EGC), a surface current which flows south along the shelf break and exports fresh cold Polar Surface Water from the Arctic (Nilsson et al., 2008). The East Greenland Coastal Current (EGCC) which flows closer to shore south from the Denmark Strait (Fig. 1) also occupies this coastal region. Interannual variability in the composition of the EGC/EGCC is high; increases in the freshwater component in the late 1990s were attributed to increased Greenland glacial runoff, and in 2005 to an increase in sea ice meltwater resulting from a peak in sea-ice export through the Fram Strait (Cox et al., 2010), an increase in freshwater which may explain the cooling and/or lack of warming in surface waters on the shelf compared with further offshore.

3.2 Frontal positions and velocities

Time series of flow speeds and frontal positions are discussed in the following subsections, starting with Kangerdlugssuaq and other glaciers in the southeast and working clockwise around the ice sheet. In each case, flow speeds near the front were picked from the feature-tracking data at a location which maximised the number of possible retrievals through the observation period; the locations are marked on the velocity maps in Fig. 1.

3.2.1 Southeastern glaciers

This sector has experienced significant and accelerating mass loss over the last decade, although rates of mass loss are now declining (Schrama et al., 2011), and many outlet glaciers have accelerated and retreated (Walsh et al., 2012).

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Kangerdlugssuaq and Helheim glaciers have attracted the most attention because they account for a substantial portion of the regional mass loss (Howat et al., 2011) and were among the first to have been observed to have undergone change (Luckman et al., 2006) and subsequent stabilisation (Murray et al., 2010). Here (Fig. 4) we extend the published record of flow speeds back in time by all data points prior to 1992, that is 6 yr for Kangerdlugssuaq and 7 yr for Helheim. The temporal extent and sampling of ice-front positions is also an improvement on the published record.

Although some interannual variability is in evidence, the 25 yr record of surface speed and ice-front position (Fig. 4) reaffirms that the speed-ups in the mid-2000s were exceptional in the satellite record and were similar in timing and magnitude despite the 300 km separation between glaciers. Prior to retreat and acceleration Helheim is shown to be stable for at least 16 yr. Similarly, Kangerdlugssuaq is known to have been flowing at similar speeds in 1966, 1988 and 1995/96 (Csatho et al., 1999; Thomas et al., 2000), and our data confirm the stability between 1985 and 1996.

The ice-front and speed records also exhibit two major differences between this pair of glaciers (Fig. 4). First, there is a contrast in the timing of the response to the mid-2000's event. Helheim seems to begin its period of retreat and speed-up from 2002, a response which accelerated to a maximum in 2005, while Kangerdlugssuaq underwent a simple step-change between 2004 and 2005. Second, bearing in mind that the temporal sampling in some years is poor, the seasonal fluctuation in ice-front position is generally more pronounced for Kangerdlugssuaq than for Helheim. Kangerdlugssuaq's ice-front is normally seen to advance to a maximum in the middle of the calendar year, and retreat to a minimum at the end of December or in early January. There are only two exceptions to this pattern in the long-term record, the first in 1995/96 coincided with an increase in speed of about 6 $\mathrm{m\,d^{-1}}$, and the second in 2004/05 which coincided with the well known larger speed-up. In these two cases the atypical behaviour is characterised by an unusually long phase of retreat into February or March and an increase in surface speed which was much more pronounced in the 2004/05 event than in the earlier one (1995/96) (Fig. 4).

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The Ikertivaq glaciers A to E are a series of outlet glaciers draining the catchment immediately south of Helheim and are labelled north to south. Only outlet D shows no sign of the acceleration between 2000 and 2005 (Fig. 5) characteristic of the southeast region (Rignot and Kanagaratnam, 2006; Howat et al., 2008). Between 1986 and 2000 none of the 5 outlets show any signs of significant flow change other than that which could be attributed to seasonal velocity variations. All except B exhibit intra-annual changes in frontal position of the order of 1 km, and after 2000 A, C and E begin retreats of 1.5 to 2 km over a period of 8 yr coincident with acceleration, with only E appearing to have stabilised by 2011.

Gyldenlove glacier is one of three glaciers discharging into a single fjord; one other discharges at a similar rate, the other is less active. From 1985 until 1998 flow speeds show intra-annual variability of $\pm 1\,\mathrm{m\,d^{-1}}$, but no overall change. There is a 2.6 km advance and retreat in ice front during 1985, and again in 1989 to 1990, the front then remains at a more retreated position for the remainder of the record. From 1998 onwards this glacier appears to follow a typical southeastern outlet glacier cycle of acceleration and retreat followed by deceleration from 2004, although with no sign of a readvance (Fig. 5).

3.2.2 Western glaciers

Measurements of flow speed and frontal position for Jakobshavn Isbrae are presented for a point 1.4 km behind the most retreated frontal position (Fig. 1). Measurements for various locations on this glacier have been published for most of this time series (Joughin et al., 2004; Luckman and Murray, 2005; Joughin et al., 2008; Motyka et al., 2011; Howat et al., 2011), new data here are limited to the 1989, 1992 and 2011 data points (Fig. 6).

Flowing at over $25\,\mathrm{m\,d^{-1}}$ Jakobshavn Isbrae was the fastest flowing outlet glacier of the GrIS in 2011, and drains about 5 % of the ice sheet. After retreating from its 1850 Little Ice Age maximum extent, with periods of rapid thinning between 1902 and 1913 and between 1930 and 1959 (Csatho et al., 2008), it remained stable and in equilibrium until 1997 (Joughin et al., 2008; Motyka et al., 2011), even thickening sporadically between 1993 and 1998 (Thomas et al., 2003). In 1998 Jakobshavn Isbrae began a multi-year period of retreat and acceleration (Joughin et al., 2004; Rignot and Kanagaratnam, 2006; Motyka et al., 2011), during which time speeds near the front doubled and the ice shelf disintegrated. Between 2000 and 2010, 321 ± 12 Gt of ice mass were lost (Howat et al., 2011). Seasonal velocity variations over the first 30 km upstream of the grounding line have been detected only since 1995 (Luckman and Murray, 2005) and appear to be driven by fluctuations in ice-front position rather than by seasonal melt input (Joughin et al., 2008). The amplitude of these oscillations increased from an initial 10 % to almost 50 % by 2009 (Howat et al., 2011). Seasonal fluctuations in ice-front position of 5–10 km are not uncommon.

Joughin et al. (2004) reported a slowdown of the order of 15 % in mean velocity between 1985 and 1992, followed by stable flow speeds until 1997. We see no evidence of a slowdown over this period, including a measurement made in 1989, and suggest that the results of Joughin et al. (2004) may have been a result of sampling seasonal variations (Luckman and Murray, 2005). The 1985 measurement related to July and the 1992 speed was a temporal average based on feature-tracking of five SAR pairs. The glacier now appears to be recovering from maximum flow speeds reached in 2009 and 2010, and in 2011 has slowed by approximately 5 m d^{-1} and the front has begun to stabilise. This slowdown is unexpected; rapid velocity increases have been predicted until 2015 on the basis of continued thinning in conjunction with retreat of the grounding line over a bed that deepens further inland (Thomas et al., 2011).

Rink Isbrae, Ingia Isbrae and Umiamako (Fig. 1) are located in a region where, between 2000 and 2009, coincident periods of retreat, thinning and acceleration were common but not in a manner that was synchronous between glaciers (McFadden et al., 2011).

Rink Isbrae is the southern most of this set of glaciers and exhibits a strong seasonal variation in frontal position and speed, with retreat correlated with speed (Howat et al., 2010). Unusually for the region it displayed no overall speed-up between 2000 and

2005 (Rignot and Kanagaratnam, 2006; Joughin et al., 2010), and no speed up or surface elevation change between 2000 and 2009 (McFadden et al., 2011). Allowing for reported seasonal speed variations of up to 25 % (Howat et al., 2010) it can be seen that the speed is also stable between 1985 and 2002 (Fig. 6). Frontal positions show some interannual change greater than the previously reported ± 500 m seasonal variation, with an overall retreat in mean position of about 1 km over 25 yr.

Further north, Umiamako also shows stable speeds and frontal positions from 1985 (Fig. 6) until the dramatic retreat beginning around 2003 and acceleration from 2005 reported by McFadden et al. (2011). From 2008 the glacier begins to slow but does not readvance, and in 2011 still flows faster than pre-retreat speeds.

Ingia Isbrae (Fig. 6) follows a similar pattern to Umiamako, no significant change in front or speed until retreat and a more gradual acceleration beginning at the same time as Umiamako (Howat et al., 2010) but with no sign of stabilization by 2011.

Kong Oscar glacier (Fig. 1) was reported to have sped-up by 12 % between 1996 and 2000 and then to have then remained stable until 2005 (Rignot and Kanagaratnam, 2006). McFadden et al. (2011) report that it thinned by 15 m between 2000 and 2009, and retreated by more than 1 km. However, as can be seen from Fig. 7, speeds remain remarkably constant between 1985 and 2006. Prior to 2002 the ice front was approximately 5–10 km beyond the mouth of the fjord but messy and difficult to digitise precisely. From 2002 the front retreated 3 km over the next 5 yr and McFadden et al. (2011) report that it thinned by 15 m during this period. After 2008 the ice front becomes stable with signs of a readvance by 2010.

3.2.3 Northern glaciers

The northern sector of the GrIS, including the Petermann and Nioghalvfjerdsbrae glaciers, was thinning along the coast in the periods 1994–1999 (Krabill et al., 2000) and 1997–2003 (Krabill et al., 2004), and glacier fronts and grounding lines were retreating between 1992 and 1996 (Rignot et al., 2001). Although it was speculated that the change must be dynamic in origin, little change in flow speeds were detected on

Petermann at intervals between 1991 and 2005/06 (Joughin et al., 1999, 2010) and a small deceleration was reported on Nioghalvfjerdsbrae 1996 to 2000 and 2000 to 2005 (Rignot and Kanagaratnam, 2006). Allowing for seasonal variations, the time series (Fig. 7) suggests that Petermann glacier flow speeds were stable from 1985 until 2011, despite a major calving event in 2011 (Nick et al., 2012), although the highest velocities are in the most recent years. The Nioghalvfjerdsbrae decelerations (Rignot and Kanagaratnam, 2006) are not apparent in our time series in Fig. 7, although we have no data between 1999 and 2005 inclusive; speeds have evidently recovered by 2006 and are as fast as in they were in the late 1990s.

Positions presented here for Petermann add to the long time series presented by Falkner et al. (2011) dating back to 1876, and Johannessen et al. (2011) from 1953. An analysis of Nioghalvfjerdsbrae frontal positions is not included as the complex shape of the calving zone and the almost permanent fjord ice make it difficult to confidently identify the ice front.

Lastly, Daugaard Jensen glacier drains an estimated 4 % of the Greenland ice sheet, has a short floating tongue of approximately 6 km, and discharges into the northwest corner of the Scoresby Sund fjord system in East Greenland. Daugaard Jensen glacier is included with the northern glaciers as it is known to be exhibiting unusual stability (Rignot et al., 2004; Stearns et al., 2005; Bevan et al., 2012) more akin to the northern glaciers than the southeastern glaciers. Our 1985 to 2011 record of flow speeds and frontal positions for this glacier (Fig. 7) repeat those presented in Bevan et al. (2012) and are included here to allow comparison with other glaciers. The record shows that Daugaard Jensen has maintained stable flow speeds and frontal position throughout the period 1985–2010; current velocities and ice-front position match those of 1968 (Stearns et al., 2005).

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4 Discussion

Flow speeds for all glaciers shown were stable throughout the early part of the 25 yr time series of measurements. The stability is also clearly apparent in ice-front positions after allowing for the seasonal advance and retreat pattern common to many glaciers. For a number of glaciers the summer advance is not detected every year, for example Helheim, and Ikertivaq C, D and E. On Gyldenlove an advance occurs only in 1985 and in 1989 to 1990, and not again for the remainder of the record.

This 10 yr period of stability in ice-front and speed greatly emphasises the exceptional subsequent behaviour of those glaciers which experience and respond to changes in climate. During the following 15 yr, as detected in many other studies, tidewater glaciers in the southeast and west both accelerated and retreated. The exceptions observed here are Rink Isbrae in the west which does not seem to accelerate and retreats only slightly, and a range of behaviours within the Ikertivaq outlets in the southeast. Both the Ikertivaq outlets and Rink Isbrae are exposed to the same temperature regimes as other glaciers in the immediate vicinity which do experience retreat, and we presume unknown features in bed geometry may be stabilising these outlets. We also note that Kong Oscar exhibits similar behaviour to Ingia Isbrae, Umiamako and Jakobshavn Isbrae in terms of frontal retreat/loss of floating tongue; but unusually there is no detectable impact here on flow speeds. Prior to 2002 Kong Oscar ice front existed as a semi-coherent 5–10 km floating tongue extending beyond the coast as a conglomeration of partly connected tablular icebergs. By 2002 the front retreated to a well defined, presumably grounded, linear ice-front, and calved much narrower icebergs. The lack of acceleration was presumably because the loss did not affect the stress balance as the ice removed was not bounded by fjord walls as noted by McFadden et al. (2011).

Elsewhere, glaciers exhibiting no signs of instability during the later period are Petermann glacier and Nioghalvfjerdsbrae in the north and Daugaard Jensen in the east. The first two both experience major calving events on timescales of decades (Reeh et al., 2001; Falkner et al., 2011; Johannessen et al., 2011), but there is no evidence of these events having any lasting effect on flow speeds on Petermann (Nick et al., 2012). Daugaard Jensen has remained stable in spite of observed thinning (Pritchard et al., 2009; Bevan et al., 2012) and mass losses for the region (Wouters et al., 2008; Schrama and Wouters, 2011).

The time series (Figs. 4 to 7) show that, for a subset of glaciers analysed, the later part of the period for which we have velocities is characterised by an increase in the variability of the flow speeds, as well as the well publicised speed ups. In order to measure the strength of this increase a Levene test (Levene, 1960) was chosen to test the null hypothesis that the variances before and after 1995 are equal, as it does not require the underlying data to be normally distributed. All speed measurements were included apart from those based on SAR tracking, as these are measurable all year round and would have disproportionately emphasised the seasonal signal in the later time period. The p-values for the null hypothesis are listed in Table 1, with those less than or equal to 0.10 in bold, and it should be noted that temporal sampling is variable between glaciers. For glaciers in the southeast and west the variance in speed increased significantly after 1995. This finding could be the result of an increase in the amplitude of the seasonal signal (e.g., Umiamako, (Howat et al., 2010)), of change occurring over a multi-annual timescale (e.g., Helheim), or a combination of these causes.

The increase in flow-speed variance after 1995 for most western glaciers coincides with increases in both nearby summer-mean air and sea surface temperatures. In the southeast, local air temperatures were increasing but SSTs adjacent to the coast were not. Noting that SSTs here may not be representative of temperatures at depth due to the surface currents, it may be more appropriate to consider the warming SSTs over the Irminger Sea as an indicator of the subsurface waters controlling submarine melt of the glacier fronts in this region (Straneo et al., 2010; Murray et al., 2010; Andresen et al., 2012).

In contrast, the stable northern glaciers of Petermann and Nioghalvfjerdsbrae, with high p-values, are in contact with the ocean in regions where SSTs have cooled extensively, even offshore. Daugaard Jensen has also remained remarkably stable in spite of its more southerly location and increased summer air temperatures (Fig. 2). This stability may be a reflection of the fjord bathymetry or remoteness from the ocean hindering warm water access to the front, or due to the restricted latitudinal extent of recent changes in North Atlantic circulation. These circulation changes are thought to be bringing warm subtropical waters to the Irminger Sea and onto the continental shelf of Southeast Greenland (Seale et al., 2011; Walsh et al., 2012).

In order to test the strength of the relationship between ice-front position and speed we calculated the Pearson's correlation coefficient between the two. The correlations are inverse and significant at the 99 % level for all glaciers tested except for Ikertivaq C, Petermann and Daugaard Jensen which are significant at 95 % (Table 1). The correlations indicate either an interdependence between retreat and acceleration, consistent with the idea that a loss of resistive stress through ice-front retreat causes speed-up, or a mutual response to an external forcing. Glaciers with a less significant or weaker correlation either show little change in either parameter such as Daugaard Jensen, or show advances or retreats in frontal position not accompanied by velocity changes, such as Petermann and Gyldenlove. On Petermann it has been shown that resistive stresses near the terminus region are too small relative to the driving forces to have a significant effect on flow speed (Nick et al., 2012). By analogy with Petermann, we propose that the ice-front advances and retreats on Gyldenlove, and on Kong Oscar (where there were insufficient velocity measurements to derive a correlation coefficient), were also a result of the formation or loss of all or part of a floating tongue.

5 Conclusions

From 1985 to 1995, during a climatically stable period of the twentieth century for Greenland, Kangerdlugssuaq, Helheim, Jakobshavn Isbrae and 13 other major tidewater glaciers around the ice sheet maintained constant flow speeds and ice-front positions. Following this period, during 1995 to 2010, there were then widespread increasing trends in summer-mean air and sea surface temperatures; the later period was warmer on average in the summer than the earlier period everywhere except in the far north. During the later period there was a significant increase in the variance of flow speed for many glaciers, caused mostly by multi-year accelerations as, for example, on Kangerdlugssuaq, Helheim and Jakobshavn Isbrae glaciers. In some instances the increase in variance was due to an increase in seasonal flow variability (e.g., Umiamako glacier) and sometimes a combination of this and multi-year accelerations. All glaciers showing a significant increase in flow-speed variance also showed a strong linear correlation between retreat and acceleration.

The major exceptions to these responses were Kong Oscar, Petermann, Nioghalvfjerdsbrae and Daugaard Jensen glaciers which showed neither acceleration nor increase in seasonality. These glaciers were either not in a region of combined atmospheric and oceanic warming (Petermann and Nioghalvfjerdsbrae), or had a geometry such that retreat probably did not alter the stress balance at the ice front (Kong Oscar), or were remote from ocean warming influences even though atmospheric temperatures over land were increasing (Daugaard Jensen).

The data presented here support the concept that under conditions of increasing atmospheric and/or oceanic temperatures, the loss of floating tongues or retreat of grounded ice-fronts changes the balance of forces at the termini of tidewater glaciers resulting in rapid glacier acceleration and thinning. The mechanism allows a rapid response to climate change, with individual fjord and bed geometries mediating that response. On the basis of the data studied here, heat delivery by the oceans is a prerequisite for acceleration and retreat of tidewater glaciers, but we cannot rule out the requirement for concomitant increases in air temperature. With annual average temperatures for Greenland predicted to warm by in excess of 3 °C by 2100 (Gregory et al., 2004), and subsurface (200–500 m depth) oceans surrounding the ice sheet predicted to warm by 1.7–2.0 °C over the same period (Yin et al., 2011) – a figure twice the global mean value – acceleration and retreat of Greenland's tidewater glaciers is highly likely to continue whilst they remain in contact with the ocean.

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References

Amundson, J. M., Fahnestock, M., Truffer, M., Brown, J., Lüthi, M. P., and Motyka, R. J.: Ice mélange dynamics and implications for terminus stability, Jakobshavn Isbræ, Greenland, J. Geophys. Res., 115, F01005, doi:10.1029/2009JF001405, 2010. 1639

Andersen, M. L., Larsen, T. B., Nettles, M., Elosegui, P., van As, D., Hamilton, G. S., Stearns, L. A., Davis, J. L., Ahlstrøm, A. P., de Juan, J., Ekström, G., Stenseng, L., Khan, S. A., Forsberg, R., and Dahl-Jensen, D.: Spatial and temporal melt variability at Helheim Glacier, East Greenland, and its effect on ice dynamics, J. Geophys. Res., 115, F04041, doi:10.1029/2010JF001760, 2010. 1639

Andresen, C. S., Straneo, F., Ribergaard, M. H., Bjork, A. A., Andersen, T. J., Kuijpers, A., Norgaard-Pedersen, N., Kjaer, K. H., Schjoth, F., Weckstrom, K., and Ahlstrom, A. P.: Rapid response of Helheim Glacier in Greenland to climate variability over the past century, Nat. Geosci., 5, 37–41, doi:10.1038/ngeo1349, 2012. 1641, 1653

Bamber, J. L., Layberry, R. L., and Gogineni, S. P.: A new ice thickness and bed data set for the Greenland Ice Sheet 1. Measurement, data reduction, and errors, J. Geophys. Res., 106, 33773–33780, doi:10.1029/2001JD900054, 2001. 1645

Benn, D. I., Warren, C. R., and Mottram, R. H.: Calving processes and the dynamics of calving glaciers, Earth-Science Rev., 82, 143–179, doi:10.1016/j.earscirev.2007.02.002, 2007. 1639

Bevan, S. L., Murray, T., Luckman, A. J., Hanna, E., and Huybrechts, P.: Stable dynamics in a Greenland tidewater glacier over 26 years despite reported thinning, Ann. Glaciol., 53, accepted, 2012. 1644, 1645, 1651, 1653

Box, J. E., Yang, L., Bromwich, D. H., and Bai, L.-S.: Greenland Ice Sheet surface air temperature variability: 1840–2007, J. Climate, 22, 4029–4049, doi:10.1175/2009JCLI2816.1, 2009. 1640

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Chen, J. L., Wilson, C. R., and Tapley, B. D.: Satellite gravity measurements confirm accelerated melting of Greenland Ice Sheet, Science, 313, 1958–1960, doi:10.1126/science.1129007, 2006. 1639

Christoffersen, P., Mugford, R. I., Heywood, K. J., Joughin, I., Dowdeswell, J. A., Syvitski, J. P. M., Luckman, A., and Benham, T. J.: Warming of waters in an East Greenland fjord prior to glacier retreat: mechanisms and connection to large-scale atmospheric conditions, The Cryosphere, 5, 701–714, doi:10.5194/tc-5-701-2011, 2011. 1640

Costa-Cabral, M. C. and Burges, S. J.: Digital elevation model networks (DEMON): a model of flow over hillslopes for computation of contributing and disperal areas, Water Resour. Res., 30, 1681–1692, 1994. 1645

Cox, K. A., Stanford, J. D., McVicar, A. J., Rohling, E. J., Heywood, K. J., Bacon, S., Bolshaw, M., Dodd, P. A., la Rosa, D., and Wilkinson, D.: Interannual variability of Arctic sea ice export into the East Greenland Current, J. Geophys. Res., 115, C12063, doi:10.1029/2010JC006227, 2010. 1646

Csatho, B., Schenk, T., van der Veen, C. J., and Krabill, W. B.: Intermittent thinning of Jakobshavn Isbrae, West Greenland, since the Little Ice Age, J. Glaciol., 54, 131–144, doi:10.3189/002214308784409035, 2008. 1648

Csatho, B. M., Bolzan, J. F., van der Veen, C. J., Schenk, A. F., and Lee, D. C.: Surface velocities of a Greenland outlet glacier from high-resolution visible satellite imagery, Polar Geography, 23, 71–82, 1999. 1647

Falkner, K. K., Melling, H., Münchow, A. M., Box, J. E., Wohlleben, T., Johnson, H. L., Gudmandsen, P., Samelson, R., Copland, L., Steffen, K., Rignot, E., and Higgins, A. K.: Context for the recent massive Petermann Glacier calving event, EOS T. Am. Geophys. Un., 92, 117–124, doi:10.1029/2011EO140001, 2011. 1651, 1652

Gray, A. L., Short, N., Mattar, K. E., and Jezek, K. C.: Velocities and flux of the Filchner ice shelf and its tributaries determined from speckle tracking interferometry, Can. J. Remote Sens., 27, 193–206, 2001. 1644

Gregory, J. M., Huybrechts, P., and Raper, S. C. B.: Climatology: threatened loss of the Greenland ice-sheet, Nature, 428, 616, doi:10.1038/428616a, 2004. 1655

Hanna, E. and Cappelen, J.: Recent cooling in coastal Southern Greenland and relation with the North Atlantic Oscillation, Geophys. Res. Lett., 30, 1132, doi:10.1029/2002GL015797, 2003. 1640

Hanna, E., Huybrechts, P., Steffen, K., Cappelen, J., Huff, R., Shuman, C., Irvine-Fynn, T., Wise, S., and Griffiths, M.: Increased runoff from melt from the Greenland Ice Sheet: a response to global warming, J. Climate, 21, 331–341, doi:10.1175/2007JCLI1964.1, 2008. 1640, 1643
Hanna, E., Cappelen, J., Fettweis, X., Huybrechts, P., Luckman, A., and Ribergaard, M. H.: Hydrologic response of the Greenland Ice Sheet: the role of oceanographic warming, Hydrol. Process., 23, 7–30, doi:10.1002/hyp.7090, 2009. 1641
Hanna, E., Huybrechts, P., Cappelen, J., Steffen, K., Bales, R. C., Burgess, E., McConnell, J. R., Steffensen, J. P., van den Broeke, M., Wake, L., Bigg, G., Griffiths, M., and Savas, D.: Greenland Ice Sheet surface mass balance 1870 to 2010 based on twentieth century reanalysis, and links with global climate forcing, J. Geophys. Res., 116, D24121, doi:10.1029/2011JD016387, 2011. 1639
Holland, D. M., Thomas, R. H., de Young, B., Ribergaard, M. H., and Lyberth, B.: Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters, Nat. Geosci., 1, 659–664, doi:10.1038/ngeo316, 2008. 1639, 1641
Howat, I. M., Joughin, I., Tulaczyk, S., and Gogineni, S.: Rapid retreat and acceleration of Helheim Glacier, East Greenland, Geophys. Res. Lett., 32, L22502, doi:10.1029/2005GL024737, 2005. 1639, 1640
Howat, I. M., Joughin, I., and Scambos, T. A.: Rapid changes in ice discharge from Greenland outlet glaciers, Science, 315, 1559–1561, doi:10.1126/science.1138478, 2007. 1639
Howat, I. M., Joughin, I., Fahnestock, M., Smith, B. E., and Scambos, T. A.: Synchronous retreat and acceleration of Southeast Greenland outlet glaciers 2000–06: ice dynamics and coupling to climate, J. Glaciol., 54, 646–660, doi:10.3189/002214308786570908, 2008. 1648
Howat, I. M., Box, J. E., Ahn, Y., Herrington, A., and McFadden, E. M.: Seasonal variability in the dynamics of marine-terminating outlet glaciers in Greenland, J. Glaciol., 56, 601–613, doi:10.3189/002214310793146232, 2010. 1649, 1650, 1653
Howat, I. M. and Eddy, A.: Multi-decadal retreat of Greenland's marine-terminating glaciers, J. Glaciol., 57, 389–396, doi:10.3189/002214311796905631, 2011. 1640
Howat, I. M., Ahn, Y., Joughin, I., van den Broeke, M. R., Lenaerts, J. T. M., and Smith, B.: Mass balance of Greenland's three largest outlet glaciers, 2000–2010, Geophys. Res. Lett., 38, L12501, doi:10.1029/2011GL047565, 2011. 1647, 1648, 1649
Jakobsson, M., Macnab, R., Mayer, L., Anderson, R., Edwards, M., Hatzky, J., Schenke, H. W., and Johnson, P.: An improved bathymetric portrayal of the Arctic Ocean: implications for

ocean modeling and geological, geophysical and oceanographic analyses, Geophys. Res. Lett., 35, L07602, doi:10.1029/2008GL033520, 2008. 1666

Johannessen, O. M., Babiker, M., and Miles, M. W.: Petermann Glacier, North Greenland: massive calving in 2010 and the past half century, The Cryosphere Discuss., 5, 169–181, doi:10.5194/tcd-5-169-2011, 2011. 1651, 1652

Joughin, I., Abdalati, W., and Fahnestock, M.: Large fluctuations in speed on Greenland's Jakobshavn Isbrae glacier, Nature, 432, 608–610, 2004. 1639, 1640, 1648, 1649

Joughin, I., Howat, I. M., Fahnestock, M., Smith, B., Krabill, W., Alley, R. B., Stern, H., and Truffer, M.: Continued evolution of Jakobshavn Isbrae following its rapid speedup, J. Geophys. Res., 113, F04006, doi:10.1029/2008JF001023, 2008. 1648, 1649

Joughin, I., Smith, B. E., Howat, I. M., Scambos, T., and Moon, T.: Greenland flow variability from ice-sheet-wide velocity mapping, J. Glaciol., 56, 415–430, doi:10.3189/002214310792447734, 2010. 1650, 1651

Joughin, I. R., Fahnestock, M. A., Kwok, R., Gogineni, P., and Allen, C.: Ice flow of Humboldt, Petermann and Ryder Gletscher, Northern Greenland, J. Glaciol., 45, 231–241, 1999. 1651

Khan, S. A., Wahr, J., Bevis, M., Velicogna, I., and Kendrick, E.: Spread of ice mass loss into Northwest Greenland observed by GRACE and GPS, Geophys. Res. Lett., 37, L06501, doi:10.1029/2010GL042460, 2010. 1639

Krabill, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., and Yungel, J.: Rapid thinning of parts of the Southern Greenland Ice Sheet, Science, 283, 1522–1524, doi:10.1126/science.283.5407.1522, 1999. 1638

Krabill, W., Abdalati, W., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., Wright, W., and Yungel, J.: Greenland Ice Sheet: high-elevation balance and peripheral thinning, Science, 289, 428–430, 2000. 1638, 1650

Krabill, W., Hanna, E., Huybrechts, P., Abdalati, W., Cappelen, J., Csatho, B., Frederick, E., Manizade, S., Martin, C., Sonntag, J., Swift, R., Thomas, R., and Yungel, J.: Greenland Ice Sheet: increased coastal thinning, Geophys. Res. Lett., 31, L24402, doi:10.1029/2004GL021533, 2004. 1650

Le Brocq, A. M., Payne, A. J., and Siegert, M. J.: West Antarctic balance calculations: impact of flux-routing algorithm, smoothing algorithm and topography, Comput. Geosci., 32, 1780–1795, doi:10.1016/j.cageo.2006.05.003+, 2006. 1645

Levene, H.: Robust tests for equality of variances, in: Contributions to Probability and Statistics: Essays in Honor of Harold Hotelling, edited by: I. Olkin, S. G. Ghurye, W. Hoeffding and W. G. Madow, Stanford University Press, Stanford, Calif., 278–292, 1960. 1653

Lucchitta, B. K., Rosanova, C. E., and Mullins, K. F.: Velocities of Pine Island Glacier, West Antarctica, from ERS-1 SAR images, Ann. Glaciol., 21, 277–283, 1995. 1644

Luckman, A. and Murray, T.: Seasonal variations in velocity before retreat of Jakobshavn Isbrae, Greenland, Geophys. Res. Lett., 32, L08501, doi:10.1029/2005GL022519, 2005. 1639, 1648, 1649

Luckman, A., Murray, T., Jiskoot, H., Pritchard, H., and Strozzi, T.: ERS SAR feature-tracking measurement of outlet glacier velocities on a regional scale in East Greenland, Ann. Glaciol., 36, 129–134, doi:10.3189/172756403781816428, 2003. 1644

Luckman, A., Murray, T., de Lange, R., and Hanna, E.: Rapid and synchronous ice-dynamic changes in East Greenland, Geophys. Res. Lett., 33, L03503, doi:10.1029/2005GL025428, 2006. 1639, 1644, 1647

Luthcke, S. B., Zwally, H. J., Abdalati, W., Rowlands, D. D., Ray, R. D., Nerem, R. S., Lemoine, F. G., McCarthy, J. J., and Chinn, D. S.: Recent Greenland ice mass loss by drainage system from satellite gravity observations, Science, 314, 1286–1289, doi:10.1126/science.1130776, 2006. 1639

McFadden, E. M., Howat, I. M., Joughin, I., Smith, B. E., and Ahn, Y.: Changes in the dynamics of marine terminating outlet glaciers in West Greenland (2000–2009), J. Geophys. Res., 116, F02022, doi:10.1029/2010JF001757, 2011. 1640, 1649, 1650, 1652

Moon, T. and Joughin, I.: Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007, J. Geophys. Res., 113, F02022, doi:10.1029/2007JF000927, 2008. 1640

Motyka, R. J., Hunter, L., Echelmeyer, K. A., and Connor, C.: Submarine melting at the terminus of a temperate tidewater glacier, LeConte Glacier, Alaska, USA, Ann. Glaciol., 36, 57–65, doi:10.3189/172756403781816374, 2003. 1640

Motyka, R. J., Truffer, M., Fahnestock, M., Mortensen, J., Rysgaard, S., and Howat, I.: Submarine melting of the 1985 Jakobshavn Isbræ floating tongue and the triggering of the current retreat, J. Geophys. Res., 116, F01007, doi:10.1029/2009JF001632, 2011. 1640, 1648, 1649

Münchow, A., Falkner, K. K., Melling, H., Rabe, B., and Johnson, H. L.: Ocean warming of Nares Strait bottom waters off Northwest Greenland, 2003–2009, Oceanography, 24, 114–123, 2011. 1646

Murray, T., Scharrer, K., James, T. D., Dye, S. R., Hanna, E., Booth, A. D., Selmes, N., Luckman, A., Hughes, A. L. C., Cook, S., and Huybrechts, P.: Ocean regulation hypothesis for glacier dynamics in Southeast Greenland and implications for ice sheet mass changes, J. Geophys. Res., 115, F03026, doi:10.1029/2009JF001522, 2010. 1639, 1640, 1641, 1647, 1653

Nick, F. M., Vieli, A., Howat, I. M., and Joughin, I.: Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus, Nat. Geosci., 2, 110–114, doi:10.1038/ngeo394, 2009. 1639, 1640

Nick, F. M., Luckman, A., Vieli, A., der Veen, V., van As, D., de Wal, V., Pattyn, F., Hubbard, and Floricioiu, D.: The response of Petermann Glacier, Greenland, to large calving events, and its future stability in the context of atmospheric and oceanic warming, J. Glaciol., 58, 229–239, doi:10.3189/2012JoG11J242, 2012. 1651, 1653, 1654

Nilsson, J., Björk, G., Rudels, B., Winsor, P., and Torres, D.: Liquid freshwater transport and polar surface water characteristics in the East Greenland current during the AO-02 Oden expedition, Prog. Oceanogr., 78, 45–57, doi:10.1016/j.pocean.2007.06.002, 2008. 1646

Pritchard, H., Murray, T., Luckman, A., Strozzi, T., and Barr, S.: Glacier surge dynamics of Sortebræ, East Greenland, from synthetic aperture radar feature tracking, J. Geophys. Res., 110, F03005, doi:10.1029/2004JF000233, 2005. 1644

Pritchard, H. D., Arthern, R. J., Vaughan, D. G., and Edwards, L. A.: Extensive dynamic thinning on the margins of the Greenland and Antarctic ice sheets, Nature, 461, 971–975, doi:10.1038/nature08471, 2009. 1638, 1653

Reeh, N., Thomsen, H. H., Higgins, A. K., and Weidick, A.: Sea ice and the stability of North and Northeast Greenland floating glaciers, Ann. Glaciol., 474–480, doi:10.3189/172756401781818554, 2001. 1652

Reynolds, R. W., Smith, T. M., Liu, C., Chelton, D. B., Casey, K. S., and Schlax, M. G.: Daily high-resolution-blended analyses for sea surface temperature, J. Climate, 20, 5473–5496, doi:10.1175/2007JCLI1824.1, 2007. 1643

Rignot, E. and Kanagaratnam, P.: Changes in the velocity structure of the Greenland Ice Sheet, Science, 311, 986–990, doi:10.1126/science.1121381, 2006. 1648, 1649, 1650, 1651

Rignot, E., Gogineni, S., Joughin, I., and Krabill, W.: Contribution to the glaciology of Northern Greenland from satellite radar interferometry, J. Geophys. Res., 106, D24, doi:10.1029/2001JD900071, 2001. 1650

TCD
6, 1637–1672, 2012

Rignot, E., Braaten, D., Gogineni, S. P., Krabill, W. B., and McConnell, J. R.: Rapid ice discharge from Southeast Greenland glaciers, Geophys. Res. Lett., 31, L10401, doi:10.1029/2004GL019474, 2004. 1651

Rignot, E., Koppes, M., and Velicogna, I.: Rapid submarine melting of the calving faces of West Greenland glaciers, Nat. Geosci., 3, 187–191, doi:10.1038/ngeo765, 2010. 1639, 1640

Rignot, E., Velicogna, I., van den Broeke, M. R., Monaghan, A., and Lenaerts, J.: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise, Geophys. Res. Lett., 38, L05503, doi:10.1029/2011GL046583, 2011. 1639

Scambos, T. A., Dutkiewicz, M. J., Wilson, J. C., and Bindschaler, R. A.: Application of image cross-correlation to the measurement of glacier velocity using satellite image data, Remote Sens. Environ., 42, 177–186, 1992. 1644

Schrama, E., Wouters, B., and Vermeersen, B.: Present day regional mass loss of Greenland observed with satellite gravimetry, Surv. Geophys., 1–9, doi:10.1007/s10712-011-9113-7, 2011. 1638, 1639, 1646

Schrama, E. J. O. and Wouters, B.: Revisiting Greenland Ice Sheet mass loss observed by GRACE, J. Geophys. Res., 116, B202407, doi:10.1029/2009JB006847, 2011. 1639, 1653

Seale, A., Christoffersen, P., Mugford, R. I., and O'Leary, M.: Ocean forcing of the Greenland Ice Sheet: calving fronts and patterns of retreat identified by automatic satellite monitoring of eastern outlet glaciers, J. Geophys. Res., 116, F03013, doi:10.1029/2010JF001847, 2011. 1639, 1640, 1654

Sole, A., Payne, T., Bamber, J., Nienow, P., and Krabill, W.: Testing hypotheses of the cause of peripheral thinning of the Greenland Ice Sheet: is land-terminating ice thinning at anomalously high rates?, The Cryosphere, 2, 205–218, doi:10.5194/tc-2-205-2008, 2008. 1638

Stearns, L. A., Hamilton, G. S., and Reeh, N.: Multi-decadal record of ice dynamics on Daugaard Jensen Gletscher, East Greenland, from satellite imagery and terrestrial measurements, Ann. Glaciol., 42, 53–58, doi:10.3189/172756405781812565, 2005. 1651

Straneo, F., Hamilton, G. S., Sutherland, D. A., Stearns, L. A., Davidson, F., Hammill, M. O., Stenson, G. B., and Rosing-Asvid, A.: Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland, Nat. Geosci., 3, 182–186, doi:10.1038/ngeo764, 2010. 1640, 1653

Straneo, F., Curry, R. G., Sutherland, D. A., Hamilton, G. S., Cenedese, C., Vage, K., and Stearns, L. A.: Impact of fjord dynamics and glacial runoff on the circulation near Helheim Glacier, Nat. Geosci., 4, 322–327, doi:10.1038/ngeo1109, 2011. 1640

Strozzi, T., Luckman, A., Murray, T., Wegmüller, U., and Werner, C. L.: Glacier motion estimation using SAR offset-tracking procedures, IEEE T. Geosci. Remote, 40, 2384–2391, 2002. 1644
Sutton, R. T. and Hodson, D. L. R.: Atlantic Ocean forcing of North American and European summer climate, Science, 309, 115–118, doi:10.1126/science.1109496, 2005. 1641
Thomas, R., Atkins, T., Csatho, B., Fahnestock, M., Gogineni, P., Klim, C., and Sonntag, J.: Mass balance of the Greenland Ice Sheet at high elevations, Science, 289, 426–428, 2000. 1647
Thomas, R., Frederick, E., Krabill, W., Manizade, S., and Martin, C.: Progressive increase in ice loss from Greenland, Geophys. Res. Lett., 33, L10503, doi:10.1029/2006GL026075, 2006. 1638
Thomas, R., Frederick, E., Li, J., Krabill, W., Manizade, S., Paden, J., Sonntag, J., Swift, R., and Yungel, J.: Accelerating ice loss from the fastest Greenland and Antarctic glaciers, Geophys. Res. Lett., 38, L10502, doi:10.1029/2011GL047304, 2011. 1649
Thomas, R. H., Abdalati, W., Frederick, E., Krabill, W. B., Manizade, S., and Steffen, K.: Investigation of surface melting and dynamic thinning on Jakobshavn Isbrae, Greenland, J. Glaciol., 231–239, doi:10.3189/172756503781830764, 2003. 1649
van den Broeke, M., Bamber, J., Ettema, J., Rignot, E., Schrama, E., van de Berg, W. J., van Meijgaard, E., Velicogna, I., and Wouters, B.: Partitioning recent Greenland mass loss, Science, 326, 984–986, doi:10.1126/science.1178176, 2009. 1639
van den Broeke, M., Bamber, J., Lenaerts, J., and Rignot, E.: Ice sheets and sea level: thinking outside the box, Surv. Geophys., 32, 495–505, doi:10.1007/s10712-011-9137-z, 2011. 1638, 1639
van der Veen, C. J., Plummer, J. C., and Stearns, L. A.: Controls on the recent speed-up of Jakobshavn Isbrae, West Greenland, J. Glaciol., 57, 770–782, 2011. 1639
Velicogna, I.: Increasing rates of ice mass loss from the Greenland and Antarctic ice sheets revealed by GRACE, Geophys. Res. Lett., 36, L19503, doi:10.1029/2009GL040222, 2009. 1639
Velicogna, I. and Wahr, J.: Greenland mass balance from GRACE, Geophys. Res. Lett., 32, L18505, doi:10.1029/2005GL023955, 2005. 1639
Wake, L. M., Huybrechts, P., Box, J. E., Hanna, E., Janssens, I., and Milne, G. A.: Surface mass-balance changes of the Greenland Ice Sheet since 1866, Ann. Glaciol., 50, 178–184, doi:10.3189/172756409787769636, 2009. 1639

Walsh, K. M., Howat, I. M., Ahn, Y., and Enderlin, E. M.: Changes in the marine-terminating glaciers of central east Greenland, 2000–2010, The Cryosphere, 6, 211–220, doi:10.5194/tc-6-211-2012, 2012. 1646, 1654
Wouters, B., Chambers, D., and Schrama, E. J. O.: GRACE observes small-scale mass loss in Greenland, Geophys. Res. Lett., 35, L20501, doi:10.1029/2008GL034816, 2008. 1639, 1653
Yin, J., Overpeck, J. T., Griffies, S. M., Hu, A., Russell, J. L., and Stouffer, R. J.: Different magnitudes of projected subsurface ocean warming around Greenland and Antarctica, Nat. Geosci., 4, 524–528, doi:10.1038/ngeo1189, 2011. 1655

Table 1. Glacier outlet catchment areas and locations for speed measurements (behind the most retreated frontal position). P-values are based on a Levene test for the null hypothesis that there is no difference in flow speed variance before and after 1995; values less than 0.1 are in bold. The correlation coefficient (CC) is that between speed and frontal position over the full time series.

Glacier	Area (km^2)	Map date (Fig. 1)	Measurement location (km)	P-value	CC
Kangerdlugssuaq	5.14×10^4	16 Sep 1985	1.8	**0.0**	−0.80
Helheim	5.19×10^4	24 Jul 1992	0.9	**0.0**	−0.85
Ikertivaq A	1.57×10^4	26 Sep 1986	0.9	**0.09**	−0.79
Ikertivaq B	in		1.4	**0.07**	−0.76
Ikertivaq C	total		0.2	0.19	−0.59
Ikertivaq D			0.3	0.37	−0.64
Ikertivaq E			0.6	0.22	−0.87
Gyldenlove	0.74×10^4	18 Apr 1989	1.0	0.46	−0.52
Jakobshavn Isbrae	8.88×10^4	1 Apr 1989	1.4	**0.0**	−0.97
Rink	3.32×10^4		0.9	0.12	−0.61
Ingia Isbrae	in	2 May 1987	0.7	0.16	−0.70
Umiamako	total		0.7	**0.0**	−0.92
Kong Oscar	2.69×10^4	7 Aug 1985		0.60	
Nioghalvfjerdsbrae	6.57×10^4	26 May 1985		0.77	
Petermann	7.40×10^4	22 Jul 2006	44	0.29	−0.53
Daugaard Jensen	4.86×10^4	3 Aug 1986	5.5	0.95	−0.17

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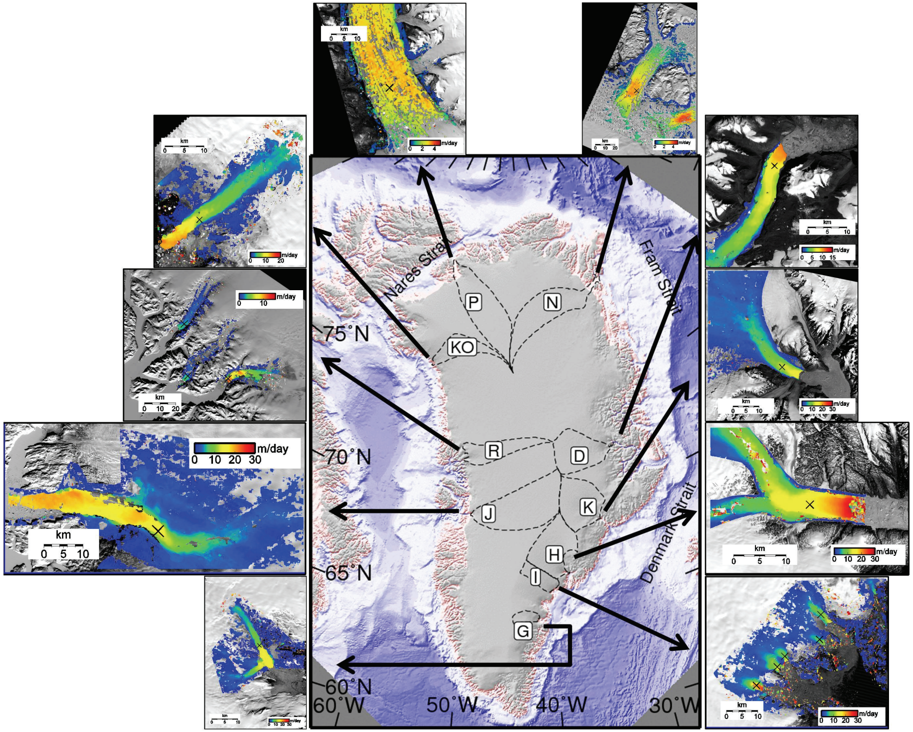

Fig. 1. Outlet glacier catchments. D = Daugaard Jensen, K = Kangerdlugssuaq, H = Helheim, I = Ikertivaq, G = Gyldenlove, J = Jakobshavn Isbrae, R = Rink Isbrae (including Umiamako and Ingia Isbrae), KO = Kong Oscar, P = Petermann, N = Nioghalvfjerdsbrae. Dates for the sample speed map images are listed in Table 1, and the velocity data extraction points are marked with X's. Shaded relief and bathymetry based on the International Bathymetric Chart of the Arctic Ocean (Jakobsson et al., 2008).

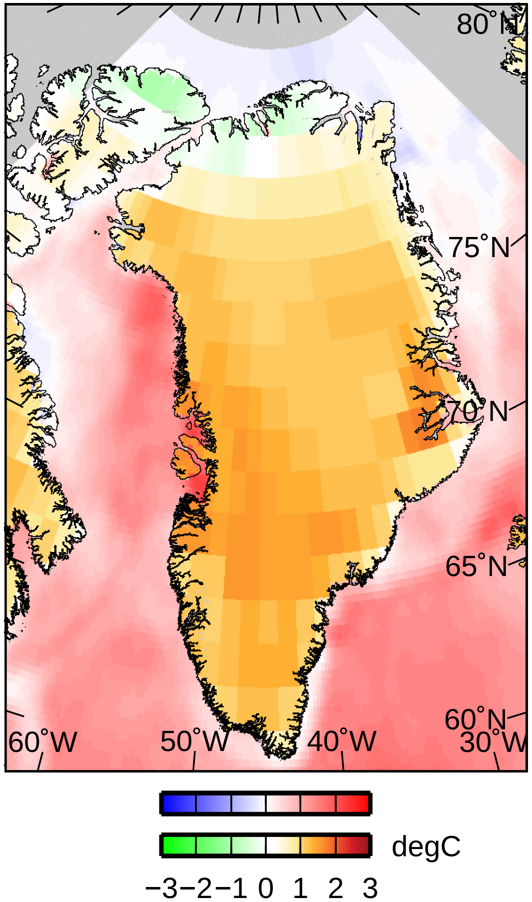

Fig. 2. Difference in mean summer temperature between 1982–1995 and 1996–2010. Over land: ERA-interim summer (June–August) 2 m air temperature. Over ocean: OISST summer (July–September) sea surface temperature.

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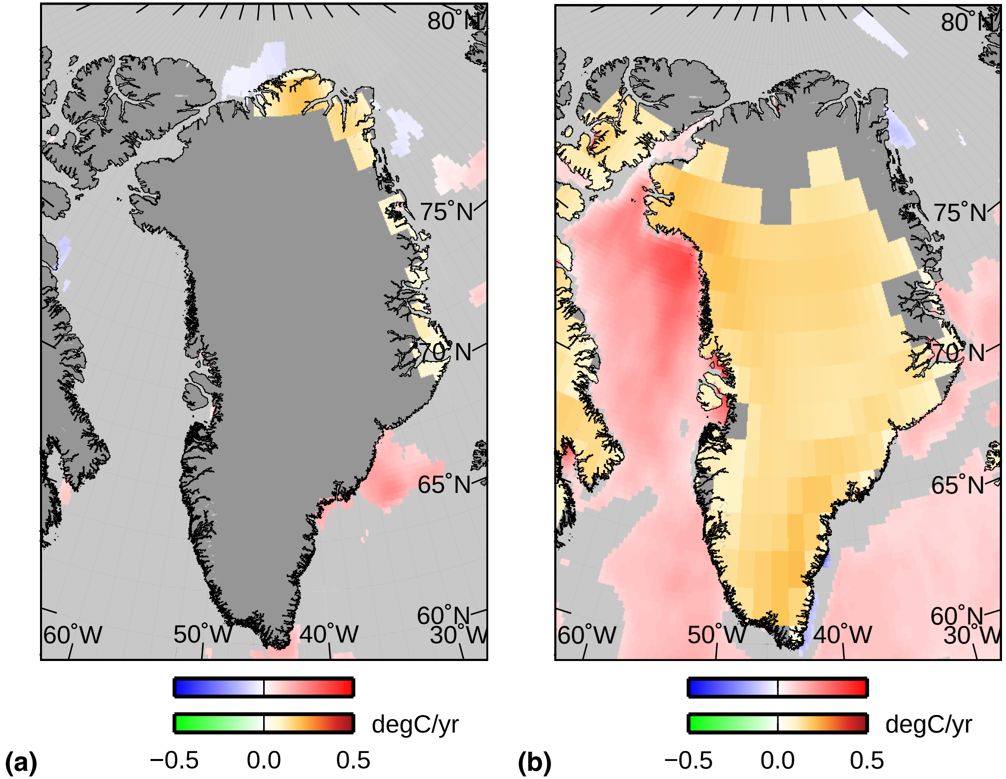

Fig. 3. Linear trend in temperature over the periods **(a)** 1982 to 1995 and **(b)** 1995 to 2010, where significant at the 95 % level. Over land: ERA-interim summer (June–August) mean 2 m air temperatures. Over ocean: OISST summer (July–September) sea surface temperatures.

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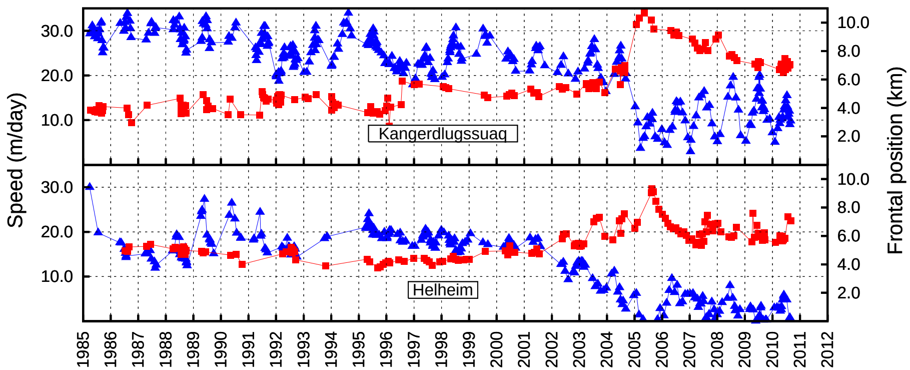

Fig. 4. Surface flow speeds (red squares) and frontal positions (blue triangles) for Kangerdlugssuaq and Helheim glaciers (see Fig. 1 for locations).

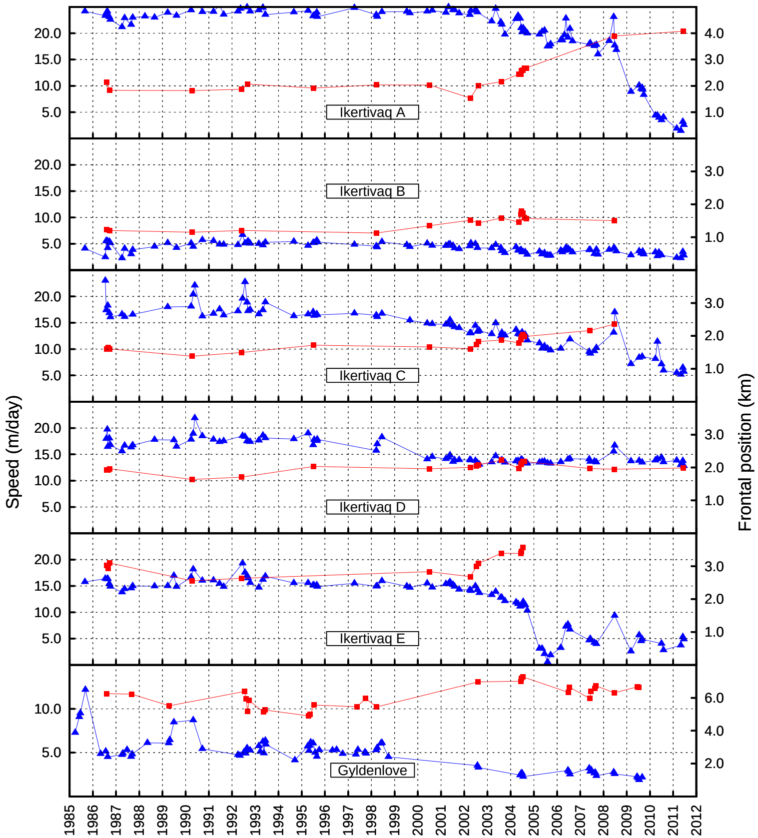

Fig. 5. Surface flow speeds (red squares) and frontal positions (blue triangles) for the Ikertivaq and Gyldenlove glaciers (see Fig. 1 for locations).

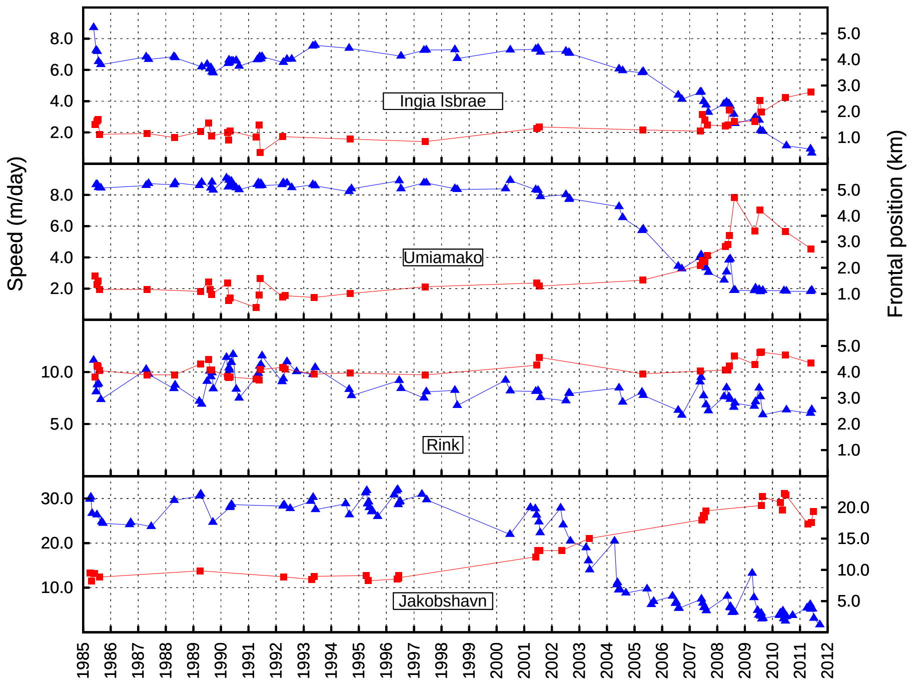

Fig. 6. Surface flow speeds (red squares) and frontal positions (blue triangles) for the Umiamako, Ingia Isbrae, Rink Isbrae and Jakobshavn Isbrae glaciers (see Fig. 1 for locations).

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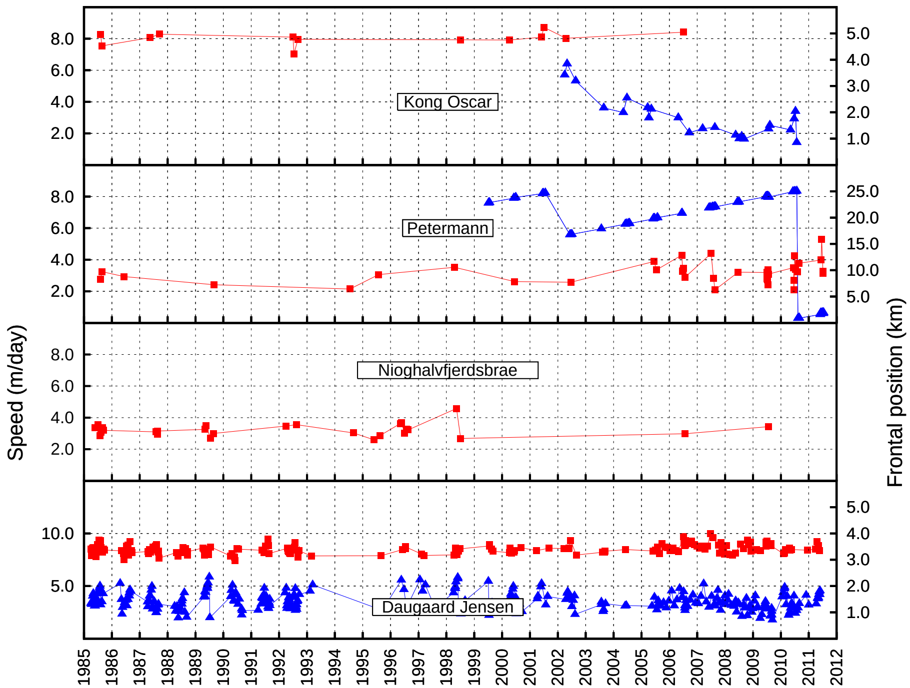

Fig. 7. Surface flow speeds (red squares) and frontal positions (blue triangles) for the Kong Oscar, Petermann, Nioghalvfjerdsbrae and Daugaard Jensens glaciers (see Fig. 1 for locations).