LETTER

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Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage

Aud Venke Sundal[1], Andrew Shepherd[1], Peter Nienow[2], Edward Hanna[3], Steven Palmer[1] & Philippe Huybrechts[4]

Fluctuations in surface melting are known to affect the speed of glaciers and ice sheets[1–7], but their impact on the Greenland ice sheet in a warming climate remains uncertain[8]. Although some studies suggest that greater melting produces greater ice-sheet acceleration[7,9], others have identified a long-term decrease in Greenland's flow despite increased melting[3]. Here we use satellite observations of ice motion recorded in a land-terminating sector of southwest Greenland to investigate the manner in which ice flow develops during years of markedly different melting. Although peak rates of ice speed-up are positively correlated with the degree of melting, mean summer flow rates are not, because glacier slow-down occurs, on average, when a critical run-off threshold of about 1.4 centimetres a day is exceeded. In contrast to the first half of summer, when flow is similar in all years, speed-up during the latter half is 62 ± 16 per cent less in warmer years. Consequently, in warmer years, the period of fast ice flow is three times shorter and, overall, summer ice flow is slower. This behaviour is at odds with that expected from basal lubrication alone[7,9]. Instead, it mirrors that of mountain glaciers[10–12], where melt-induced acceleration of flow ceases during years of high melting once subglacial drainage becomes efficient. A model of ice-sheet flow that captures switching between cavity and channel drainage modes[13] is consistent with the run-off threshold, fast-flow periods, and later-summer speeds we have observed. Simulations of the Greenland ice-sheet flow under climate warming scenarios should account for the dynamic evolution of subglacial drainage; a simple model of basal lubrication alone misses key aspects of the ice sheet's response to climate warming.

Recent studies addressing the mass balance of the Greenland Ice Sheet (GrIS) show that snowfall-driven thickening of the interior[14] is more than offset by near-coastal mass loss caused by increased surface melting[15] and accelerated glacier flow[16]. Enhanced basal sliding due to the penetration of surface melt-water to the base of the ice sheet is one proposed mechanism for the observed increase in glacier flow[7]. Theoretical work[9] suggests that the direct coupling between increased surface melting and ice-sheet flow may substantially hasten the mass loss of the GrIS. However, our ability to incorporate surface melt-induced acceleration into ice-sheet models is limited by a lack of knowledge of the extent and characteristics of the hydrological forcing. In consequence, the potential impact of surface melting on ice dynamics has not been incorporated into the ice-sheet models that form the basis of the Intergovernmental Panel on Climate Change sea level projections[8]. This study provides an improved understanding of the relationship between ice-sheet dynamics and hydrology through a comparison of inter-annual, altitudinal, and seasonal variations in ice velocity and modelled run-off rates across the land-terminating section of the GrIS draining westwards between 66° 39′ N to 67° 56′ N (Fig. 1). The analysis is based on data from 1993 and 1995–1998 (see Methods Summary).

We explored spatial and temporal variations in ice flow by comparing velocities recorded in all five years along the centre-lines of the six major glaciers in the study area (Fig. 1 and Fig. 2). The average winter (days 330 to 60) speed of the six glaciers in this part of the ice sheet is 122 m yr^{-1}, ranging from 80 m yr^{-1} (glacier 5) to 207 m yr^{-1} (glacier 3). During the height of summer speed-up (May–June), average speeds range from 138 m yr^{-1} (glacier 5) to 314 m yr^{-1} (glacier 3). Overall, there is a significant flow increase in summer relative to winter at all six glaciers, with average speed-ups of 50% to 125% that are similar to earlier observations[1]. There is also a marked decrease in the variance of ice speed in winter compared to summer (shaded areas, Fig. 2). The seasonal velocity fluctuations are broadly coincident with fluctuations in the degree of surface melting (Fig. 3), adding further support to hypotheses that seasonal surface melting drives seasonal cycles in ice-sheet

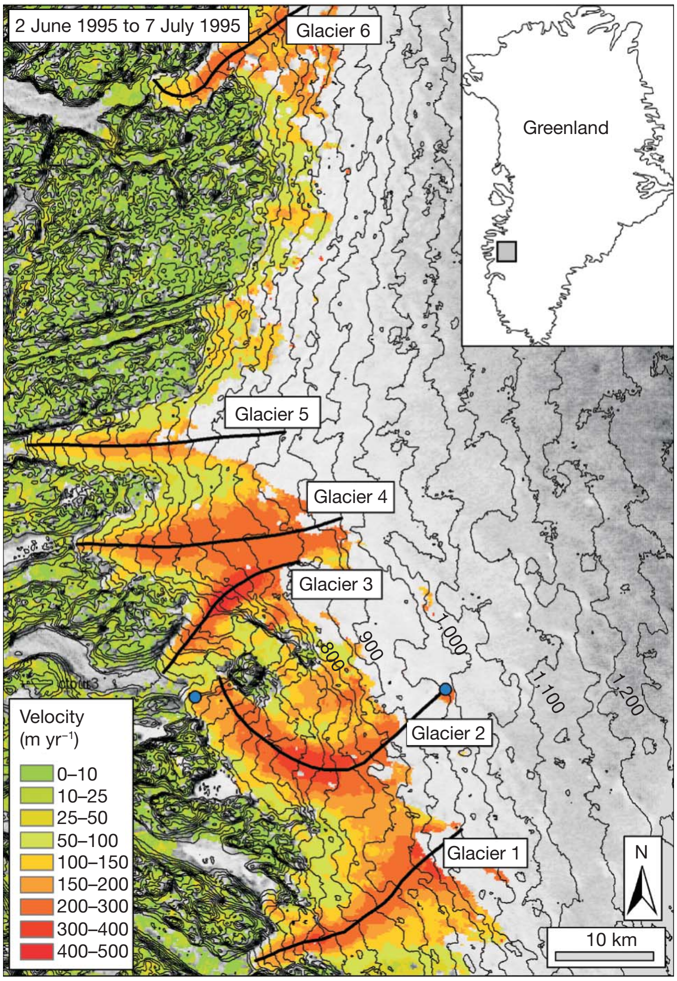

Figure 1 | Ice-velocity map of the study area. Example of a two-dimensional ice-velocity map for the selected study area derived using intensity tracking between two European Remote Sensing satellite synthetic aperture radar images separated by 35 days (2 June 1995 to 7 July 1995).

[1]School of Earth and Environment, University of Leeds, Woodhouse Lane, Leeds, LS2 9JT, UK. [2]School of Geosciences, University of Edinburgh, Drummond Street, Edinburgh, EH8 9XP, UK. [3]Department of Geography, University of Sheffield, Winter Street, Sheffield, S10 2TN, UK. [4]Earth System Sciences & Departement Geografie, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium.

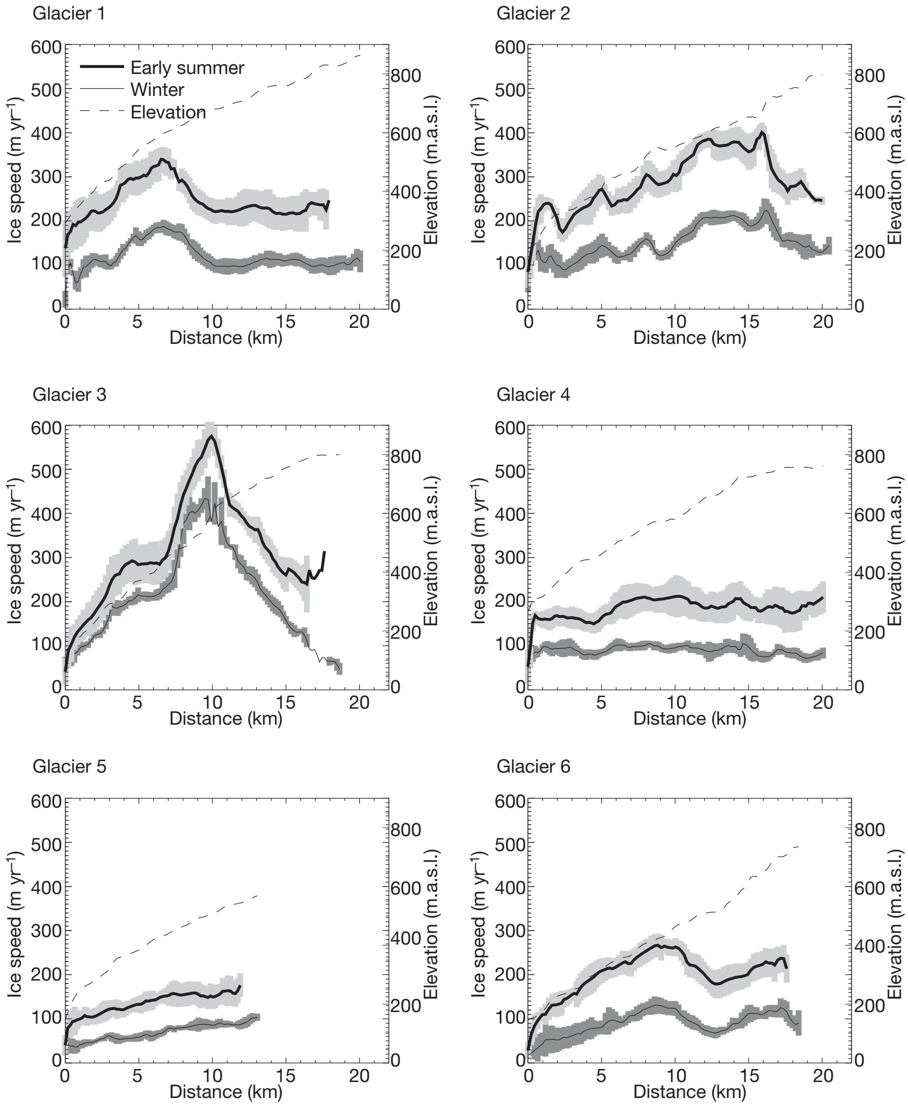

Figure 2 | Ice-velocity profiles along six glaciers in the study area. Average ice velocities during winter (days 330 to 60) and during the height of summer speed-up (May–June) on all five years along the centre-lines of the six major glaciers in the study area, with one standard deviation shown as shaded area. The median error of the data set is 17 m yr^{-1}. The elevation data set is derived from the ASTER Global Digital Elevation Model (http://www.ersdac.or.jp/GDEM/E/index.html). We note that local ice-velocity maxima generally correspond to areas of steeper ice surface slopes. m.a.s.l., metres above sea level.

flow[1–4,7]. To explore this relationship further, we compared velocity data at two distinct altitudes at glacier 2 (see Fig. 1) to assess the impact of delays in melting on ice speed-up. Using a lag-correlation of monthly averaged velocity data (see Supplementary Information and Supplementary Fig. 1), we estimate that summer speed-up at 950 m above sea level is delayed by 18 days compared to the changes recorded at 250 m above sea level. This speed-up delay is in close agreement with the ~20-day delay in the onset of surface melting between the same altitudes recorded in the temperature data set at Kangerlussuaq (Danish Meteorological Institute, station 04231) modified by a local atmospheric lapse rate[17]. Within the range of elevations encompassed by our survey, summer speed-up closely follows the rate at which melting propagates inland.

It is well known that variations in the degree of melting affect the rate at which coastal sectors of the GrIS flow[1–7]. Factors contributing to the manner in which seasonal velocity cycles may evolve include variations in the timing, extent and quantity of surface run-off, and potential variations in the routeing of water to and at the ice-sheet base. In the absence of details of the englacial and subglacial hydraulic network, we investigated the extent to which fluctuations in surface run-off affected the ice flow by contrasting ice velocity observations during the years with highest (1995 and 1998) and lowest (1993, 1996, and 1997) run-off and melt extent[18] (see Supplementary Table 1). For the purpose of these calculations, we define summer as the period of surface run-off (see Fig. 3 and Table 1), and divide it further into equally long early-summer and late-summer periods. Peak summer is defined as the period when ice flow exceeds the winter rate by more than 100%, and winter encompasses the common period when no significant temporal flow variation occurs. Data from all five years were included when calculating the average winter velocity. The velocity data used in our comparison were extracted from locations with a continuous record across all years. Four glaciers (glaciers 2, 4, 5 and 6) exhibit a marked difference in the pattern of seasonal speed-up on years of low and high melting (Fig. 3). Although glacier 3 showed similar behaviour, the degree of speed-up was small in relation to other glaciers—possibly owing to the steep slopes and high speeds in the region of our comparison (Fig. 2), which may complicate glacier 3's response to fluctuations in surface melting—so we excluded it from our inter-annual comparison.

In contrast to the early-summer period, when flow is similar in all years, the average speed-up of glaciers 2, 4, 5 and 6 during late-summer was 39 ± 14% in years of high melting and 102 ± 9% in years of lower melting (Table 1 and Fig. 3). Although the peak rate of speed-up is greater during years of high melting (123 ± 8% versus 104 ± 9%), the period of peak flow is far shorter (~30 days versus ~90 days). The

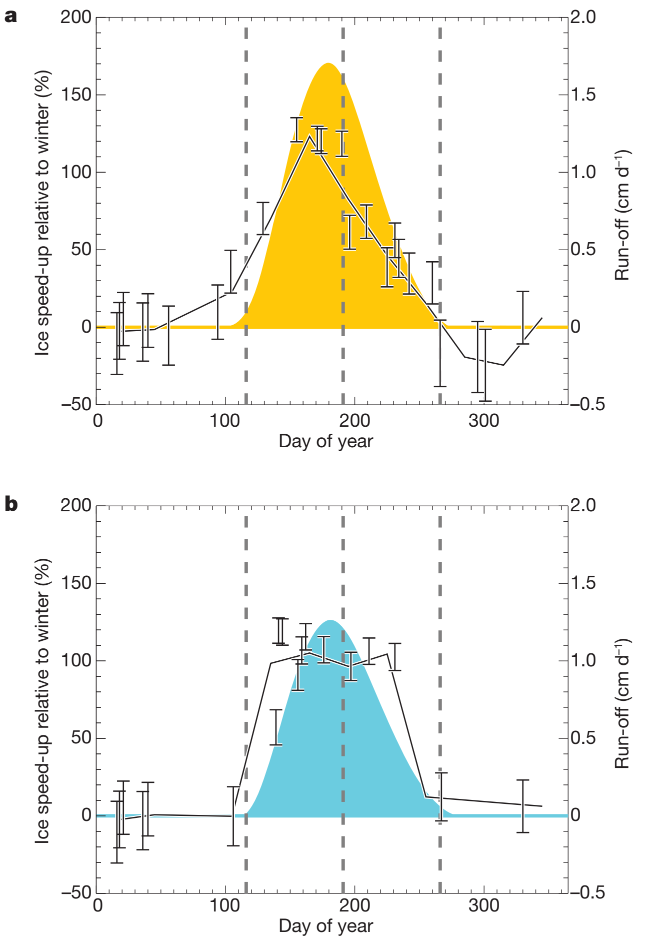

Figure 3 | Ice speed-up relative to winter during years of high and low surface melting. a, Speed-up in years of high melting (1995 and 1998). **b**, Speed-up in years of low melting (1993, 1996 and 1997). Point data are 35-day ice-velocity averages relative to the winter mean within the elevation band 500–600 m above sea level on glaciers 2, 4 and 6 and the elevation band 400–500 m above sea level on glacier 5. Glacier 1 was excluded owing to paucity of data. Error bars show the one-sigma uncertainty of speed-up measurements at each epoch. Monthly averaged data are shown as solid lines. Also shown (in colour) are model estimates of daily surface run-off rates within the study area averaged during the years of high (orange) and low (blue) melting. Vertical dashed lines indicate the shoulders and midway-point of the run-off period, which are used to define the summer period over which average speed-up is calculated.

ratio of peak speed-up to positive degree days (R. van de Wal, personal communication) recorded in our catchment (~0.3% per positive degree day) are similar to those measured elsewhere (~0.2% per positive degree day from the data of ref. 7). To calculate the integrated effect of these fluctuations, we computed the average degree of speed-up during the entire period of summer melting (days 116 to 266). On average, summer ice flow was 67 ± 12% and 102 ± 9% greater than during winter in years of high and low melting, respectively. Overall, summer ice flow was 34 ± 15% slower in warmer years. There is some evidence of flow variability at times beyond the run-off period (Fig. 3). For example, in warm years, a small (~25%) degree of speed-up occurs before run-off begins and a comparable degree of slowdown occurs after run-off ceases. We are, however, not able to make inter-annual comparisons over these periods owing to the paucity of data in colder years.

Table 1 | Glacier speed-up

Period	Start day	End day	ΔV_{warm} (%)	ΔV_{cold} (%)	ΔV_{cold} minus ΔV_{warm} (%)
Early summer	116	191	112 ± 8	102.2 ± 9	−9 ± 12
Late summer	191	266	39 ± 14	101.8 ± 9	62 ± 16
Summer	116	266	67 ± 12	102.1 ± 9	34 ± 15

Average speed-up (ΔV) (with one-sigma uncertainty) of glaciers 2, 4, 5 and 6 at an altitude of 400–600 m above sea level in warm (1995 and 1998) and cold (1993, 1996 and 1997) years during fixed time periods relative to winter (days 330 to 60). The periods of early and late summer are defined using model estimates of run-off (see Fig. 3). We point out that the similarity of ΔV_{cold} during early summer, late summer and all summer is a coincidence of the data.

Although the lower degree of late-summer speed-up we observe in years of high melting is at odds with that expected due to basal lubrication alone[7], the behaviour can be explained by inter-annual differences in the evolution of subglacial drainage. Abundant melt-water can trigger a switch from inefficient (cavity[19]) to efficient (channelized[20]) modes of drainage and, consequently, to a reduction in subglacial water pressure and ice speed. Such events have been observed at High Arctic[10] and Alaskan valley glaciers[11], where summer speed-up is of shorter duration during years of high melting. A numerical simulation of idealized ice-sheet flow that incorporates dynamic switching between drainage modes[13] is able to capture the key aspects of flow variations we observe in southwest Greenland. This model[13] predicts that glacier slowdown occurs above a critical rate of water flow in the range 1–2 cm per day. It also predicts that the period of speed-up is shorter than the period of melt-supply by a factor proportional to the intensity of melting. Imposing a melt-supply of ~10 cm per day or ~20 cm per day for ~100 days, for example, leads to overall speed-up periods of ~70 days or ~40 days, respectively, and late-summer speeds that are about half those in early summer. Our observations show that in warm years, slowdown occurs when the monthly run-off rate exceeds about 1.4 cm per day (see Fig. 3 and Supplementary Table 1) and that, in consequence, the period of fast-flow (double the winter rate) is about three times shorter and late-summer speeds are 73 ± 16% lower than in early summer.

The effect of melt-induced velocity fluctuations on the GrIS remains a subject of debate[1–9,21]. Although some studies have shown that greater melting produces greater ice-sheet acceleration[7,9], others have identified a long-term (17-year) decrease in Greenland's flow during a period of increased melting[3]. Our data reconcile these contradictory findings: although the peak rate of flow increases during years of high melting, the associated faster transition to a period of more efficient subglacial drainage reduces both the duration of rapid flow and the average summer speed when compared to years of low melting. In regions where the critical run-off threshold[13] is not breached, we would not expect to see the effects of efficient drainage on flow. On the basis of our data set, we are not able to establish whether the transition between distinct modes of flow is an abrupt or gradual process. Furthermore, we recognize that the classification of our data into two discrete categories could mask intermediate behaviour, and that changes in flow associated with shorter period melting variability[2] cannot be captured by our satellite observations. The small speed-up observed before the summer period in warm years, for example, may be driven by brief melting events that are not recorded by our run-off model. These changes are, however, small in comparison to the overall speed-up during summer, and are not central to our analysis of how flow responds to drainage mode switching. Altogether, our data show that the subglacial drainage system in southwest Greenland evolves in response to variable surface melting in a way similar to that of mountain glaciers[10–12].

Rates of surface melting at the Greenland ice sheet are predicted to double over the course of the twenty-first century[22]. One model of the ice-sheet response to climate warming[9] has estimated that melt-induced acceleration could add between 0.15 m and 0.40 m to global sea levels by 2500. However, several authors[11,21] have cautioned against the notion[7,9] that increases in ice flow are simply proportional to increases in surface melting. Our data are the first to reveal a drop in summer speed-up of the GrIS in years of high melting compared to years of low melting, and support views[3,11,21] that the ice-sheet subglacial drainage system may adjust to accommodate increased melting in a way that does not lead to proportionate increases in flow. The net effect of melt-induced speed-up and efficient drainage remains uncertain; numerical experiments[13] suggest that their combined impact depends upon how both the mean supply and short-period spikes in melting develop over time. According to our data set, which covers a range of melting conditions[23] that is small in comparison to predicted changes over the next century[22], increases in surface melting lead to a reduction in rates of summertime ice flow in the lower ablation zone of southwest Greenland. An improved understanding of subglacial drainage is therefore an essential step towards developing numerical models that capture the link between ice-sheet hydrology and ice motion. Until the influence of changes in melting on ice-sheet velocity are more firmly established, the response of the cryosphere to climate change and its ultimate contributions to sea level will remain uncertain.

METHODS SUMMARY

We used synthetic aperture radar intensity tracking[24] to determine ice velocity within our study area (see Supplementary Information). We applied the method to 37 European Remote Sensing satellite synthetic aperture radar 35-day repeat-track pairs acquired between 1993 and 1998. The median velocity error was estimated to be 17 m yr^{-1} by measuring the mean difference from zero of large samples of data over areas of static rock present within each image[25]. Run-off data were extracted from a monthly degree-day surface melt-water run-off/retention model[23] adapted from an annual degree-day run-off/retention model[26] using the European Centre for Medium-Range Weather Forecasts as input parameters (see Supplementary Information). On the basis of their combination of anomalously high run-off and melt-extent[18], we classified 1995 and 1998 as high-melt years, and 1993, 1996 and 1997 as low-melt years (see Supplementary Information).

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions A.S. designed the research. A.V.S. produced the ice velocity data. E.H. and P.H. produced the run-off data. A.V.S. and A.S. analysed the data sets and produced the results. A.V.S. and A.S. wrote the manuscript. All authors discussed the results and commented on the manuscript.

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