LETTERS
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# Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier

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**The Greenland ice sheet contains enough water to raise sea levels by 7 m. However, its present mass balance and future contribution to sea level rise is poorly understood[1]. Accelerated mass loss has been observed near the ice sheet margin, partly as a result of faster ice motion[2-4]. Surface melt waters can reach the base of the ice sheet and enhance basal ice motion[5,6]. However, the response of ice motion to seasonal variations in meltwater supply is poorly constrained both in space and time. Here we present ice motion data obtained with global positioning system receivers located along a ∼35 km transect at the western margin of the Greenland ice sheet throughout a summer melt season. Our measurements reveal substantial increases in ice velocity during summer, up to 220% above winter background values. These speed-up events migrate up the glacier over the course of the summer. The relationship between melt and ice motion varies both at each site throughout the melt season and between sites. We suggest that these patterns can be explained by the seasonal evolution of the subglacial drainage system similar to hydraulic forcing mechanisms for ice dynamics that have been observed at smaller glaciers.**

Recent studies have focused on the role that seasonal changes in hydrological forcing have on ice motion of the Greenland ice sheet[3–5,7,8] (GrIS) and suggest that surface melting generates large enough volumes of melt water to lubricate basal flow should it reach the bed[9]. This process has the potential to create a positive feedback between climate warming and ice velocity that has not been considered in ice sheet models that predict sea level rise[1]. A theoretical mechanism of hydrofracture[10,11] proposes how surface melt water can penetrate to the bed through cold ice >1,000 m thick and has been invoked to explain changes in vertical and horizontal components of ice motion in response to a lake drainage event[5]. Simultaneous measurements of ice velocity and air temperature have established, over short timescales, a correlation between local surface melting and velocity fluctuations over a widespread area[4,8,9]. However, it has been shown that higher annual ablation does not necessarily lead to increased annual ice velocities[8] and the importance of this relationship for large-scale dynamic behaviour of the GrIS remains equivocal. It is suggested[9] that alpine glaciers may provide an appropriate analogue for the evolution of the GrIS in a warming climate. In alpine and high Arctic polythermal valley glaciers, ice motion depends on variations in the structure, hydraulic capacity and efficiency of the subglacial drainage system[12], each of which evolves spatially and temporally on a seasonal basis[13–17]. Until now, limited data sets have been unable to confirm this hypothesis for the GrIS.

We used global positioning system (GPS) observations to provide continuous ice velocity measurements, from 7 May, during the 2008 melt season and the subsequent winter at four sites along a land-terminating transect in the ablation zone of the western margin of the GrIS at ∼67.10° N (Fig. 1). Simultaneous measurements of air temperature were made at each site.

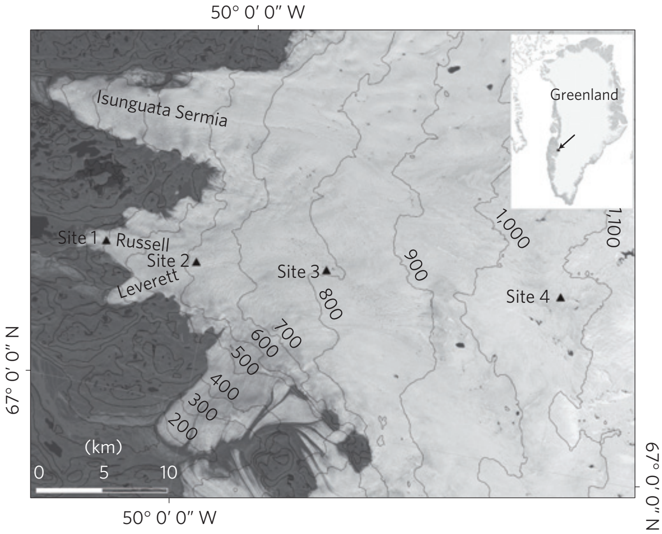

**Figure 1 | Location of the GPS transect on the western margin of the GrIS.** The four GPS sites are located in the ablation zone of the GrIS across an altitudinal range of 395–1,060 m a.s.l., contours show altitude where ice thickness ranges from ∼270–920 m (ref. 29) and are located along a flowline from the ice sheet interior as determined by interferometric synthetic aperture radar observations[30]. Simultaneous measurements of air temperature were made at each site to constrain surface melt rates.

The GPS observations show that each site experienced changes in daily ice velocity that were >110% above winter motion over the course of our survey (Fig. 2). This variability is consistent with, but much stronger than, previously reported observations[6,8,9]. When our survey began, melt had commenced near the ice margin and site 1 was already experiencing motion above winter background level. At sites 2, 3 and 4 a common pattern of seasonal ice velocity variation is characterized by an initial period of slow flow at winter levels, followed by a 70–100% increase in horizontal velocity, following the onset of melt, that marks a change in the dynamic regime to higher mean velocities. These sites gradually return to velocities below their winter values by the end of the summer, although individual high-velocity events occur throughout the summer. Average rates of ice motion at sites 1, 3 and 4, following the seasonal increase in horizontal velocity, were 114, 132 and 142 m yr$^{-1}$, respectively. The net increases in ice motion above winter background motion, owing to these summer

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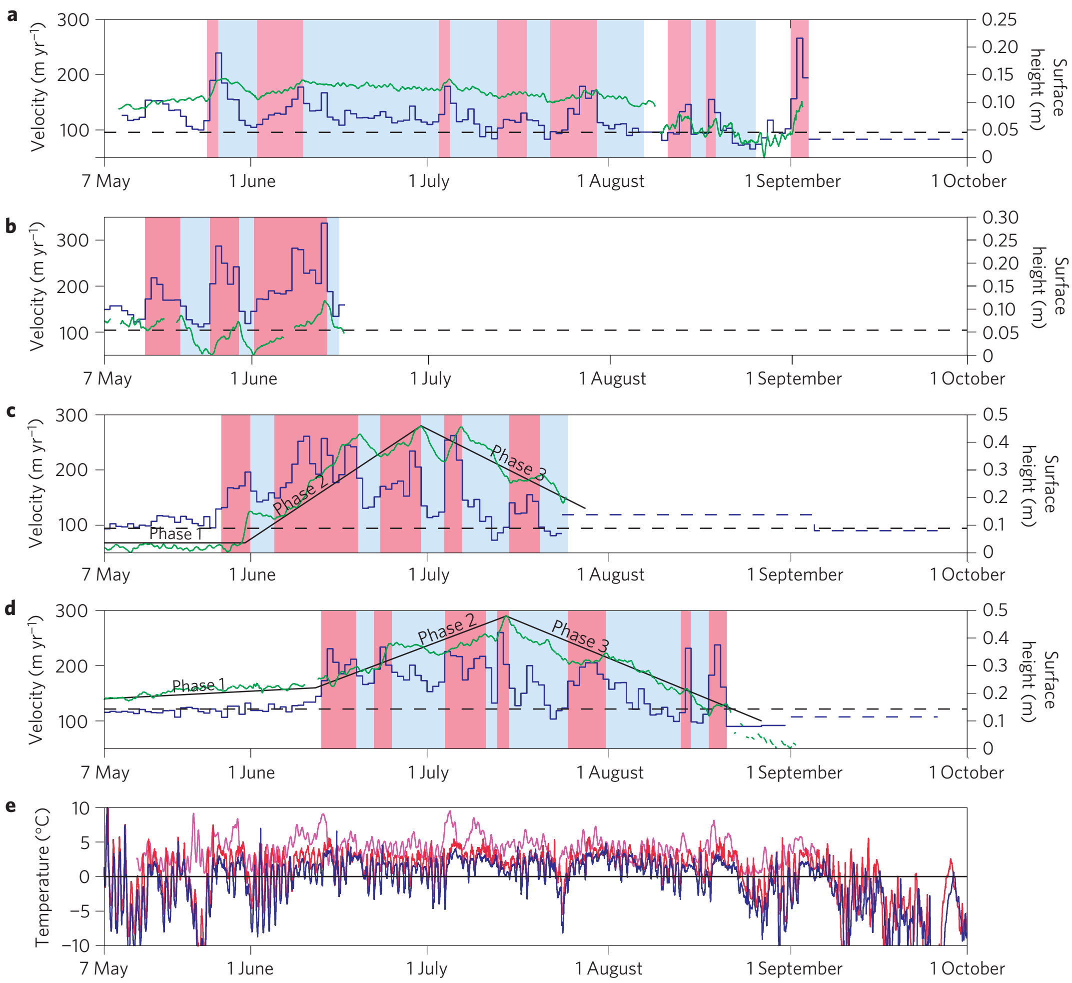

**Figure 2 | Seasonal development of melt-induced ice velocity variations. a–d**, 24-h horizontal velocity (blue) and surface height (green) at GPS site 1 (395 m a.s.l.) (**a**), site 2 (618 m a.s.l.) (**b**), site 3 (795 m a.s.l.) (**c**) and site 4 (1,063 m a.s.l.) (**d**). The surface height is shown relative to an arbitrary datum with a linear, surface-parallel, slope removed. The dashed lines show winter background velocity (black) and velocities from periods with sparse data (blue). The shaded sections identify periods of ice acceleration associated with ice-surface uplift (red), and slower ice motion associated with a decrease in surface height (blue). The solid lines indicate different phases of longer-term ice velocity versus surface uplift relationship. **e**, Temperature record from sites 1 (magenta), 3 (red) and 4 (blue).

variations, are 19%, 40% and 17%, equating to an increase in annual ice flux of 8%, 14% and 6%. In addition, the data reveal an up-glacier evolution in the onset of horizontal acceleration, and in the subsequent slowdown. Site 2 began to speed up on 15 May and sites 3 and 4 followed on 27 May and 11 June, respectively.

At all sites, the highest horizontal velocities coincide with uplift of the ice sheet surface, up to 12 cm in a single event, and reductions in velocity occur when the surface is lowering or stable. The highest daily horizontal velocities occur during periods of rapid uplift, rather than at peak elevation. Clear longer-term seasonal changes in surface elevation are associated with variations in the horizontal flow regime, particularly at sites 3 and 4, and can be categorized into three phases. Phase 1 is characterized by no enhanced surface uplift and low horizontal velocities (7–30 May at site 3; 7 May–10 June at site 4), and the slow-flowing inland ice (sites 3 and 4) seems to be unaffected by the faster ice downstream (sites 1 and 2). During phase 2, the rate of uplift increases, as do the horizontal velocities (31 May–19 June at site 3; 11 June–14 July at site 4), and in phase 3, surface elevations gradually decrease towards (site 3) and below (site 4) their early season levels (20 June–21 July at site 3; 15 July–29 August at site 4) but can fluctuate by $\sim 0.05$ m d$^{-1}$.

We used air temperature data to derive positive degree days (PDDs) at each site to investigate relationships between surface melt (as inferred from PDDs) and ice velocity. For the melt season as a whole, there was a weak but significant correlation between PDD and daily ice velocity at each site but there is no link between the intensity of seasonal melting and the mean horizontal velocity increase (Fig. 3a).

Studies of hydromechanical coupling at alpine and subpolar glaciers reveal that intra-seasonal changes in the hydraulic efficiency of the subglacial drainage system are a principal control on the sensitivity of ice motion to meltwater inputs[13–17]. Our data show that: (1) phase 1 (pre-melt) velocities are low and show no relationship to PDD (Fig. 3c,d); (2) phase 2 (enhanced surface uplift) mean velocities are high (>50% above winter background) and positively correlated with PDD (Fig. 3b–d); and (3) during phase 3 (surface lowering), the sensitivity of the relationship between PDD and velocity changes such that only periods of most intense melting (that is, high PDDs; Fig. 3b–d) are associated with substantial enhanced surface velocity (>50% above winter background). This accounts for the gradual decline in ice velocities, but explains the sporadic high-velocity events.

From the association between the onset of surface melting, surface uplift and enhanced horizontal velocities, we infer rapid delivery of surface melt water to the ice sheet bed following the establishment of a hydraulic connection[5,6,8,9]. This melt water increases

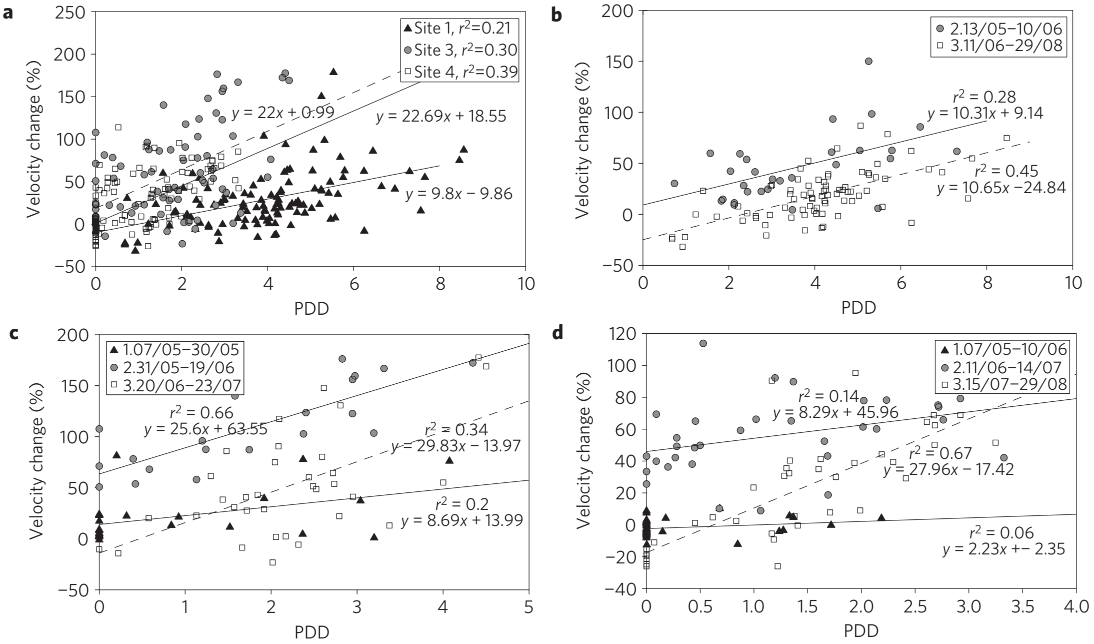

**Figure 3 | Intra-seasonal changes in surface melting versus ice velocity relationships. a**, Positive degree day (PDD) versus velocity change at sites 1, 3 and 4 for the whole season. 24-h velocities are shown as percentage change relative to winter background. **b–d**, PDD versus velocity for different phases of ice velocity versus uplift relationship—1. 'pre-melt', 2. 'enhanced surface uplift' and 3. 'surface lowering'—at GPS site 1 (**b**), site 3 (**c**) and site 4 (**d**).

basal sliding by reducing friction between overlying ice and its bed, probably through hydraulic jacking or cavitation[15,18]. Although changes in surface elevation can also result from changes in bedrock topography and strain rates[19], the patterns we observe cannot be attributed to these effects alone. We would expect acceleration of downstream ice to cause thinning upstream, yet observe the opposite, and would not expect bedrock obstacles to be expressed at the ice sheet surface on the length scales of the changes in our data. The coincidence of highest velocities with rate of uplift, rather than peak elevation, suggests 'stick–slip' behaviour similar to that observed in an alpine-type glacier[15,18,20], whereby separation of the ice and bed allows the immediate release of built-up stresses in the overlying ice.

Our observations of temperature and the pattern of changes in horizontal and vertical motion at each site, suggest a local, temperature-related, forcing mechanism for the seasonal changes in ice motion. As also observed at alpine and high Arctic polythermal glaciers[14,15,17], the initiation of summer velocity changes is dependent on the establishment of a hydraulic connection between the ice surface and bed, which occurs first in the lowest parts of the ablation zone, through thinner ice, and migrates progressively up-glacier (Fig. 2). However, our results from Greenland suggest that a temporally consistent relationship between surface melt and ice velocity does not exist once a hydraulic connection has been made. Instead, the relationship evolves both at a point and develops up-glacier. When melt first accesses the bed, the onset of high surface velocities and uplift (phase 2; Fig. 3) is indicative of an inefficient basal hydraulic system in which basal water pressures are highly sensitive to relatively small inputs of water[13]. During the last part of the melt season (phase 3), the gradual surface lowering and ice slow down indicates a more efficient channelized system in which basal water pressures are generally lower[13]. Only during very high meltwater inputs are basal water pressures raised enough to reduce basal friction significantly and enhance surface velocity[21]. This categorization is complicated by a small number of examples of high horizontal velocity in our data in the absence of high temperatures (for example, site 4 on 14 August (Fig. 2)), which may be caused by rapid drainage of surface lakes to the ice sheet bed[5,6].

Sites 3 and 4 do not show velocity increases to above winter values even when sites downstream have started accelerating (Fig. 2), suggesting that longitudinal coupling is not effective over >10 km at these locations. Although numerical studies have suggested that it may be possible for seasonal acceleration of inland ice to be explained through longitudinal coupling to marginal ice[22], and our data do not preclude its effectiveness in other parts of the GrIS, we do not observe that process here at length scales of >10 km. Therefore, enhanced surface velocity is primarily a consequence of local hydrological forcing at each site and the efficiency of the hydrological system.

Thus, the ice sheet exhibits a transient dynamic response to seasonal melting at each site[3,4,18]. We find that, in addition to surface melt rates, a key control on the magnitude and location of enhanced basal sliding is the structure and efficiency of the subglacial drainage system, which evolves seasonally, in a similar manner to alpine glaciers[15,18,23]. The seasonal and spatial increase in subglacial hydraulic efficiency is probably responsible for the lack of correlation between seasonal ablation rates and velocity changes that has caused previous authors to question the existence of positive feedback between climate warming and annual ice velocity of the GrIS (refs 8,24). Using a more extensive data set, we find that the relationship between melt rate and ice motion evolves through time at each site and with distance up-glacier, suggesting that its significance lies at higher elevations. Although our data extend only up to 1,000 m altitude, further ground-based observations have also detected ice-motion variations during late summer that are strongly associated with changes in surface hydrology, at elevations above 1,400 m in the same region[9].

In a warming climate, with longer and more intense summer melt seasons, we would expect that water will reach the bed farther inland[25] and a larger portion of the ice sheet will experience summer velocity changes. Modelling studies have suggested that the enhancement of summer ice motion is critical in drawing down ice from the accumulation zone, thereby reducing the surface elevation of the ice sheet, exposing more of the ice sheet to surface ablation[7]. Furthermore, the low gradient of the GrIS interior ensures that a small rise in temperature will induce melt across a spatially extensive area and substantial melt at elevations above 1,600 m is already evident in the presence of supraglacial lakes[26,27]. Our findings emphasize the importance of both surface melting and seasonal evolution of the subglacial drainage system on ice motion in marginal regions of the GrIS and will help parameterize numerical models that predict the future evolution of the GrIS.

## Methods

Each GPS antenna was mounted on a support pole drilled several metres into the ice, which froze in subsequently, providing measurements of ice motion that are independent of ablation. The GPS receivers collected data that were processed kinematically using a Precise Point Positioning approach (sites 2, 3 and 4 at 300 s intervals), and relative to a local (<2.5 km, 10 s intervals) base station for site 1 (ref. 28). Estimates of the uncertainty associated with positioning are ±1.5 cm in the horizontal direction and ±2.5 cm in the vertical direction. The precision and resolution of the data set is therefore sufficient to study changes along the flowline on seasonal and shorter (<1 day) timescales. Daily horizontal velocities reported in this letter are calculated by differencing 1-h mean positions every 24 h. Vertical profiles are generated by filtering the whole data set to suppress noise without over-smoothing the time series.

The GPS units were powered by solar panels. The GPS receiver at site 2 lost power on 16 June and our analysis is focused mainly on the three remaining sites. The receiver at site 1 was installed 3 days later than the others on 10 June. We also experienced power problems later in the season at site 3 and data from the beginning of September onwards is sporadic. This means that the detail of the ice motion record is unavailable at the very end of the melt season and through the subsequent winter. However, using occasional GPS positions (Fig. 2a–d, dashed blue lines), horizontal ice motion can still be calculated over longer periods, allowing us to assess the net velocity increase in summer compared with winter. The values for net summer velocity over winter background reported in this paper are calculated on the basis of ice motion from the onset of speed-up (the beginning of the survey period in the case of site 1) until the end of summer, when melting has finished at all sites and the effect of 'slower than winter' motion that we observe in late summer has been incorporated—as such they may be considered minimum estimates of summer velocity.

The values for background velocities are derived from the displacement of each site over the subsequent winter, following the end of the summer melting period (between 11 October and 27 February at Site 1, 26 September and 2 May at site 2, 26 September and 8 May at site 3 and 11 October and 8 May at site 4). The reported contribution to annual ice flux from the hydrologically forced summer ice velocity variations is the percentage by which the observed displacement exceeds that which would occur if the ice flowed at calculated winter rates all year round. At sites 3 and 4, the pre-speed-up velocities bear close agreement with over-winter velocities, however, are not included in the calculations to retain consistency between the approach adopted for each site.

Measurements of air temperature were made using shielded HOBO air temperature sensors. PDDs, used as a proxy for rates of surface melting, are derived using mean daily air temperature. A lack of ablation data meant that it was not possible to obtain degree-day factors, which vary for ice and snow. However, accumulation rates are low in this part of Greenland and snow depths when the GPSs were deployed at the beginning of May were less than 20 cm.

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## Author contributions

All authors contributed extensively to the work presented in this letter. P.N. and D.M. conceived the project. M.A.K. processed the GPS data. I.B., P.N., D.M., A.H. and A.S. collected the field data. I.B. wrote the manuscript. All authors discussed the results and implications and commented on the manuscript.

## Additional information

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