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Greenland ice sheet motion coupled with daily melting in late summer

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[1] We use ground-based and satellite observations to detect large diurnal and longer-period variations in the flow of the Greenland Ice Sheet (GrIS) during late summer that are strongly coupled with changes in its surface hydrology. The diurnal signals are associated with periodic changes in surface melting, and the longer-period signals are associated with the episodic drainage of supra-glacial lakes. Ice velocity doubles around 2 hours after peak daily melting and returns approximately to wintertime levels around 12 hours afterwards, demonstrating an intimate link between the surface and basal hydrology. During late summer, the ice sheet accelerates by 35% per positive degree-day of melting. The observed link between surface melting and enhanced flow is typical of Alpine glaciers, which may provide an appropriate analogue for the evolution of the GrIS in a warming climate. **Citation:** Shepherd, A., A. Hubbard, P. Nienow, M. King, M. McMillan, and I. Joughin (2009), Greenland ice sheet motion coupled with daily melting in late summer, *Geophys. Res. Lett.*, *36*, L01501, doi:10.1029/2008GL035758.

1. Introduction

[2] The Greenland ice sheet (GrIS) is losing mass through increased surface melting [*Hanna et al.*, 2005] and accelerated glacier flow [*Rignot and Kanagaratnam*, 2006], and observations [*Zwally et al.*, 2002] have demonstrated an apparent correlation between these processes near to the equilibrium line. Supra-glacial lakes [*McMillan et al.*, 2007; *Sneed and Hamilton*, 2007] may contribute to this effect, as their episodic drainage through a process of hydrofracture enables water pathways (moulins) to develop through thick ice [*Das et al.*, 2008; *Fountain et al.*, 2005; *Luthje et al.*, 2006; *van der Veen*, 2007]. Because the climate of the GrIS is expected to warm over the 21st century, the prospect of accelerated sea level rise due to melting-induced acceleration of the GrIS has become a subject of concern [*Meehl et al.*, 2007].

[3] While the delivery of surface water to the base of the GrIS provides a mechanism for enhanced ice flow, the ice sheet models underpinning the 2007 IPCC sea level projections [*Meehl et al.*, 2007] did not include an assessment of its potential impact because a clear physical mechanism was lacking. Since then, however, a number of studies have documented aspects of the coupling; interferometric synthetic aperture radar (InSAR) observations [*Joughin et al.*, 2008] have characterised a seasonal speedup of ice along the western flank of the GrIS, ground-based observations [*Das et al.*, 2008] have demonstrated fracture-propagation to the ice sheet base during supra-glacial lake drainage followed by ice acceleration, and a Global Positioning System (GPS) survey [*van de Wal et al.*, 2008] has identified large and rapid melting-induced velocity changes which appear to have had no long-term (decadal) impact on ice-sheet motion. Here, we present GPS measurements along a flow-line of the GrIS that reveal an instantaneous coupling between ice motion and the daily cycle of surface melting.

2. Data and Methods

[4] We deployed GPS sensors along a flow-line of the Russell Glacier in southwest Greenland (Figure 1), on average 12 km from the "K-transect" [*van de Wal et al.*, 2008], to investigate controls on ice motion during late summer (days 201 to 206) in 2007. GPS were sited 37 km (site 1), 53 km (site 2), and 72 km (site 3) inland of the ice sheet margin on ice 890, 1050, and 1120 m thick, respectively [*Bamber et al.*, 2001]. The region is representative of most of the GrIS margin, the vast majority of which experiences summer melting [*Hanna et al.*, 2005], accumulates supra-glacial lakes [*Box and Ski*, 2007], terminates on land [*Weidick*, 1995], and is comparably thick [*Bamber et al.*, 2001]. GPS positions were determined [*Chen*, 1998] at 30-second intervals [*King*, 2004] relative to an off-ice reference station, and motion was constrained to suppress noise without over-smoothing the time-series. International GNSS Service satellite orbits were fixed [*Dow et al.*, 2005], solid-Earth tides were modelled and, in this region and over these baselines, ocean tide loading displacements effectively cancelled. Periodic signals due to GPS multi-path errors were small (<10 mm) relative to the ice motion. GPS positions were averaged over 3-hour intervals to determine ice velocity to an accuracy of $\sim$5 m yr^{-1}. Air temperature was recorded at each GPS site at 30-second intervals to an accuracy of 0.2°C.

[5] We used satellite observations to study changes in the hydrology and dynamics of the wider catchment. We monitored the seasonal evolution of supra-glacial lakes using 9 MODIS satellite images acquired over a 112 day period encompassing the dates of the GPS survey to estimate temporal changes in their area [*Box and Ski*, 2007], and we used an estimate [*McMillan et al.*, 2007] of the average depth of supra-glacial lakes obtained within the same region to estimate fluctuations in lake water discharge. We used satellite InSAR to characterise the ice sheet morphology and flow [*Joughin et al.*, 1996]; European

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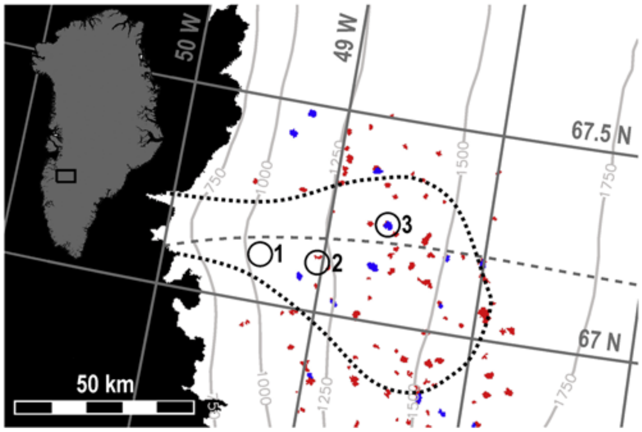

Figure 1. Location of GPS sensors sited at the Russell Glacier. Also shown are the supra-glacial lakes present before (red) and after (blue) the survey period, an approximate flow-line determined from the surface topography (grey dashed line), and the glacier drainage basin delimited from InSAR data (black dotted line).

Remote Sensing (ERS) satellite tandem (1-day repeat) data were used to determine the ice surface topography across a 5,750 km^2 area during winter 1996, while Radarsat Arctic Ice Mapping Mission (24-day) data were used to determine the seasonal fluctuation in ice speed at a location near to (7 km downstream of) GPS site 1 during 2006, and the wintertime level across the wider catchment.

3. Results

[6] The average rate of ice motion at GPS sites 1, 2, and 3 (Figure 1) was 166, 138, and 134 m yr^{-1}, respectively (Figure 2a). These data, however, also reveal that substantial diurnal and longer-period variations in ice motion occurred during the period of our survey. The diurnal signal, which at our lowest altitude site (site 1) amounts to a 110% fluctuation in speed, is greatest towards the ice sheet margin and diminishes inland. All sites also exhibit a simultaneous 1 to 4 cm diurnal uplift of the ice sheet surface (Figure 2b). A longer period 50 to 60% decrease in horizontal motion affected the inland sites (sites 2 and 3, Figure 2a). Both the diurnal and secular velocities reduce to within 10% of wintertime levels during the survey period.

[7] Although the diurnal signal is not captured in the satellite observations because their 24-day temporal resolution is too coarse, the average daily speedup recorded in the GPS data was 55%, and is comparable to the 60% speedup recorded by InSAR during the GPS survey period (late summer) relative to wintertime levels. On average, ice speed in this sector of the GrIS during late summer is 31% and 52% greater than in spring and winter, respectively. Near to GPS site 1, the averaged peak summertime velocity exceeds the wintertime minima by a factor of two (Figure 2c), and heightened speeds are sustained for around 100 days in summer. The seasonal velocity fluctuations result in an average annual speed that is 14% greater than in wintertime.

[8] Although correlated vertical and horizontal velocity changes occur in ice due to longitudinal strain-rate or stress-gradient coupling, the signals we observe cannot be attributed *solely* to these effects. While the magnitude of thickness changes originating due to longitudinal coupling may be comparable to the elevation changes we have recorded, thinning and acceleration at downstream sites would under normal circumstances lead to thinning upstream. However, the opposite behaviour (uplift) is observed at all three sites (Figure 2b). It is difficult, therefore, to attribute the periodic fluctuations in uplift and acceleration to the effects of longitudinal coupling alone.

[9] We considered the impact of fluctuations in surface hydrology on ice flow at each GPS location. First, we used the air temperature data and a PDD model [*Reeh*, 1991] to estimate the quantity of melt-water produced within the catchment. According to this model, melting ranged from 0.02 to 0.04 km^3 day^{-1} (Figure 2d), equivalent to an average runoff of between 0.5 to 1.0 cm day^{-1} across the 4,100 km^2 catchment - values that are comparable to the degree of uplift recorded by the GPS data. On each day of our survey, the quantity of melt-water was positively correlated (r = 0.81) with the degree of diurnal ice speedup (Figure 3) and, during late summer, the peak daily rate of

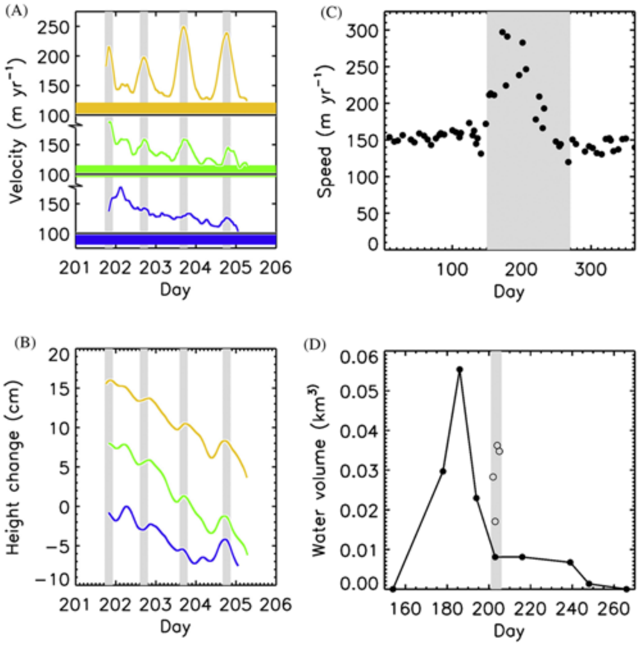

Figure 2. (a) Fluctuations in ice speed and height derived from GPS measurements at sites 37 km (site 1, yellow), 53 km (site 2, green) and 72 km (site 3, blue) inland of the ice margin at Russell Glacier in 2007. Also shown are winter 2006 velocities determined from InSAR (solid horizontal lines of matching colour). (b) Vertical motion at each site. Grey bars highlight the approximate periods of peak daily velocity. (c) Seasonal fluctuation in ice speed near to GPS site 1 derived from InSAR. (d) Estimated volume of water stored in supra-glacial lakes (solid circles) and generated via melting at the ice sheet surface (open circles) across a 4,100 km^2 sector. The periods of the lake and GPS observations are highlighted in grey in Figures 2c and 2d, respectively.

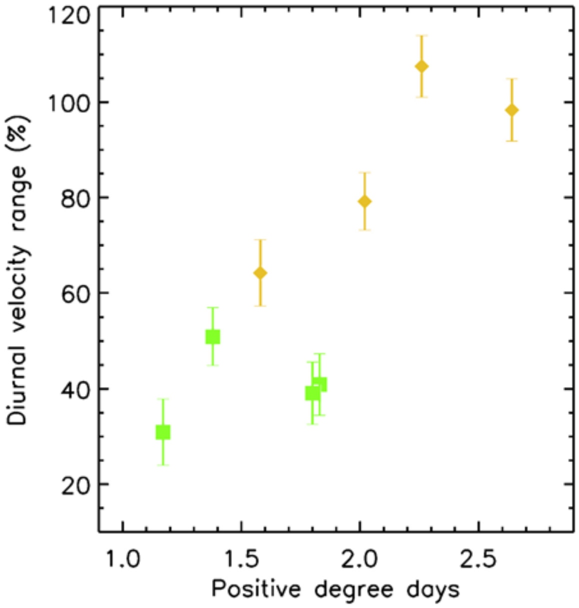

Figure 3. Scatter plot of positive degree days against diurnal velocity range at GPS sites 1 and 2 (yellow and green), which exhibit diurnal variation.

ice motion was 35% PDD^{-1} faster than the daily minimum. Next, we estimated the volume of water released via drainage of supra-glacial lakes (Figure 2d) by recording temporal changes in lake area using the MODIS imagery and by assuming an average lake depth of 2.7 m (a value determined [*McMillan et al.*, 2007] for ~150 lakes in this region in summer 2001). Lake discharge peaked 1–2 weeks prior to the GPS survey period, releasing ~0.05 km^3 of water predominantly at high elevations (above site 3) with no apparent latitudinal variation (Figure 1). Although ice speedup (Figure 2c) starts in early summer, as has previously been observed [*van de Wal et al.*, 2008], it is most pronounced after the cycle of lake-drainage (Figure 2d). Thereafter, diurnal velocity variations are driven and sustained by surface melting.

4. Discussion

[10] The coincident fluctuations in ice melting, elevation and velocity are consistent with the process of *jacking*, whereby hydraulically-efficient pathways (moulins) channel water from the ice sheet surface to its base. Diurnal fluctuations in velocity and uplift occur ~2 hours after the peak rate of surface melting in a region where ice is about a kilometre thick, suggesting water is transferred rapidly to the bed as commonly occurs in Alpine glaciers [*Fountain and Walder*, 1998]. Although the longer-period deceleration at sites 2 and 3 continues for several days after the majority of lakes have drained, the temporal resolution of the MODIS data is insufficiently fine to rule out a water supply from lakes that is distributed over a greater time period. The deceleration is also consistent with an increase in the hydraulic efficiency of the subglacial drainage system in response to a sudden input of surface melt-water [*Kamb*, 1987].

[11] The contrasting dynamical behaviour observed at the three GPS sites suggests differences in the structure and seasonal evolution of the sub-glacial drainage system. At site 1, the data are consistent with that of channelised subglacial drainage during the latter part of the melting-season, where the highest water pressures (and enhanced vertical uplift and horizontal motion) occur only during periods of peak melt-water input [*Iken and Bindschadler*, 1986; *Nienow et al.*, 2005]. At site 2, diurnal cycles are comparable in magnitude to a gradual deceleration during the survey period, suggesting that an additional longer-period perturbation is also affecting the subglacial drainage system. An obvious source of such a perturbation is the large volumes of water discharged from supra-glacial lakes prior to the survey period (Figure 2d), which may result in pressurisation of the drainage system over several days [*Box and Ski*, 2007]. At site 3, the dominant velocity signal is the longer-period deceleration with diurnal cyclicity on day 205, behaviour that is consistent with a gradual decrease in basal water pressure which occurs, for example, as hydraulic efficiency increases within a developing channelised drainage system [*Kamb*, 1987].

[12] The extent to which melting-induced fluctuations in motion will affect the GrIS mass over the 21st century remains uncertain. Although satellite observations [*Joughin et al.*, 2008] show that both land- and marine-terminating sectors of the GrIS exhibit seasonal flow variability, a 17-year GPS survey [*van de Wal et al.*, 2008] has shown that sectors of the GrIS margin have slowed down in the face of increased melting. The conclusions of numerical experiments are also equivocal; while a sensitivity study [*Parizek and Alley*, 2004] has predicted substantial mass losses from the GrIS if melting were to accelerate, another experiment [*Price et al.*, 2008] has demonstrated that seasonal variations in flow occurring far inland can be explained as the expression of a remote perturbation originating closer to the ice sheet margin – conditions that are normal and may in consequence have limited impact on the ice sheet even in a warming climate.

[13] From our data, we (i) confirm that the link between surface melting and velocity fluctuations [*Joughin et al.*, 2008; *van de Wal et al.*, 2008; *Zwally et al.*, 2002] is due to an instantaneous coupling of the surface and basal hydrology, and we establish that (ii) the forcing is local and not remote, (iii) the effect is widespread and not isolated, (iv) supra-glacial lakes are a key factor in priming water conduits linking the ice surface and base, and (v) that the coupling may be characterised via an empirical parameterisation suitable for modelling the ice sheet evolution.

[14] Questions remain as to the evolution of the GrIS in a warming climate. Details on the coupling between ice-motion and melting over a full season and at elevations above the equilibrium line are lacking. In Alpine glaciers, where melting-induced seasonal accelerations have long been studied, ice motion depends on variations in the structure, hydraulic-capacity, and efficiency of the subglacial drainage system, each of which evolve seasonally [*Bingham et al.*, 2003; *Kamb*, 1987]. Increases in the efficiency of drainage, for example, may ultimately lead to reductions in rates of ice flow. A greater understanding of flow-enhancement due to longitudinal and transverse coupling [*Price et al.*, 2008] is also required. To resolve these issues, ground-based velocity observations of comparable temporal resolution to those we present here, but of greater duration, and satellite-based

velocity observations of wider spatial extent than are currently available [*Joughin et al.*, 2008] are required.

5. Conclusions

[15] In late summer, a strong and instantaneous coupling exists between the surface and basal hydrology of the GrIS in a region where ice is over 1 km thick. Such a link has been long established in Alpine glaciers [*Iken and Bindschadler*, 1986; *Kamb*, 1987; *Nienow et al.*, 2005], which are considerably thinner, and their behaviour may provide an appropriate analogue for studying the evolution of the GrIS in a warming climate. A direct consequence of this coupling is that, under a warming climate, land terminating sectors of the GrIS will evolve in a manner that is currently not accounted for [e.g., *Gregory et al.*, 2004]. The detailed response of marine-terminating sectors of the ice sheet will, however, be complicated by other factors [*Joughin et al.*, 2008].

[16] The magnitude of the velocity fluctuations (50–100%) is comparable to those observed across discrete time intervals in decadal [*Rignot and Kanagaratnam*, 2006], monthly [*Joughin et al.*, 2008], and shorter-period [*van de Wal et al.*, 2008] surveys of the GrIS flow. A further consequence is that the interpretation of data acquired over periods shorter than the summer season requires care to avoid aliasing cyclical signals. Although the apparent correlation between ice melting and acceleration (Figure 3) provides a first step towards parameterisations of this coupling, until the physics associated with the hydrology of Alpine glaciers is incorporated into models of the GrIS, projections of its evolution in a warming climate will remain speculative.

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