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Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers

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[1] We present ice velocities from a land-terminating transect extending >115 km into the western Greenland Ice Sheet during three contrasting melt years (2009–2011) to determine whether enhanced melting accelerates dynamic mass loss. We find no significant correlation between surface melt and annual ice flow. There is however a positive correlation between melt and summer ice displacement, but a negative correlation with winter displacement. This response is consistent with hydro-dynamic coupling; enhanced summer ice flow results from longer periods of increasing surface melting and greater duration ice surface to bed connections, while reduced winter motion is explicable by drainage of high basal water pressure regions by larger more extensive subglacial channels. Despite mean interannual surface melt variability of up to 70%, mean annual ice velocities changed by <7.5%. Increased summer melting thereby preconditions the ice-bed interface for reduced winter motion resulting in limited dynamic sensitivity to interannual variations in surface melting. **Citation:** Sole, A., P. Nienow, I. Bartholomew, D. Mair, T. Cowton, A. Tedstone, and M. A. King (2013), Winter motion mediates dynamic response of the Greenland Ice Sheet to warmer summers, *Geophys. Res. Lett.*, *40*, 3940–3944, doi:10.1002/grl.50764.

1. Introduction

[2] Meltwater generated at the surface of the Greenland Ice Sheet (GrIS) drains through the ice into the subglacial hydraulic system and influences rates of basal motion by altering effective pressure at the ice-bed interface, defined as ice overburden minus subglacial water pressure. Lower effective pressure (i.e., higher water pressure) encourages faster sliding by reducing friction between the ice and its bed [*Iken and Bindschadler*, 1986]. Ice velocities in marginal areas of the GrIS are consequently greater in summer than winter [*Bartholomew et al*., 2010, 2012; *Joughin et al*., 2008; *Sundal et al*., 2011; *Van de Wal et al*., 2008; *Zwally et al*., 2002], and if the long-term relationship between meltwater production and ice motion is positive [*Zwally et al*., 2002], this mechanism could increase significantly GrIS mass loss under climate warming [*Parizek and Alley*, 2004].

[3] In response to sustained inputs of surface meltwater, however, theory and data suggest that subglacial drainage systems develop from hydraulically inefficient structures into efficient channels, which operate at lower pressures for a given discharge [*Kamb*, 1987; *Röthlisberger*, 1972; *Schoof*, 2010, *Cowton et al*., 2013], thereby reducing the lubrication effect of further meltwater inputs. This reasoning can explain why GrIS ice velocities in late summer are lower than those in early summer [*Bartholomew et al*., 2010; *Sundal et al*., 2011]. Recent theoretical [*Pimentel and Flowers*, 2011; *Schoof*, 2010], remote sensing, and field [*Sundal et al*., 2011; *Van de Wal et al*., 2008] studies have proposed that marginal ice will flow *more slowly* in higher melt years since subglacial channelization will occur more quickly in response to increased inputs of meltwater, thereby reducing the dynamic sensitivity of the GrIS to climate warming. However, these studies have been limited to areas close to the ice sheet margin [*Sundal et al*., 2011] or utilize measurements which cannot resolve the seasonal behavior that determines the observed interannual velocity variations [*Van de Wal et al*., 2008]. The dynamic behavior of the whole ablation zone in different melt seasons and the resulting impact on annual ice motion therefore remain uncertain.

2. Data and Methods

[4] We present data between May 2009 and May 2012 from seven sites along a land-terminating transect in west Greenland at ~67°N that extends 115 km from the ice margin to 1715 m elevation (Figure 1). At each site, we measured continuous site position and air temperature and annual ablation (see supporting information for details). Meltwater discharge was recorded from the Leverett Glacier hydrological catchment, incorporating our lowest three sites [*Bartholomew et al*., 2011b] (Figure 1). In the following analysis, mean winter velocities (MWV) for each site represent its average displacement over the 2009–2010, 2010–2011, and 2011–2012 winters (1 September–30 April).

3. Results and Discussion

[5] Mean summer (May–August) temperatures measured at our sites in 2010 and 2011 were 2.3°C and 1.1°C warmer, respectively, than in 2009. Catchment runoff was 92% and 19% greater in 2010 and 2011, respectively, than 2009, while mean surface melt increased by 70% and 34%, respectively (Figure 2b). National Centers for Environmental Prediction/National Center for Atmospheric Research reanalysis data show that May–August 1000 mb temperature anomalies in

Additional supporting information may be found in the online version of this article.

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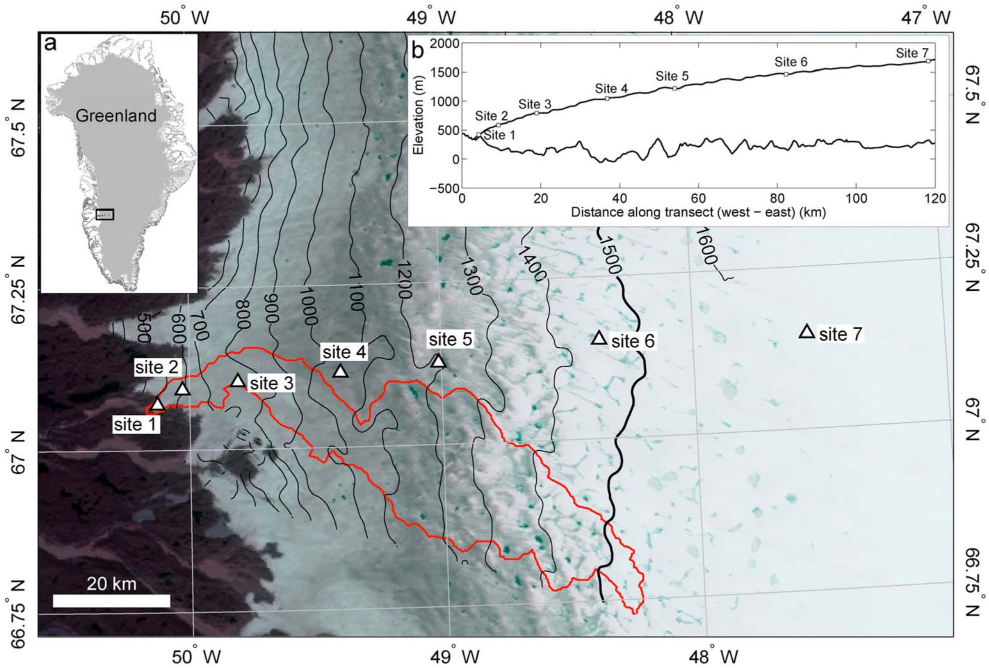

Figure 1. (a) Location of the study region on the western margin of the GrIS. (b) Ice surface and bed elevation along our transect as measured by IceBridge ATM (ILATM2) and MCoRDS (IRMCR2), respectively, in 2010 and 2011 [*Allen*, 2011]; main panel, location of GPS sites. Contours (100 m intervals) from a digital elevation model are derived from InSAR [*Palmer et al.*, 2011]. The bold contour (1500 m) represents the approximate equilibrium line altitude [*van de Wal et al.*, 2008]. The Leverett Glacier hydrological catchment is shown in red [*Bartholomew et al.*, 2011b].

west Greenland near to Kangerlussuaq (approximately 25 km west of site 1) were between −0.3 and +0.3°C in 2009 and 2011, and +2.4°C in 2010 (relative to the 1981–2010 mean). These contrasting melt characteristics provide an opportunity to evaluate the effect that increased summer temperatures, commensurate with predictions for climate warming over the next century [*Meehl et al.*, 2007], will have on GrIS ice motion.

[6] Along our transect, we measured daily summer velocities up to 300% above MWV. In each year, ice accelerated first near the ice sheet margin and then at progressively higher elevations (Figures 2c–2i) [*Bartholomew et al.*, 2010, 2011a; *Sundal et al.*, 2011]. We also observed end-of-melt-season slow-downs below MWV at sites 2 and 4 in 2009, 1–7 in 2010 and 1–6 in 2011 when daily velocities were up to 44% below MWV. While such minima have been observed in this region previously [*Bartholomew et al.*, 2010] and elsewhere in Greenland [*Colgan et al.*, 2011, 2012; *Joughin et al.*, 2008; *Zwally et al.*, 2002], their effect on interannual ice displacement variations has not been quantified.

[7] Mean annual ice velocity for sites 2–7 was 105.8 my^{-1} in 2009, 104.7 my^{-1} in 2010 (−1.0% cf. 2009), and 97.8 my^{-1} in 2011 (−7.5% cf. 2009) (Table S2). Site 1 is not included in this comparison because power failure in 2011 disrupted data collection. We found no statistically significant relationship ($r = 0.1$, $p = 0.9$) between annual ice displacement and surface melt at individual sites (Figure S1). In order to explain both the limited interannual ice flow variability and lack of a statistically significant relationship between annual ice flow and surface melt, we divided each year into "seasons." Summer is defined as 1 May to 31 August subdivided into early and late summer on 1 July; winter as 1 September to 30 April; and annual as 1 May to 30 April.

[8] Our summer data describe a significant positive correlation between normalized ice motion (see supporting information for details of normalization method) and surface melt ($r = 0.79$, $p < 0.05$) with most sites flowing faster in the warmer summers (Figure 3b). While additional sources of water, such as rainfall and geothermal and basal melting also contribute to the basal hydraulic system, they are typically small relative to surface melting, so we do not incorporate them into our analysis. There was however an exceptional rainfall event in 2011 which we discuss later. Each summer, the lowest sites showed the greatest speed-up above MWV with the effect attenuating inland (Figures 2c–2i, 3a and 3f). Sites 1–3, below 1000 m, recorded mean summer velocities 45.9 to 65.7% above MWV, while sites 5–7, above 1200 m, displayed mean increases of <34% (Figure 3f). The summer speed-up at our lowest sites started 20 and 35 days earlier in 2010 (2 May) than 2009 and 2011, respectively (Figures 2c–2i). Comparisons between the Leverett Glacier hydrographs and ice velocities at sites 1–3 (Figures 2b–2e) reveal that ice velocities were greatest while catchment discharge was rising, between 2 June and 17 July (45 days) in 2009, 8 May and 1 July (54 days) in 2010, and 9 June and 15 July (36 days) in 2011, and became subdued once discharge stabilized or declined. While meltwater inputs are consistently rising, our data suggest that steady state hydrological conditions do not apply, even once the subglacial drainage system has become channelized [*Bartholomew et* al., 2012, *Röthlisberger*, 1972]. Instead, enhanced ice velocities are sustained by constantly challenging the drainage system to accommodate larger volumes of water [*Bartholomaus et al.*, 2008; *Bartholomew et al.*, 2012].

[9] In summer 2009, site 7 did not speed-up appreciably above MWV (1.6%) and delimited approximately the

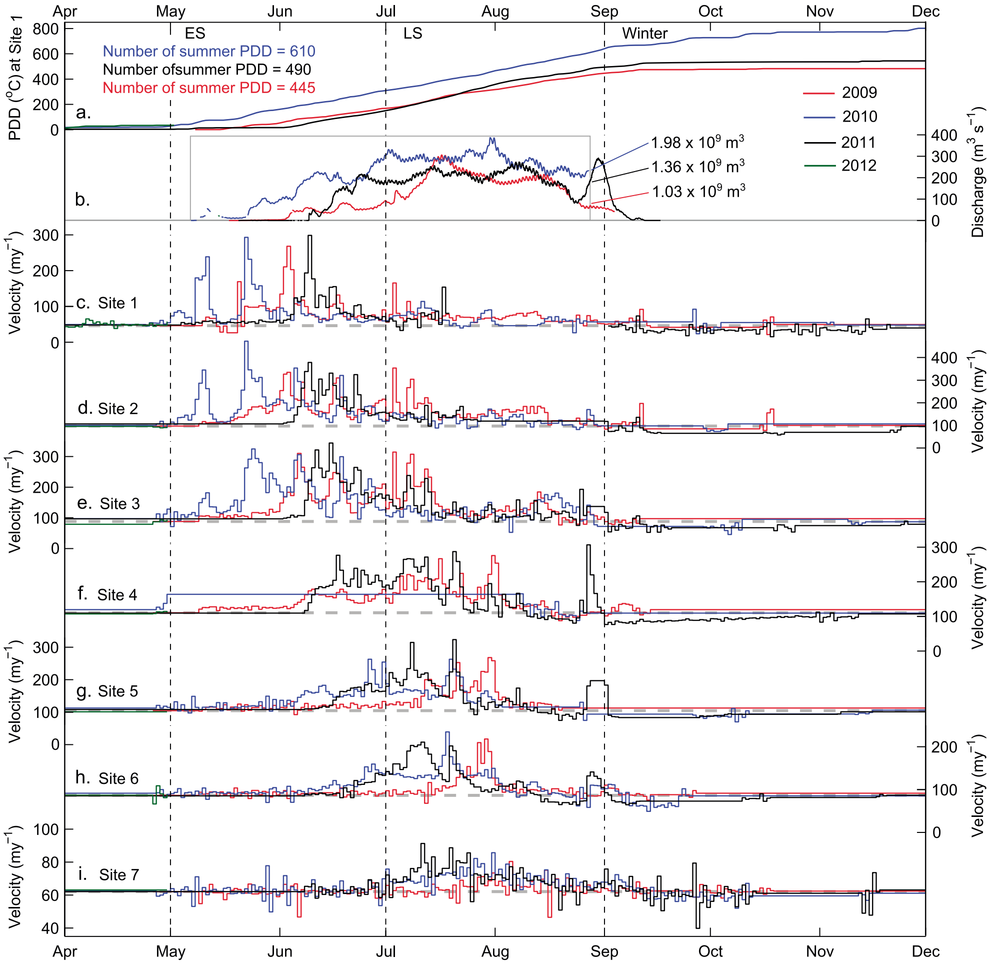

Figure 2. (a) Cumulative PDD at site 1 showing summer PDD sums (PDD calculated as described in the supporting information). (b) Discharge hydrograph for Leverett Glacier catchment with the cumulative discharge between 7 May and 27 August (delimited by the hollow grey box) for each year. (c–i) 24 h horizontal velocity at sites 1–7 for 2009, 2010, 2011, and the early part of 2012. Mean 2009–2010, 2010–2011, and 2011–2012 winter velocities for each site (MWV = grey dashed line) are also shown.

inland extent of hydrologically forced velocity variations [*Bartholomew et al.*, 2011a]. In 2010 and 2011, when the May–August mean temperatures at site 7 were 2.9°C and 2.7°C warmer than in 2009, increases in summer motion relative to MWV were 7.2% and 6.9%, respectively, indicating that ice flow variations propagate further into the ice sheet in warmer years (Figure 3a).

[10] The summer flow enhancement does not however typically result in increased annual ice displacement (Figure 3d) because warmer summers are generally followed by reduced winter ice flow. This is demonstrated by a significant negative correlation ($r = -0.55$, $p < 0.05$; Figure 3c) between normalized winter ice velocity and late summer melt (as characterized by Positive Degree Days (PDD)). Ice velocity typically reaches a minimum in early winter before recovering to within a few percent of MWV by the start of the next melt season (e.g., Figure 2f, 2011). This pattern of ice motion can also be explained by hydrodynamic coupling. The reduced sensitivity of ice flow to variations in meltwater input toward the end of each melt season, shown by our data and observed previously [e.g., *Bartholomew et al.*, 2011a], indicates that efficient channels extended beneath much of our transect during the late summer of each year. Such channels are however likely to be spatially limited to areas downstream from surface meltwater sources, with inefficient drainage elsewhere [*Hewitt*, 2011]. Once surface melting ceases at the end of the summer, the subglacial channels will operate at low pressure. We postulate that the resulting hydraulic gradient will drain water from adjacent areas of higher water pressure to the low pressure subglacial channels as observed over diurnal timescales at Alpine glaciers [*Hubbard et al.*, 1995], leading to a net reduction in basal water pressure and consequent decline in ice velocity [*Hewitt*, 2011]. By the end of each winter, measured ice velocities return to within a few percent of MWV at all our sites, presumably due to gradual repressurization of the subglacial hydraulic system from basal melting and channel creep closure [*Zwally et al.*, 2002]. We suggest that enhanced surface melting associated with warmer conditions in late summer is able to sustain larger and more widespread low-pressure subglacial channels. This in turn promotes more extensive and prolonged drainage of high pressure water from adjacent regions resulting in a greater drop in net basal water pressure and reduced displacement over the subsequent winter (Figure 3c).

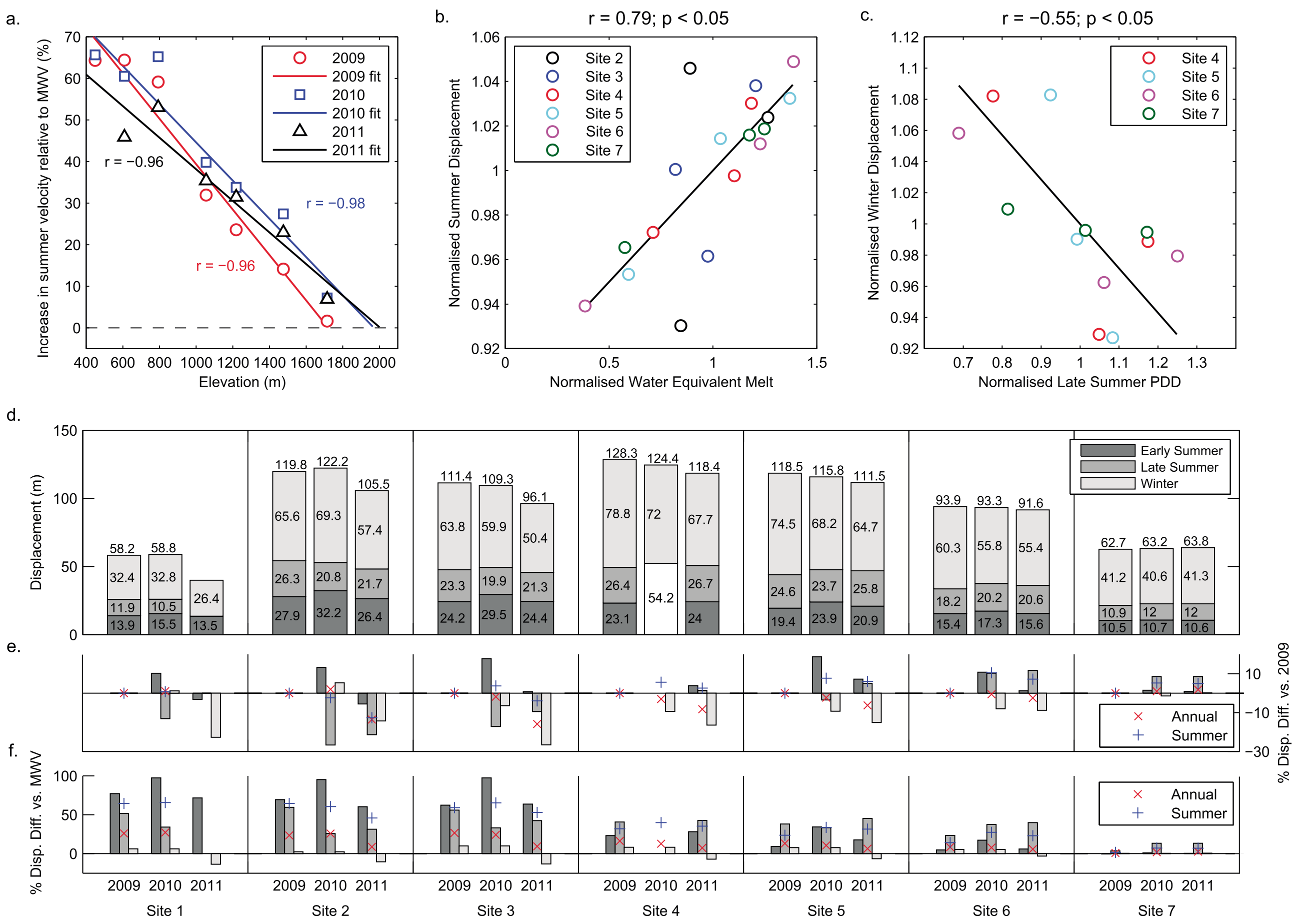

Figure 3. (a) Increase in summer ice velocity relative to MWV for all sites in 2009, 2010, and sites 2–7 in 2011. The extrapolated intercepts of zero percent (i.e., no difference with respect to MWV) and the respective best-fit lines represent estimates of the inland extent of summer ice flow variations. (b) Relationship between normalized water equivalent melt and normalized summer ice displacement. (c) Relationship between normalized late summer PDD and normalized winter ice displacement. Not all sites could be included in these statistical analyses due to GPS power failure in 2011 at site 1 and missing temperature data at sites 2 and 3. (d) Displacement at each site in 2009, 2010, and 2011 for early summer (dark grey), late summer (medium grey), and winter (light grey). (e) Difference in early summer, late summer, summer, winter, and annual ice displacement between 2009, 2010, and 2011 as a percentage of the 2009 value (same color scheme as above). (f) Difference between measured early summer, late summer, summer, winter, and annual ice displacement in 2009, 2010, and 2011 as a percentage of equivalent MWV (same color scheme as above). Missing late summer and annual data at site 1 in 2011, and early and late summer data for site 4 in 2010 (shown by the white bar) are due to several power failures as described in supporting information. Data contributing to this figure are included in Tables S1, S2, and S3.

[11] The net response is a general pattern of *faster* summer but *slower* winter ice flow in warmer years relative to cooler years (Figures 3d and 3e) with the opposing effects of *enhanced* summer and *reduced* winter velocity in warmer years acting to limit the effect of hydrodynamic forcing on annual ice motion. That ice displacements were further reduced in 2011, despite less extreme surface melt rates than in 2010 can be explained by the timing of runoff variations, and specifically a late summer event when annual discharge reached its maximum (Figure 2b). Sites 3–6 display a sharp increase in ice flow rate at the end of August, concurrent with the increase in runoff, indicating that the effect on the subglacial drainage system was widespread and not limited to the Leverett Glacier catchment. This unseasonal late summer runoff event was driven by exceptional rainfall (cumulative precipitation of 29.4 mm from 23 August to 2 September measured at the Danish Meteorological Institute meteorological station at Kangerlussuaq airport http://www.dmi.dk/dmi/tr13-11.zip) which is why it is not evident in the PDD record (Figure 2a). The rainfall-derived runoff would have reopened or enlarged existing subglacial channels leading to slower overwinter repressurization of the subglacial drainage system (e.g., Figure 2f) resulting in 2011 winter velocities across all sites that were on average 12.5% lower than in 2009. Interannual variations in winter velocity are thus as important as those in summer for determining annual ice displacement, and the prescription of a mean winter velocity based on combining several years' data precludes accurate comparison of ice displacement from one year to the next.

4. Conclusions

[12] We find no statistically significant correlation between normalized surface melt and annual ice flow. Splitting the data into "summer" and "winter" periods reveals that, while in warmer years, the ice generally flows faster in summer, it

also moves slower the following winter. Our results do not therefore support the hypothesis that increased surface melting will reduce summer ice flow due to earlier channelization of the subglacial drainage system [*Pimentel and Flowers*, 2011; *Sundal et al*., 2011; *Van de Wal et al*., 2008]. Instead, our data suggest that summer velocities will *increase* due to both longer melt-seasons and more prevalent unsteady conditions in subglacial channels. This annual pattern of ice motion is consistent with coupling to glacier hydrology; enhanced summer ice motion is caused by longer periods of consistently increasing surface melting and greater duration ice surface to bed connections, while reduced winter motion is induced via drainage of high basal water pressure regions by larger and more extensive subglacial channels.

[13] The net result is that despite interannual variations in mean surface melt of up to 70%, mean annual ice velocities changed by less than 7.5%. Increased summer melting may therefore precondition the ice-bed interface for reduced winter velocity limiting the ice sheet's dynamic sensitivity to interannual variations in surface temperature and melt. This self-regulating behavior can explain previous, apparently contradictory observations which show that (a) summer velocity enhancement scales with summer temperatures [*Bartholomew et al*., 2011a; *Zwally et al*., 2002]; while (b) over longer time periods, ice velocities decrease slightly, despite generally increasing surface melt [*Van de Wal et al*., 2008].

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