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Key Points:
- Ice flow in the accumulation area accelerated year-on-year between 2009 and 2012
- The acceleration correlates with the inland expansion of supraglacial lakes
- This dynamic response contrasts with observations from the ablation zone

Supporting Information:
- Readme
- Tables S1 to S5
- Figure S1
- Figure S2
- Data and methods

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Persistent flow acceleration within the interior of the Greenland ice sheet

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Abstract We present surface velocity measurements from a high-elevation site located 140 km from the western margin of the Greenland ice sheet, and ~ 50 km into its accumulation area. Annual velocity increased each year from 51.78 ± 0.01 m yr^{-1} in 2009 to 52.92 ± 0.01 m yr^{-1} in 2012—a net increase of 2.2%. These data also reveal a strong seasonal velocity cycle of up to 8.1% above the winter mean, driven by seasonal melt and supraglacial lake drainage. Sole et al. (2013) recently argued that ice motion in the ablation area is mediated by reduced winter flow following the development of efficient subglacial drainage during warmer, faster, summers. Our data extend this analysis and reveal a year-on-year increase in annual velocity above the equilibrium line altitude, where despite surface melt increasing, it is still sufficiently low to hinder the development of efficient drainage under thick ice.

1. Introduction

Our knowledge of the dynamics of the Greenland ice sheet (GrIS) has improved markedly over the last decade. The recent observation that reduced winter velocities offset faster summer velocities in warmer years [*Sole et al*., 2013], consolidated the seemingly contradictory findings that the magnitude of the summer acceleration correlates with surface melt intensity [*Zwally et al*., 2002], yet the long-term trend is of a slight decline in annually-averaged flow despite an increasingly negative surface mass balance [*van de Wal et al*., 2008]. *Sole et al*. [2013] argued that this regulating reduction in winter motion is caused by the evolution of a larger, more extensive subglacial drainage system in warmer summers, which drains regions of high basal water pressure and increases subsequent ice-bed coupling and traction. Although this process may hold for marginal areas of the ice sheet that experience intense summer surface melt and extensive delivery of meltwater to the basal interface (where the data supporting the hypothesis of *Sole et al*. [2013] were collected), it may be less effective at higher elevations, where melt rates are lower and ice thicknesses greater. Hence, we hypothesize that there exists an inland zone, most likely within and around the wet snow zone, that is characterized by enough surface melt to induce a seasonal acceleration but which is insufficient to develop the effective subglacial drainage required to regulate this acceleration through subsequent reduced winter flow. Although it has been speculated that the inland expansion of melt and supraglacial lakes (SGLs) will influence ice motion in this difficult to access zone [e.g., *Howat et al*., 2013; *Liang et al*., 2012], to date, velocity data have not been available to test this hypothesis. Field-based Global Positioning System (GPS) measurements are currently the only method capable of determining long-term changes in flow within the ice sheet's interior; remote-sensing techniques fail due to a lack of coherence [e.g., *Joughin et al*., 2010].

In this paper, we present a 5 year (September 2008–September 2013) time series of ice surface velocity measurements recorded by a dual-frequency GPS receiver located within the accumulation area. The aims of this analysis are (i) to report and evaluate the nature of the site's velocity record, particularly in relation to seasonality and interannual change and (ii) to evaluate the transferability of the self-regulation model of *Sole et al*. [2013] to higher elevations within the ice sheet's interior.

2. Data and Methods

We applied rigorous processing to dual-frequency GPS data sampled at a 10 s interval from September 2008 onward by a receiver deployed at the highest site (S10) on the land-terminating K-transect in West Greenland

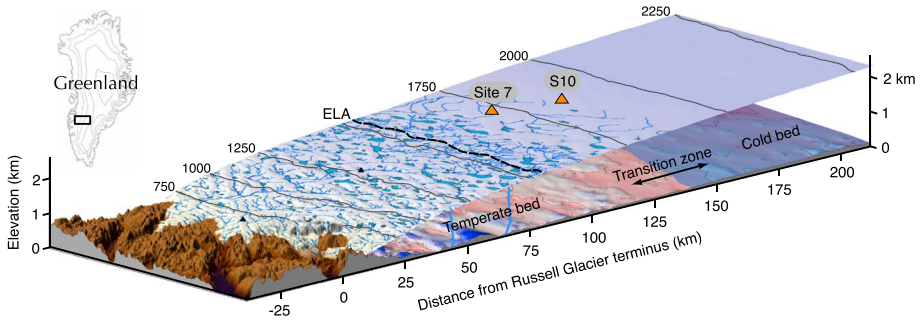

Figure 1. Cross section of Russell Glacier catchment showing the locations of the GPS sites, including S10 of this study and Site 7 of *Sole et al*. [2013]. The surface elevation is from *Howat et al*. [2014], the bed topography is from *Bamber et al*. [2013], and the basal thermal regime is conceptual. The maximum SGL and stream extent between 2002 and 2012, adapted from *Fitzpatrick et al*. [2014], and the mean 1990–2011 ELA of 1553 m asl [*van de Wal et al*., 2012] are also shown. The black box on the inset map shows the location of the study area in Greenland.

(Figure 1). S10 (N67.00°, W47.02°) is colocated with an automated weather station at 1840 m above sea level (asl), 140 km from the ice margin and more than 50 km inland from the 21-year-mean mass balance equilibrium line altitude (ELA) of 1553 m asl, as estimated by *van de Wal et al*. [2012]. These data, from five contrasting melt seasons (2009 to 2013), encompass high seasonal and interannual variability in melt conditions. Periods of power outage reduced the continuity of GPS measurements prior to April 2011. Although these outages do not degrade the long-term velocity record, they prevent analysis of transient velocity variations during the summers of 2009 and 2010 (Figure 2a). Long-term trends in velocity are reported using summer (1 May to 10 September), winter (10 September to 1 May), and annual (1 May to 1 May) periods. These surface velocity data are compared with contemporaneous meteorological variables [*van As et al*., 2012], proglacial discharge [*Hasholt et al*., 2013], and SGL data [*Fitzpatrick et al*., 2014]. Further details of the methods employed are given in the supporting information.

3. Results

The mean rate of ice motion at S10 between September 2008 and September 2013 was 52.26 ± 0.01 m yr^{-1} to the west (274.5°). Over this period, ice flow was consistently faster during the summer than the winter, and in the years with available data, the timing and amplitude of the seasonal velocity cycle correlates with the duration and intensity of the melt season (Figure 2). In 2011 and 2012, initial accelerations in May of ~ 1% above the mean winter velocity (51.89 m yr^{-1}), were followed by larger (5.2% in 2011 and 8.1% in 2012) and longer, midsummer velocity increases between June and September (Figure 2a). In the cooler 2013 summer, although still apparent, this seasonal pattern was retarded with a small initial acceleration of 1.3 to 1.7% above the winter mean persisting for longer into July before flow increased to 4.6% above winter values in early August (Figure 2a). Maximum velocity occurred in early August and in years with available data velocities returned to mean winter values, or below, by the end of September (Figure 2a). These patterns are consistent with previous observations from Greenland [*Fitzpatrick et al*., 2013; *Joughin et al*., 2010; *Joughin et al*., 2008; *Zwally et al*., 2002], which reveal that ice flow gradually increases over winter from an all year minimum in autumn. Within error, no short-term variation in surface elevation was detected, which lowered commensurate with downslope ice motion at a mean rate of 1.08 ± 0.06 m yr^{-1} (Figure S1).

Our velocity record from S10 (Figures 2a and 3a) supports observations of faster summer flow during warmer years [e.g., *Zwally et al*., 2002; *Sole et al*., 2013]. Mean summer velocity increased during successively warmer years, from 51.82 ± 0.04 m yr^{-1} in 2009 to 52.66 ± 0.04 m yr^{-1} in 2010 and 52.94 ± 0.04 m yr^{-1} in 2011, and was notably higher (53.96 ± 0.04 m yr^{-1}) during the record melt year of 2012 (Figure 3a). In contrast to previous studies [e.g., *van de Wal et al*., 2008], we also find evidence for a long-term increase in ice velocity at S10. Summer of 2013 was still the second fastest (53.18 ± 0.04 m yr^{-1}) on record despite cool conditions, and the previous winter velocity of 52.33 ± 0.02 m yr^{-1} was substantially above average—even exceeding the 2009 mean summer velocity by 0.5 m yr^{-1}. Excluding winter 2010/2011, year-on-year winter flow accelerated by ~ 0.05 ± 0.03 m yr^{-2} between 2009 and 2012 (Figure 3a; Table S1). These cumulative trends in summer and winter flow yield a long-term increase in mean annual surface velocity at S10 (Figure 3a; Table S2).

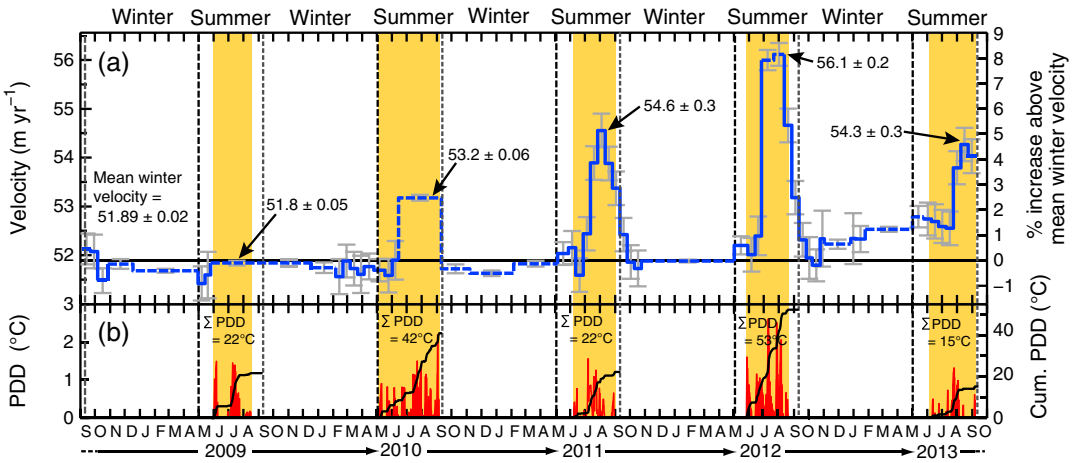

Figure 2. (a) Velocity at S10 between September 2008 and October 2013. Dashed lines indicate averaging periods longer than 15 days, which may reduce the apparent amplitude of velocity variations, particularly during summer 2009 and summer 2010. The horizontal grey line represents the mean winter velocity, averaged over all five winters, of 51.89 m yr^{-1}, (b) positive degree days (PDD) at S10 in red, with the cumulative PDD in black. The orange shading highlights the melt seasons at S10. The vertical dashed black lines and arrows delineate the summer (1 May to 10 September), winter (10 September to 1 May), and annual (1 May to 1 May) averaging periods used in this study.

4. Discussion

Drawing on existing glaciohydrological theory, *Sole et al.* [2013] posited that enhanced ice motion across the ablation area during warmer summers is offset by reduced winter velocities caused by the drainage of areas of high basal water pressure by larger and more extensive subglacial channels. Our observations at S10 of higher winter velocities following warmer, faster summers, and the ensuing year-on-year increase in net flow (Figure 3a), contrasts with these findings of *Sole et al.* [2013], which are based on the analysis of GPS data from sites within the ablation area. The year-on-year annual flow acceleration measured at S10 (1840 m asl) is, however, consistent with their uppermost GPS site (Site 7; 1715 m asl), which is also located above the ELA (Figure 4). Between 2009 and 2012, the mean annual (May to May) increase in velocity at S10 of 0.7% per year is directly comparable to the 0.9% increase per year between 2009 and 2011 at Site 7 of *Sole et al.* [2013]. The seasonal variations in velocity—the percentage summer increase above the subsequent winter mean—are also similar, with the 0.1% (2009), 1.8% (2010), 2.0% (2011), and 3.0% (2012) measured at S10 comparable to, though expectedly lower than the 0.2% (2009), 7.2% (2010) and 6.9% (2011) seasonal accelerations measured at Site 7.

We argue that although the observations of net flow acceleration at S10 and Site 7 conflict with the main conclusions of *Sole et al.* [2013], they remain compatible with generalized glaciohydrological theory [e.g., *Fountain and Walder*, 1998; *Hubbard and Nienow*, 1997; *Iken and Truffer*, 1997; *Rothlisberger and Lang*, 1987; *Schoof*, 2010] by considering the reduced likelihood of developing an effective subglacial drainage system in the ice sheet's interior. Such development will be hindered by at least two factors. First, lower rates of surface meltwater production and runoff over a shorter melt season at higher elevations result in substantially lower volumes of melt being delivered to the ice sheet's basal drainage system [*van As et al.*, 2012], thereby reducing the capacity of that system to develop an efficient network [*Pimental and Flowers*, 2010; *Schoof*, 2010]. Second, across and above the ELA, and away from the relatively thin ablation area, ice thickness exceeds 1200 m [*Bamber et al.*, 2013, Figure 1]. At S10, radio echo sounding indicates an ice thickness of 1590 ± 17 m. Under these conditions, high overburden pressures at the bed would theoretically force rapid (~ 1 h at S10) creep closure of any subglacial channel or cavity not completely pressurized to overburden [e.g., *Nye*, 1953; *Hooke et al.*, 1990; *Chandler et al.*, 2013]. This compares with several days for creep-closure of ice of a few hundred meters thickness at the margin [*Nye*, 1953; *Chandler et al.*, 2013]. Both of these inferences are supported by recent observations. Repeat tracing experiments suggest that (i) an efficient, channelized subglacial drainage system does develop during the melt season up to at least 41 km from the ice margin, (ii) that this system is pressurized more than 7 km from the margin, and (iii) that an inefficient, distributed drainage system is likely to dominate further inland [*Chandler et al.*, 2013]. Furthermore, at two sites, 17 and 34 km from the ice margin, *Meierbachtol et al.* [2013] observed continuously high borehole water pressures,

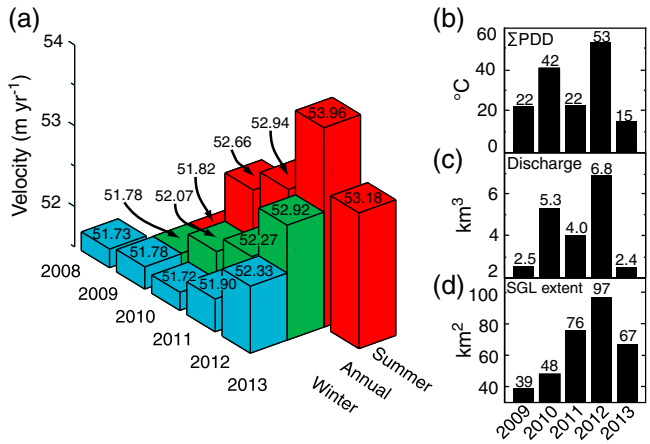

Figure 3. (a) Mean winter, annual, and summer velocities at S10 between 2009 and 2013, (b) the PDD sum at S10, (c) the total annual proglacial discharge at Watson River Bridge, and (d) the areal extent of high-elevation SGLs (those above 1400 m asl) in our study area. The data contributing to (a) are listed in Tables S1 to S3. Correlation coefficients between these variables are listed in Table S5.

which, although spatially limited, are inconsistent with drainage through an extensive network of low-pressure channels. Given these theoretical inferences and limited observations from up to 50 km from the ice margin, it is plausible that the mechanism of self-regulation invoked by *Sole et al.* [2013] across the ablation area is not prevalent at higher elevations within the ice sheet's interior.

The five contrasting melt seasons analyzed in this study provide an opportunity to examine the dynamic response of the GrIS's interior to variations in atmospherically forced melt, which we characterize using positive degree days (PDDs) and proglacial discharge (Figure 3). For the five melt seasons (2009 to 2013) the respective total PDDs at S10 were 21.7, 42.0, 21.9, 53.1, and 15.1°C (Figure 3b). The corresponding totals in proglacial discharge of 2.5, 5.3, 4.0, 6.8, and 2.4 km^3 show a similar interannual variation as the PDD sum ($r^2 = 0.96$, $p = 0.01$), with the exception of 2011 when discharge was disproportionately large (Figure 3c; Table S5). The fastest annual and summer flow at S10 occurred in 2012: a record melt season [*Nghiem et al.*, 2012] distinguished by unprecedented proglacial discharge and the highest PDD sum at S10 (Figure 3). In contrast, the year with the lowest annual and summer velocity, 2009, had the second lowest PDD sum (21.9°C) and proglacial discharge (Figure 3). Comparing the S10 velocities during the two coldest years (2009 and 2013) reveals that the PDD sum cannot, however, fully explain the interannual variations in velocity at S10. During 2009 (second coldest), velocities were low and the seasonal variation was minimal (0.1%). In contrast, the coldest summer of 2013 was the second fastest with a distinct, albeit lagged, seasonal acceleration (Figures 2a and 3).

A lack of observable crevasses, moulins, and seasonal surface uplift (Figure S1) indicates that surface water is unlikely to be accessing the bed directly beneath S10. Nevertheless, strain perturbations can be transmitted on the order of tens of kilometers by longitudinal (along-flow) stress-gradient coupling [*Hindmarsh*, 2006; *Kamb and Echelmeyer*, 1986; *Price et al.*, 2008]. Hence, the flow perturbations at S10 could have their origin down glacier where the presence of crevasses, rapidly draining SGLs, and moulins indicate that surface meltwater is directly accessing the bed. Although melt is inherently diffuse, the delivery of surface water to the bed is focused—in both space and time—by SGL drainage. Indeed, it is widely recognized that SGLs, which have formed at successively higher elevations during warmer summers over the last three decades [*Fitzpatrick et al.*, 2014; *Howat et al.*, 2013; *Liang et al.*, 2012, Figure S2], play an important role in establishing the hydraulic pathways that enable surface water to directly access the ice-bed interface through kilometer-thick ice [e.g., *Das et al.*, 2008; *Doyle et al.*, 2013].

In West Greenland, the elevation of the highest SGL increased from 1670 m asl in the mid-1980s to above 1800 m asl in 2011—representing an inland expansion of SGLs of 30 km that closely tracked the rising ELA [*Howat et al.*, 2013]. The elevation of the highest SGL in our study area increased from 1689 m asl in 2009 to 1790 m asl in 2010 and 1827 m asl in 2011, where it reformed in 2012 and 2013 (Figure S2). That no higher SGLs formed during the record melt year of 2012 compared to 2011 suggests a limit or pause in the inland expansion of SGLs. Although it has been suggested that the paucity of surface depressions in the interior may

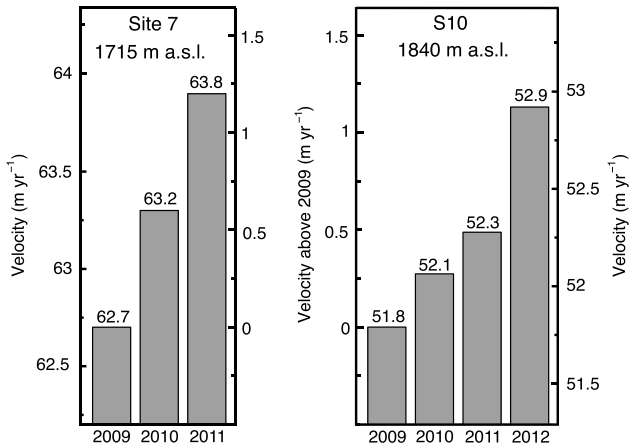

Figure 4. Annual velocity at Site 7 of *Sole et al.* [2013] and S10. The center axes show the speed above the respective 2009 velocity.

hinder the formation of SGLs [*Howat et al.*, 2013], it is also possible that the storage capacity of the firn has not yet been attained at these higher elevations [*Harper et al.*, 2012]. That the same high-elevation SGLs formed again in the relatively cold year of 2013 does, however, suggest that SGLs are self-sustaining—possibly through deepening of the lake bed by increased radiation absorption, and through the establishment of a surface drainage network, which feeds them and persists from year to year. Hence, once established, SGLs appear to reform readily in the same, high-elevation surface depressions in subsequent summers even if significantly cooler.

In our study area, the spatial extent of SGLs above 1400 m asl (hereafter termed the high-elevation SGL extent), which increased each year from 2009 to 2012, appears to scale with ice motion at S10 (Figure 3). The high-elevation lake extent shows significant positive correlation ($r^2 > 0.9$; $p < 0.1$) with mean summer, winter, and annual velocities at S10 (Table S5). The rate of inland SGL expansion even surpassed increases in atmospheric forcing. For example, despite a lower PDD sum in 2011, high-elevation SGLs were still more extensive than they were in 2010 (Figure 3). Annual total proglacial discharge was also disproportionately large in 2011 relative to the PDD sum (Figure 3). This disparity can be explained by abnormally low snowfall during the previous winter [*Box et al.*, 2011] and the progressive interannual decline in surface albedo [*Box et al.*, 2012], which increased melt generation and runoff disproportionately at high elevations during 2011 [*Box et al.*, 2011; *van de Wal et al.*, 2012]. Furthermore, the areal extent and upper limit of high-elevation SGLs was abnormally large during the relatively cold 2013 melt season (Figures 3d and S2). Hence, together with an inland migration of the ELA [*van de Wal et al.*, 2012] and the associated decrease in storage and refreeze potential of the firn, we suggest that low snowfall and surface albedo were responsible for the disproportionate increase in melt and SGL formation at high elevations between 2009 and 2013.

As SGLs expand inland, surface water may reach new areas of the bed, increasing the energy flux to this potentially frozen basal zone. It has also been hypothesized that the latent and sensible heat released by refreezing will warm the ice sheet, reducing its viscosity and enhancing internal deformation [*Phillips et al.*, 2010]. The increase in mean winter velocity at S10 following the exceptional 2012 melt season (Figure 3a)—which cannot be directly attributed to surface melt water accessing the bed during winter—could reflect such changes in rheology or basal conditions [*Phillips et al.*, 2010]. That annual ice velocity was faster at S10 during the record melt year of 2012 compared to the relatively cold year of 2009 is at odds with the observations of *Tedstone et al.* [2013] from the ablation area, which extend the time series of *Sole et al.* [2013] into 2012. Furthermore, the subsequent winter (2012/2013) at S10 was substantially faster (52.33 ± 0.02 m yr^{-1}) than all previous winters (mean = 51.78 ± 0.02 m yr^{-1}) and even exceeded the 2009 summer mean. These results suggest that the exceptional runoff during the 2012 melt season caused a fundamental change in basal conditions and ice dynamics in the vicinity of S10. Possible explanations include increased water storage at the bed following the 2012 melt season resulting in sustained higher subglacial water pressures and reduced basal traction, or increased energy flux into this potentially frozen zone, warming the ice, enhancing internal deformation, and/or decoupling frozen sticky spots. Thus, although summer flow acceleration at S10 reveals a direct response to surface meltwater production, the important observation that winter flow is also increasing

suggests a longer-term structural change in the subglacial hydrothermal regime, possibly associated with an increased flux of meltwater and energy to the ice-bed interface. Further and more direct observations (e.g., borehole instrumentation and repeat geophysical surveys to determine changes in the material and thermal properties of the bed) would be required to explain definitively why the velocity at S10 increased between 2009 and 2012, especially with regard to the increase in mean winter velocity following the exceptional melt in summer 2012.

Although the 2.2 % net velocity increase at S10 between 2009 and 2012 is modest, it should be noted that it has been previously assumed [e.g., *Colgan et al*., 2009; 2012; *Phillips et al*., 2013] that the ice sheet's interior does not experience any variation in flow. The implicit assumption in these studies is that ice motion can be attributed to internal deformation alone, which would not be expected to vary on short, seasonal timescales. Furthermore, from mass continuity considerations, as the ice thickness at S10 (1590 m) greatly exceeds that closer to the margin, the impact of any given net change in ice flow on mass flux here will be substantially greater compared to downstream zones, nearer the ice margin. Finally, although these observations of a year-on-year increase in annual velocity are limited to just two locations above the ELA (and we are unaware of any other GPS observations from this interior zone of the ice sheet), we speculate that such behavior could be pervasive over a broader lateral swath of the ice sheet's wet snow zone, since flow in this interior region may be less constrained by basal topography, which channels flow into distinct outlet units within the ablation zone [*Palmer et al*., 2011; *Fitzpatrick et al*., 2013; *Joughin et al*., 2008; 2010].

5. Conclusions

A 5 year time series of surface velocity measurements from a GPS receiver located 140 km from the ice margin reveals that seasonal variations in ice motion, of up to 8% above the winter mean, occur at least 50 km upglacier of the long-term mean ELA. Summer velocities at this site reflect variations in surface melt modulated by SGL drainage. The year-on-year increase in annual velocities at S10 between 2009 and 2012 suggests that an increased penetration of water to the ice-bed interface at successively greater distances from the ice margin is driving faster ice motion at high elevations on the GrIS.

Two distinct patterns of ice dynamic response to atmospheric forcing have now been observed. In the ablation area, *Sole et al*. [2013] argued that channelized subglacial hydrology regulates ice flow through reduced winter velocities following warmer, faster summers. Above the ELA, we find that winter, summer, and annual velocities followed an increasing trend between 2009 and 2013. Finally, in accordance with *Truffer et al*. [2005], we caution against extending observations from Alaskan glaciers [*Burgess et al*.,2013], as well as from the ablation zone [*Sole et al*.,2013; *Tedstone et al*.,2013] to interior regions of the GrIS, where greater ice thickness and lower melt precludes the development of efficient subglacial drainage and its regulating influence on ice flow.

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