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Key Points:
- Annual and seasonal ice velocities show no statistically significant relationship with annual runoff magnitude and variability
- Velocities in the North Lake region decreased during our 7 year observation period (-0.9 ± 1.1 m yr^{-2} from 2007 to 2013)
- Decreasing velocities with increasing melt are not necessarily evidence for a direct hydrologic mechanism acting on multiple-year timescales

Supporting Information:
- Supporting Information S1

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Greenland Ice Sheet flow response to runoff variability

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Abstract We use observations of ice sheet surface motion from a Global Positioning System network operating from 2006 to 2014 around North Lake in west Greenland to investigate the dynamical response of the Greenland Ice Sheet's ablation area to interannual variability in surface melting. We find no statistically significant relationship between runoff season characteristics and ice flow velocities within a given year or season. Over the 7 year time series, annual velocities at North Lake decrease at an average rate of -0.9 ± 1.1 m yr^{-2}, consistent with the negative trend in annual velocities observed in neighboring regions over recent decades. We find that net runoff integrated over several preceding years has a negative correlation with annual velocities, similar to findings from the two other available decadal records of ice velocity in western Greenland. However, we argue that this correlation is not necessarily evidence for a direct hydrologic mechanism acting on the timescale of multiple years but could be a statistical construct. Finally, we stress that neither the decadal slowdown trend nor the negative correlation between velocity and integrated runoff is predicted by current ice-sheet models, underscoring that these models do not yet capture all the relevant feedbacks between runoff and ice dynamics needed to predict long-term trends in ice sheet flow.

1. Introduction

The rate of mass loss from the Greenland Ice Sheet is accelerating [*Shepherd et al*., 2012; *Enderlin et al*., 2014] due to increases in surface melt [*van den Broeke et al*., 2009; *Hanna et al*., 2013] and changes in ice sheet dynamics [*Pritchard et al*., 2009]. *Zwally et al*. [2002] presented the first in situ observations of summer ice-flow acceleration in Greenland's ablation zone and proposed that during summer months surface meltwater accesses and lubricates the ice-bed interface promoting enhanced basal sliding. This observed coupling between surface melt and ice-sheet velocities suggests a potential mechanism for a widespread dynamic response of the ice sheet to increased temperature forcing. These findings sparked a series of Global Positioning System (GPS) measurements of ice flow to test this hypothesis (Figure 1a) and to provide better constraints on the present and future dynamical component of ice-sheet mass loss [*Solomon*, 2007; *Stocker*, 2014]. With the addition of new data sets, a more detailed picture of seasonal to interannual ice-flow variability has emerged. However, contrasting ice-flow response to melt over different timescales continues to present a challenge to the interpretation of the physical processes underlying this variability.

Similar to the results of *Zwally et al*. [2002], observations of ice flow and surface mass balance in a land-terminating region of western Greenland show that velocities increase in tandem with surface melt on daily-to-weekly timescales [*van de Wal et al*., 2008, 2015]. Multiple observations from regions of slow-moving ($< \sim 100$ m yr^{-1}) ice sheet flow support the depiction of a characteristic annual velocity curve (Figure 1b) with the following: (1) slow velocities through the winter and spring, (2) a sharp increase in velocities at the onset of surface melt, (3) fast and variable velocities during summer months, and (4) a velocity minimum near the end of the melt season [*Zwally et al*., 2002; *Bartholomew et al*., 2010; *Hoffman et al*., 2011].

Velocity and hydrological observations first made on temperate alpine glaciers (reviewed by *Fountain and Walder* [1998]) led to the development of a conceptual model for subglacial drainage system evolution that can explain the seasonally varying components of the characteristic annual velocity curve for temperate alpine glaciers and the Greenland Ice Sheet [*Chandler et al*., 2013; *Cowton et al*., 2013]. This model suggests

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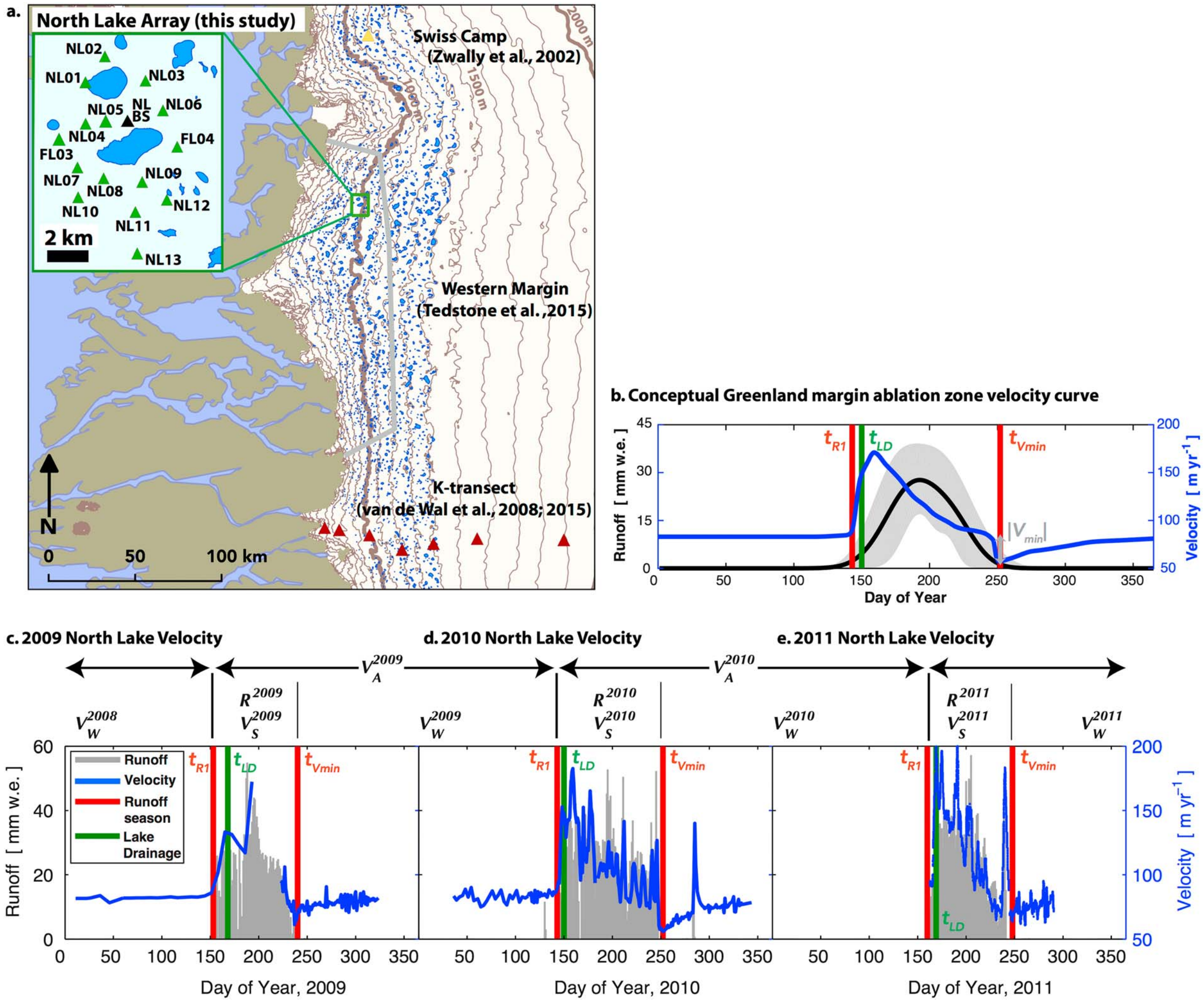

Figure 1. Greenland Ice Sheet marginal velocity campaigns. (a) Swiss Camp (yellow), North Lake (green and inset), and K-transect (red) GPS campaigns. Blue circles show maximum extent of supraglacial lakes up to 1400 m asl from 2000 to 2010 from *Yang et al*. [2015]. Brown contours show ice sheet surface elevation 100 m contours from *Howat et al*. [2014]. Western margin region of *Tedstone et al*. [2015] study in grey. (b) Conceptual ablation zone velocity curve (blue) and daily runoff $\pm 1\sigma$ in mm water equivalent (w.e.) for the North Lake region from 1958 to 2014 (black). (c) Weekly resolution and (d–e) 24 h resolution ice velocities from the North Lake GPS array (blue) plotted with daily runoff estimates (grey bars) for the North Lake region for a representative multiyear period 2009–2011. The dates of the start and end of the runoff season used to calculate seasonal velocities are shown with red bars. North Lake drainages are shown with green bars. Velocity records for all years (2006–2014) are shown in Figure S1.

that when meltwater input is low, the ice-bed interface is characterized by a slow, inefficient “distributed” subglacial hydrologic system of thin sheets, cavities, and/or porous flow through sediments. As meltwater input increases, the drainage system evolves toward a more efficient, “channelized” network of dendritic channels that draws water out of the distributed system. As the subglacial system channelizes over the melt season, this more efficient drainage system operates at lower water pressure. With this water pressure drop, a greater region of the ice sheet is in contact with the bed, leading to greater frictional coupling and reduced velocities in the second half of the melt season [*Schoof*, 2010; *Hoffman et al*., 2011]. In this model, seasonal surface melt modulates the annual velocity curve by changing basal drag; however, numerous observations show that velocity averaged over the entire year is largely insensitive to the magnitude of annual melt [*van de Wal et al*., 2008, 2015; *Sole et al*., 2013; *Tedstone et al*., 2013]. This insensitivity to melt forcing has been proposed to result from seasonal compensation between summer speedup and subsequent winter slow-down, resulting in a self-regulated system [*Sole et al*., 2013].

Yet while the shape of the annual velocity curve (Figure 1b) appears to be robust, questions remain regarding how time-averaged ice-sheet velocities respond now and in the future to long-term variability and/or trends in melt input. Specifically, a multidecadal decline in velocity has been observed in concert with increasing melt across predominantly land-terminating regions of the western Greenland Ice Sheet (notably the K-transect [*van de Wal et al*., 2008, 2015] and the ablation zone south of Jakobshavn-Isbræ [*Tedstone et al*., 2015]) (Figures 1a, 3g, and 3h). Furthermore, *Tedstone et al*. [2015] found an improved correlation when comparing 3–4 years of average past runoff with ice speed. Based on this relationship, they proposed that ice flow may respond to integrated past runoff over a multiyear timescale through a cumulative reduction of stored water in the unchannelized portions of the subglacial hydrologic system reducing basal lubrication and slowing ice velocities. The observed regional slowdown, however, is spatially variable and most pronounced near the margin below 900 m above sea level (asl). This poses the question as to how representative this effect is and whether differences in the subglacial drainage system, and therefore the dynamic ice response to increasing melt input, may vary as a function of ice thickness and/or the distribution of meltwater input to the bed.

Clearly, more and longer multiyear to decadal observations are needed to investigate relationships between meltwater runoff and ice velocity on seasonal to decadal timescales and to test the various hypotheses put forward thus far. Here we analyze a 7 year record (2007–2014) of ice flow collected using an array of GPS stations ~50 km south of the Jakobshavn-Isbræ catchment (Figure 1a). The array was situated around North Lake (68.72°N, 49.50°W), a supraglacial lake located at an elevation of ~1000 m asl. Based on the GPS data, we calculate seasonal and annual velocities alongside melt season runoff characteristics (e.g., magnitude and variability). With the K-transect and Swiss Camp observations, our data represent the third 5+ year GPS record for Greenland. In contrast to the longer-term Landsat data set along the western margin [*Tedstone et al*., 2015], our continuous GPS record provides seasonal resolution, allowing investigations of interannual flow variability at critical periods of the year, potentially providing more insight into the dynamics of the hydrological processes underlying the ice-flow variability. We examine our findings alongside the two other available decadal records to evaluate ice-flow variability on multiyear to decadal timescales and improve our understanding of the factors driving variability in annual ice velocity in the ablation region.

2. Methods

A GPS array consisting of 1–16 receivers was deployed at North Lake from July 2006 to July 2014 (Figure 1a) [*Das et al*., 2008; *Joughin et al*., 2008; *Stevens et al*., 2015]. The station data were processed individually with Track software [*Chen*, 1998] as kinematic sites relative to the 30 s resolution Greenland GPS Network KAGA base station on bedrock ~55 km away [*Bevis et al*., 2012; *Stevens et al*., 2015]. Continuous (Figures 1c–1e and S1 in the supporting information) and seasonal ice surface velocities (Figure 2a) are calculated from the horizontal GPS position estimates. For years 2011–2014 where multiple GPS stations are available, the velocities of all online stations are averaged at 30 s intervals to produce a composite, continuous velocity across the array (Text S4 and Figures 1e and S1f–S1i). The time periods over which annual and seasonal displacements (Figure 2c) and velocities (Figures 2b and 2d) were calculated are based on runoff estimates from the 11 km resolution Regional Atmospheric Climate Model (RACMO) v. 2.3 [*Noël et al*., 2015]. These runoff estimates are statistically downscaled using elevation dependence to 1 km resolution [*Noël et al*., 2016] based on a downsampled version of the Greenland Ice Mapping Project digital elevation model [*Howat et al*., 2014] (Figures 1c–1e). The start of each year is defined as the date of the 1st percentile of each year's cumulative runoff curve, $\boldsymbol{t_{R1}}$ (Figures 1b–1e). Annual velocities ($\boldsymbol{V_A}$) are split into summer velocities ($\boldsymbol{V_S}$) and winter velocities ($\boldsymbol{V_w}$). Summer velocities are calculated from $\boldsymbol{t_{R1}}$ to $\boldsymbol{t_{V\,\mathrm{min}}}$, the latter of which represents the midpoint within the characteristic velocity minimum at the end of the melt season (Figures 1b–1e). Winter velocities are calculated from $\boldsymbol{t_{V\,\mathrm{min}}}$ to $\boldsymbol{t_{R1}}$ of the following year. Because each year in the time series has different runoff characteristics, the start and end of the runoff season do not fall on consistent calendar dates (Figures 1c–1e, 2a, and S1 and Table S1). Using this method, we calculate annual and seasonal velocities for melt seasons 2007–2013. In order to improve comparisons of our results to the prior studies of *Sole et al*. [2013] and *van de Wal et al*. [2015], we also calculate seasonal and annual velocities using their fixed calendar dates method. The resulting North Lake interannual trends are nearly identical regardless of the method used to delineate seasons (supporting information Text S4, Figure S2, and Table S3).

We use the RACMO output to calculate total runoff magnitude ($\boldsymbol{R}_{\mathrm{mag}}$) in m water equivalent (w.e.), seasonal variability in runoff ($\boldsymbol{R}_{\mathrm{var}}$), and season length ($\boldsymbol{R}_{\mathrm{length}}$) for each year. We estimate the timing of North Lake

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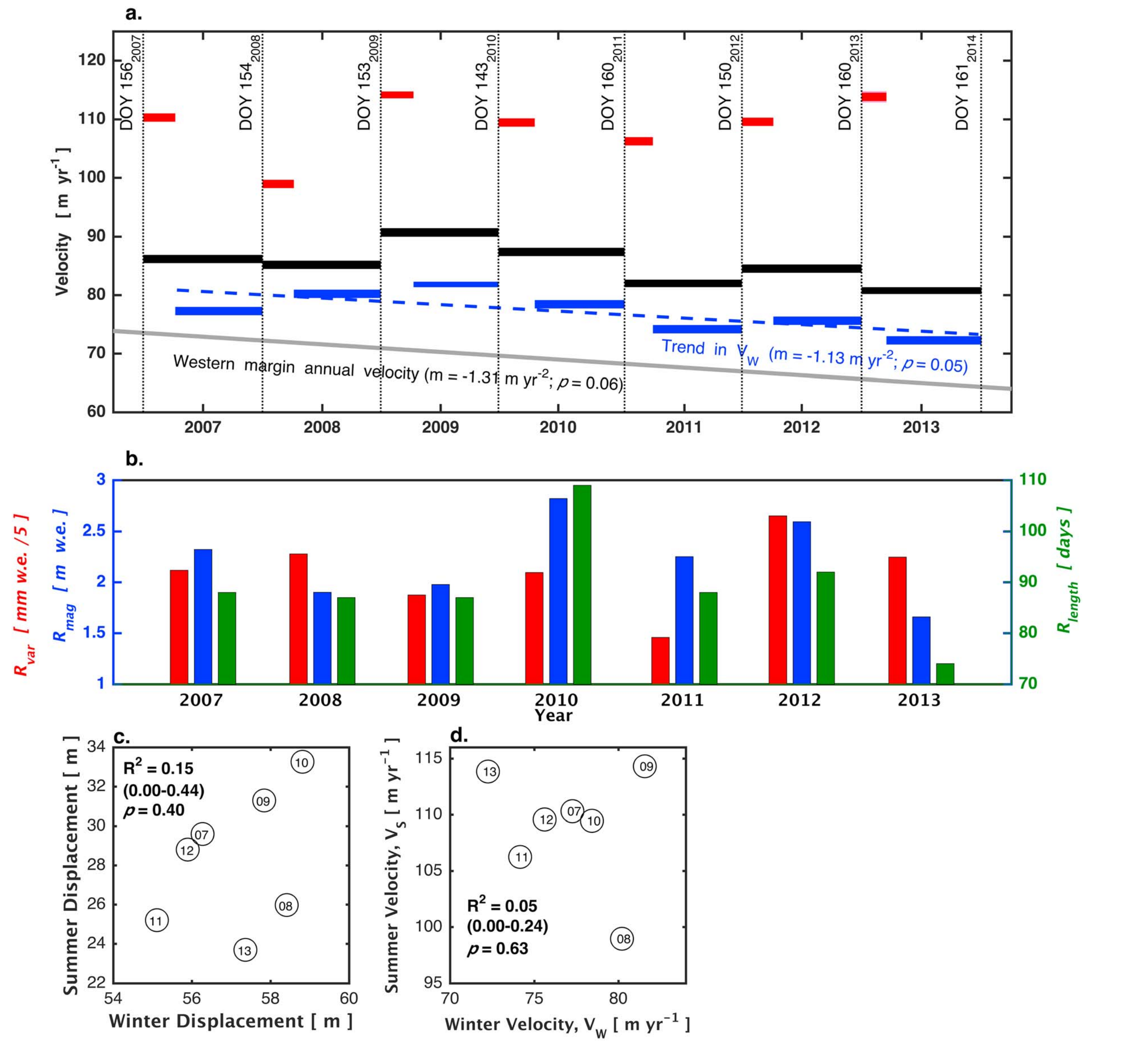

Figure 2. Seasonal ice velocity and runoff time series. (a) $\boldsymbol{V_S}$ (red), $\boldsymbol{V_W}$ (blue), and $\boldsymbol{V_A}$ (black) ± uncertainty (error bars smaller than bar width) across the North Lake array from 2007 to 2013. Time along the *x* axis is plotted in days, with vertical dashed lines marking the start of summer ($\boldsymbol{t_{R1}}$) in each year (subscript). The bar width in *x* represents the length of time over which velocities were calculated. Trend in North Lake $\boldsymbol{V_W}$ from 2007 to 2013 is shown in dashed blue line (no significant trends were found for $\boldsymbol{V_S}$ or $\boldsymbol{V_A}$). Grey line shows annual velocity trend from 2007 to 2013 of the western margin [*Tedstone et al*., 2015]. (b) $\boldsymbol{R}_{\text{mag}}$ (blue), $\boldsymbol{R}_{\text{var}}$ (red), and $\boldsymbol{R}_{\text{length}}$ (green) at North Lake from 2007 to 2013. (c) Summer versus winter displacements and (d) $\boldsymbol{V_S}$ versus $\boldsymbol{V_W}$ (error bars smaller than circle diameter) for 2007–2013.

drainage ($\boldsymbol{t}_{\text{LD}}$) from satellite data and field observations (Figures 3b and S4; see supporting information). To investigate drivers of seasonal and annual ice flow, we assess the covariance between seasonal and annual velocities and runoff parameters by evaluating the coefficient of determination (R^2) and *p* value of linear trends between all variables (Table S1 and Figures S5–S9). To illustrate the limitations of our small sample size, we calculated 5–95% confidence interval bounds for all R^2 values. We note that our results represent a measurement of local ice flow within a region of the ice sheet that exhibits substantial spatial variability in summer [*Joughin et al*., 2013] and interannual velocities [*Tedstone et al*., 2015].

3. Results and Discussion

We find a characteristic annual velocity curve consistent with results from previous studies (Figures 1c–1e). The onset of runoff is associated with an abrupt increase in velocity, followed by multiday velocity variations

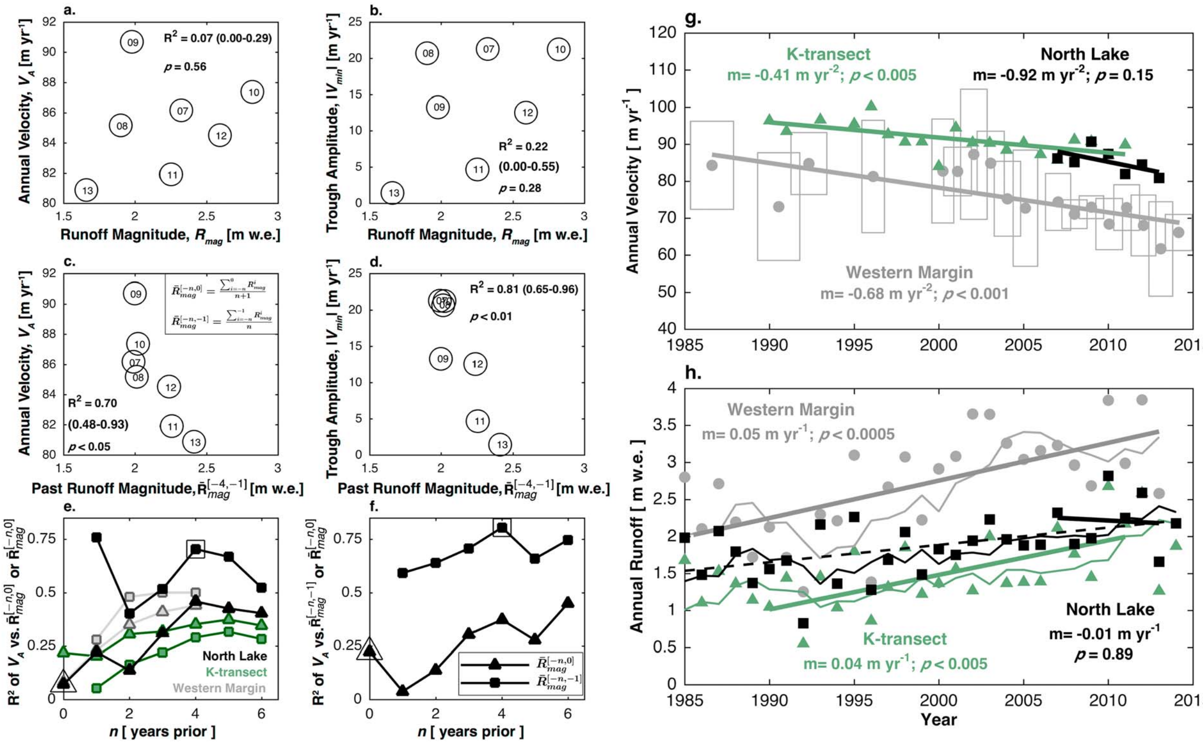

Figure 3. Annual ice velocity and past mean runoff magnitude relationships at North Lake, K-transect, and the western margin. (a) $\boldsymbol{V_A}$ and (b) trough amplitude, $|\boldsymbol{V}_{\min}|$, for 2007–2013 versus runoff magnitude $\boldsymbol{R}_{\text{mag}}$. Error bars are smaller than circle diameter. (c) $\boldsymbol{V_A}$ and (d) $|\boldsymbol{V}_{\min}|$ for 2007–2013 versus past runoff magnitude $\overline{\boldsymbol{R}}_{\text{mag}}^{[-4,\ -1]}$ (see supporting information). R^2 values for relationships between (e) $\boldsymbol{V_A}$ or (f) $|\boldsymbol{V}_{\min}|$ and past runoff magnitude: $\overline{\boldsymbol{R}}_{\text{mag}}^{[-n,\ 0]}$ (black triangles) or $\overline{\boldsymbol{R}}_{\text{mag}}^{[-n,\ -1]}$ (black squares), where $\boldsymbol{n}$ extends from 1 to 6 years of past runoff. R^2 values for relationships between past runoff magnitude and western margin velocities in grey [*Tedstone et al.*, 2015]. R^2 values for relationships between K-transect annual velocities [*van de Wal et al.*, 2015] and past runoff magnitude calculated from local daily runoff in green. Open triangles in Figures 3e and 3f correspond to relationships plotted in Figures 3a and 3b, respectively. Open squares in Figures 3e and 3f correspond the relationships plotted in Figures 3c and 3d, respectively. (g) Trends through annual velocity measurements at North Lake (black), K-transect (green [*van de Wal et al.*, 2015]), and the western margin (grey [*Tedstone et al.*, 2015]). (h) Local runoff estimates for North Lake (black) and K-transect (green) are plotted alongside the trends (thick lines) through these runoff values over the years in which annual velocities are available. Western margin runoff values and trend from *Tedstone et al.* [2015] are in grey. Runoff trend at North Lake from 1985 to 2014 shown in dashed black line. $\overline{\boldsymbol{R}}_{\text{mag}}^{[-4,\ -1]}$ calculation plotted for all three locations as a thin line.

that are correlated with spikes in runoff and/or North Lake drainage events (Figures 1c–1e and S1). At the end of the runoff season, velocities reach their annual minimum (Figures 1c–1e and S1). This annual velocity structure—and in particular the velocity minimum following melt cessation—suggests that the subglacial drainage system becomes more efficient and channelized over the runoff season, consistent with hydrological observations from other regions in Greenland [*Chandler et al.*, 2013; *Cowton et al.*, 2013].

Due to variability in the relative length of summer versus winter (see supporting information), seasonal and annual velocities are a function of both displacement (Figure 2c) and season length (Figure 2b). For example, the highest summer displacement in our record occurred in 2010 (Figure 2c), but due to that year's extremely long summer melt season (Figure 2b), the 2010 summer velocity is comparable to other years (Figures 2a and 2d). We note that by dividing each year into seasons based on runoff, the time interval over which $\boldsymbol{V_A}$ is calculated varies on a year-to-year basis (i.e., a year does not always equal 365 days). We find that $\boldsymbol{V_W}$ in the North Lake region is largely independent of $\boldsymbol{V_S}$ within the same year for both the $\boldsymbol{t_{R1}}$ to $\boldsymbol{t_{V\,\min}}$ seasonal delineation method and the fixed calendar date method (Figures 2d and S2d). This result contrasts GPS observations of seasonal velocities from *Sole et al.* [2013], which were the basis of their hypothesis that annual velocities were self-regulated through a strong inverse relationship between winter and summer velocities.

3.1. Interannual Trends and Variability in Velocity and Runoff

The mean annual velocity, $\boldsymbol{V_A}$, for the North Lake region is 85.2 ± 3.3 m yr^{-1} over the observation period, ~15 m yr^{-1} greater than the mean annual velocity for the western margin found by *Tedstone et al.* [2015] over the same time period (Figure 2a). This difference is likely due to the inclusion of the lower velocity ice margin in the larger *Tedstone et al.* [2015] region, as well as the spatial variability in velocities observed across the region more broadly [*Joughin et al.*, 2013]. The North Lake annual velocity is intermediate between the mean summer velocity ($\boldsymbol{V_S} = 109.0 \pm 5.2$ m yr^{-1}) and the mean winter velocity ($\boldsymbol{V_W} = 77.1 \pm 3.3$ m yr^{-1}) (Figure 2a), with the summer velocities displaying greater variability. We find that neither $\boldsymbol{V_A}$ nor $\boldsymbol{V_S}$ exhibits a statistically significant trend over the observation period (Figure 2a). Nonetheless, the computed trend for $\boldsymbol{V_A}$ of -0.92 m yr^{-2} ($p = 0.15$) (Figure 3g) and the statistically significant trend in $\boldsymbol{V_W}$ of -1.13 m yr^{-2} ($R^2 = 0.54$, $p = 0.05$) are similar to trends in annual velocities (-1.31 m yr^{-2}; $R^2 = 0.52$, $p = 0.06$) reported by *Tedstone et al.* [2015] from 2007 to 2013 (Figure 2a). These least squares regression slopes hold when considering error on the velocities using a weighted least squares regression (Table S4).

We also find no statistically significant trend in runoff-season magnitude, variability, or length, and/or the timing of North Lake drainage from 2007 to 2013 (Figure 2b). Rather, these parameters are most notable for their significant year-to-year variability (Figure 2b and Table S2). The largest magnitude runoff observed in 2010 ($\boldsymbol{R}_{\text{mag}} = 2.82$ m w.e.) is ~70% higher than that of the lowest runoff in 2013 ($\boldsymbol{R}_{\text{mag}} = 1.66$ m w.e.). Similar year-to-year variability is found in the longer-term runoff record, but in that case we do find an increasing trend of 0.02 m yr^{-1} ($p < 0.005$) from 1985 to 2014 (Figure 3h). Thus, given the high interannual variability in runoff, the lack of any runoff trend at North Lake during our study period likely reflects our inability to detect the longer-term increase that has been observed across the ice sheet [*van den Broeke et al.*, 2009] with only 7 years of data.

To investigate the relationship between annual velocity and runoff, we assessed the covariance between $\boldsymbol{V_A}$ and seasonal runoff characteristics. We find no statistically significant correlation between $\boldsymbol{V_A}$ and annual runoff parameters $\boldsymbol{R}_{\text{mag}}$, $\boldsymbol{R}_{\text{var}}$, $\boldsymbol{R}_{\text{length}}$, $\boldsymbol{t}_{\text{LD}}$, and $\boldsymbol{V}_{\text{min}}$ (Table S1 and Figures 3a, 3b, and S8a–S8d) even during the two extreme melt years in 2010 and 2012. These results are consistent with previous regional studies, which showed little correlation between annual velocity and runoff [*Zwally et al.*, 2002; *van de Wal et al.*, 2008, 2015; *Sole et al.*, 2013; *Tedstone et al.*, 2013]. Furthermore, summer and winter velocities show no correlations with annual runoff parameters (Table S1 and Figures S6 and S7a–S7e).

3.2. Influence of Past Runoff Magnitude on Seasonal and Annual Ice Flow

We next explored whether cumulative past runoff over multiple years has a control on ice flow in our region. Following the analysis of *Tedstone et al.* [2015], we calculated two forms of past mean runoff magnitude. The first, $\overline{\boldsymbol{R}}_{\text{mag}}^{[-n,\ \mathbf{0}]}$, represents runoff averaged over the $\boldsymbol{n}$ previous years including the present year (Figure 3d; supporting information). The second, $\overline{\boldsymbol{R}}_{\text{mag}}^{[-n,-\mathbf{1}]}$, is the mean runoff calculated from the $\boldsymbol{n}$ previous years, but not including the present year (Figure 3d; supporting information). Seasonal and annual velocities were then regressed against $\overline{\boldsymbol{R}}_{\text{mag}}^{[-n,\ -\mathbf{0}]}$ and $\overline{\boldsymbol{R}}_{\text{mag}}^{[-n,\ -\mathbf{1}]}$ for up to 6 years into the past ($0 < \boldsymbol{n} < 6$) (Figures 3a–3f, S6, and S8f–S8q). The correlations between annual velocities and $\overline{\boldsymbol{R}}_{\text{mag}}^{[-\mathbf{4},\ -\mathbf{1}]}$ are shown in Figure 3c, and the R^2 values calculated as a function of $\boldsymbol{n}$ years included in the runoff averages are shown in Figure 3e.

Both expressions for past mean runoff magnitude show improved and significant correlations with $\boldsymbol{V_A}$ (Figures 4e and S8f–S8q) and $\boldsymbol{V_W}$ (Figures S7f–S7q) similar to that found by *Tedstone et al.* [2015]. The relationship between $\boldsymbol{V_A}$ and past mean runoff magnitude is negative (higher runoff in the past years results in a lower $\boldsymbol{V_A}$ of the present year; Figure 3c), with past runoff explaining up to 70% of the variance in $\boldsymbol{V_A}$ (Figure 3e). The relationships between past mean runoff magnitude and $\boldsymbol{V_A}$ generally strengthen with increasing values of $\boldsymbol{n}$ until $\boldsymbol{n} \approx \mathbf{4}$, with the exception of a particularly high correlation for $\boldsymbol{n} = \mathbf{1}$ (Figure 3e). The relationship between $\boldsymbol{V_W}$ and past mean runoff magnitude is also negative and explains up to 82% of the variance in $\boldsymbol{V_W}$ (Figure S7i).

We stress that one must be careful not to overinterpret these results. This regression assumes a fixed relationship between the variables (velocity and runoff) with time. Our data, however, display long-term temporal trends (Figures 3g and 3h). Thus, to investigate the implications of our analysis for this study and others, we performed Monte Carlo simulations with correlated trends displaying similar magnitude year-to-year variability as observed (Text S5 and Figure S11). These simulations show an improved correlation when multiple years of runoff are included, even when the variability in the data is not correlated on an annual timescale as is the case in our data set (Figure S11). Thus, the improved correlation observed when multiple years of runoff are included is an expected outcome of analyzing two variables with long-term temporal trends, even if the mechanism generating these trends is unrelated to the annual variability.

3.3. Variability in Late Summer Slowdown

To gain further insight into the influence of runoff on the subglacial system, we take advantage of the high temporal resolution of our data to investigate variability in the amplitude of the late summer slowdown $|\boldsymbol{V}_{\min}|$. The persistent presence of a late summer velocity minimum (Figures 1b–1e and S1) supports the theory that the local subglacial hydrologic network undergoes seasonal reorganization, with increasing channelization throughout the summer resulting in increased frictional coupling that promotes this slowdown [*Bartholomew et al*., 2010; *Colgan et al*., 2011; *Hoffman et al*., 2011; *Sundal et al*., 2011; *Sole et al*., 2013; *van de Wal et al*., 2015]. Thus, larger $|\boldsymbol{V}_{\min}|$ has been proposed to represent more extensive subglacial channelization over the runoff season under higher melt conditions [*Sundal et al*., 2011]. While this relationship holds for 2010 (highest melt and largest $|\boldsymbol{V}_{\min}|$), over the 7 year study our data show that on an annual basis $|\boldsymbol{V}_{\min}|$ does not exhibit a statistically significant relationship with $\boldsymbol{R}_{\mathrm{mag}}$ ($R^2 = 0.22$ [0.00–0.55] (95% confidence interval), $p = 0.28$) (Figures 1d and 3b) or any other present season runoff variables (Figures S8a–S8c). This finding contrasts previous observations [*Sundal et al*., 2011] and theoretical studies [*Schoof*, 2010; *Hewitt*, 2013], which have shown that higher summer runoff magnitude and variability lead to a larger magnitude late summer slowdown due to increased efficiency in the subglacial drainage system.

3.4. Mechanisms for a Decadal or Multiyear Dependence of Ice Flow on Runoff

Existing decadal records show a significant decreasing trend in Greenland Ice Sheet velocity and increasing trend in annual runoff (Figures 3g and 3h). Our records exhibit similar trends, though neither of these trends are statistically significant given the high interannual variability in annual velocities and runoff over the 7 year record (Figures 3g and 3h). While there is no correlation between velocity and runoff on annual timescales [*Zwally et al*., 2002; *van de Wal et al*., 2008, 2015; *Sole et al*., 2013; *Tedstone et al*., 2015], the negative relationship between past mean runoff magnitude and annual velocity has been invoked in previous studies [*Tedstone et al*., 2015] to suggest a causal relationship where increased runoff drives slower velocities on multiyear timescales. Indeed, all three records depict a similar negative relationship between past mean runoff magnitude and annual velocity that strengthens with increasing values of $\boldsymbol{n}$ (Figures 3e, S10, and S11). However, it remains unclear whether this negative relationship is the manifestation of hydrologic mechanisms acting at the bed over multiple years [e.g., *Tedstone et al*., 2015] or opposing decadal trends in velocity and melt caused by other factors.

The co-occurrence of an increasing runoff trend and a decreasing annual velocity trend (Figures 3g and 3h) could arise for multiple reasons. Annual velocity and runoff could be changing independently of one another on decadal timescales, such that when comparing velocity and runoff annually, they show no correlation (Figure 3a). By integrating past runoff, the negative relationship with annual velocity emerges (Figures 3c) as the variability in runoff is reduced (Figures 3h and S11). Thus, in this scenario the correlation between the trends does not require causation.

Alternatively, annual velocity and runoff could be directly related to one another, but through a physical mechanism that is weakly expressed on annual timescales. For example, as the ice sheet thins, the response to small changes in driving stress (τ_d) at annual timescales is small, but the response over the longer term is enhanced due to the nonlinearity of ice flow. A change in driving stress due to ice-sheet thinning was found to account for up to a third of the velocity slowdown observed across the western margin [*Tedstone et al*., 2015].

Finally, annual velocity and runoff may be related through a hydraulic response whereby long-term evolution in the subglacial drainage system causes the annual velocity's response to melt to strengthen over multiple decades. While *Tedstone et al*. [2015] invoked this final mechanism to explain the majority of the slowdown, all three explanations could apply to the North Lake, K-transect, and western margin data.

Regardless of the co-occurrence of opposing decadal trends in velocity and runoff, annual velocities on the western margin are slowing down (Figure 3g). As the changes in driving stress due to ice-sheet thinning are insufficient to explain the observed decrease in annual velocities [*Tedstone et al*., 2015], other physical processes driving this slowdown should be considered. A slowdown driven by changes in internal deformation or basal motion through sliding and/or till deformation could be occurring independently of, or alongside, a change in subglacial hydrology. Additional observations of ice-sheet velocity, geometry, internal structure, and basal properties are needed to determine the causal relationship between annual velocity and runoff and to understand the observed slowdown of the ice-sheet margin.

3.5. Implications for Future Predictions of Ice Flow

While hydrology and ice-flow models now capture the seasonal velocity structure of the ablation zone at a qualitative level [*Schoof*, 2010; *Hewitt*, 2013; *Werder et al*., 2013], our results suggest that additional feedbacks must be considered in order to understand the details of how ice flow is related to trends in runoff and runoff variability over longer timescales. Extrapolating the trends in runoff and velocity found in our study and earlier data sets suggests that a sustained increase in runoff would lead to a systematic decrease in ice-sheet velocities. However, we stress that the correlation between annual velocity and integrated past runoff is not necessarily evidence for a hydrologic mechanism acting on the basal system over timescales of a few years and could be related to other factors including changes in ice-sheet thickness, internal deformation, or basal motion. Further, we find that in contrast to model predictions [*Schoof*, 2010; *Hewitt*, 2013], the magnitude of the late summer velocity minimum is not the product of the present summer runoff (Figure 3b). Thus, the mechanisms required to recreate seasonal ice-flow characteristics may not translate into accurate predictions of longer duration ice-flow variability. Observational studies targeted at long-term records of ice-sheet shape, subglacial hydrology, and basal motion are needed to better understand mechanisms controlling ice sheet flow on annual to decadal timescales. Moreover, future modeling studies should be evaluated alongside the available measurements of ice flow collected at North Lake, Swiss Camp, and the K-transect.

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