AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2014GL061836

Distinct patterns of seasonal Greenland glacier velocity

Twila Moon[1,2,3], Ian Joughin[2], Ben Smith[2], Michiel R. van den Broeke[4], Willem Jan van de Berg[4], Brice Noël[4], and Mika Usher[2]

[1]Earth and Space Sciences, University of Washington, Seattle, Washington, USA, [2]Polar Science Center, Applied Physics Lab, University of Washington, Seattle, Washington, USA, [3]National Snow and Ice Data Center, Cooperative Institute for Research in Environmental Sciences, University of Colorado—Boulder, Boulder, Colorado, USA, [4]Institute for Marine and Atmospheric Research, Utrecht University, Utrecht, Netherlands

Key Points:
- First multi-region seasonal velocity measurements show regional differences
- Seasonal velocity fluctuations on most glaciers appear meltwater controlled
- Seasonal development of efficient subglacial drainage geographically divided

Supporting Information:
- Readme
- Table S1
- Figures S1–S55
- Figure S56
- Figure S57

Correspondence to:
T. Moon,
twila.moon@nsidc.org

Citation:
Moon, T., I. Joughin, B. Smith, M. R. van den Broeke, W. J. van de Berg, B. Noël, and M. Usher (2014), Distinct patterns of seasonal Greenland glacier velocity, *Geophys. Res. Lett.*, *41*, 7209–7216, doi:10.1002/2014GL061836.

Received 18 SEP 2014
Accepted 9 OCT 2014
Accepted article online 14 OCT 2014
Published online 27 OCT 2014

Abstract Predicting Greenland Ice Sheet mass loss due to ice dynamics requires a complete understanding of spatiotemporal velocity fluctuations and related control mechanisms. We present a 5 year record of seasonal velocity measurements for 55 marine-terminating glaciers distributed around the ice sheet margin, along with ice-front position and runoff data sets for each glacier. Among glaciers with substantial speed variations, we find three distinct seasonal velocity patterns. One pattern indicates relatively high glacier sensitivity to ice-front position. The other two patterns are more prevalent and appear to be meltwater controlled. These patterns reveal differences in which some subglacial systems likely transition seasonally from inefficient, distributed hydrologic networks to efficient, channelized drainage, while others do not. The difference may be determined by meltwater availability, which in some regions may be influenced by perennial firn aquifers. Our results highlight the need to understand subglacial meltwater availability on an ice sheet-wide scale to predict future dynamic changes.

1. Introduction

Mass loss from the Greenland Ice Sheet increased significantly over the last several decades, and current mass losses of 260–380 Gt ice/yr [*Shepherd et al.*, 2012; *Enderlin et al.*, 2014; *Khan et al.*, 2014] contribute 0.7–1.1 mm/yr to global sea level rise [*IPCC*, 2013]. Greenland mass loss includes ice discharge via marine-terminating outlet glaciers and surface meltwater runoff, the former now making up a third to a half of total ice loss [*Shepherd et al.*, 2012; *Enderlin et al.*, 2014]. The magnitude of ice discharge depends in part on ice-flow speed, which has broadly increased since 2000 but varies locally, regionally, and from year to year [*Moon et al.*, 2012]. Research on a limited set of Greenland glaciers also shows that speeds vary seasonally [*Joughin et al.*, 2008c; *Howat et al.*, 2010; *Bevan et al.*, 2012; *Ahlstrøm et al.*, 2013; *Joughin et al.*, 2014]. For much of the west, northwest, and southeast coasts where ice loss is increasing most rapidly, however, there are few or no records of seasonal velocity variation.

Seasonal ice velocity is influenced by several key components of the ice sheet-ocean-climate system, including the subglacial environment, surface melt and runoff, and ice-ocean interaction at the ice front (terminus) [*Joughin et al.*, 2012; *Carr et al.*, 2013]. Thus, knowledge of seasonal velocity patterns is important for predicting annual ice discharge, understanding the effects of increased surface melt on total mass loss, and establishing how ice flow responds to other environmental changes, including ocean temperature [*Rennermalm et al.*, 2013; *Straneo and Heimbach*, 2013]. Spatiotemporal variation in annual glacier velocities [*Moon et al.*, 2012] suggests that a multi-region examination of seasonal velocity may also be necessary to characterize and understand the full range of intra-annual glacier behavior. Here we present results from seasonal velocity measurements for 55 glaciers along the northwest, west, southeast, and southwest coasts of the Greenland Ice Sheet.

Theory, modeling, and observations indicate that velocity fluctuations may occur as a response to changes in ice-front position [*Howat et al.*, 2008; *Joughin et al.*, 2008a, 2008b; *Nick et al.*, 2009]. For marine-terminating glaciers with a reverse-sloped bed (i.e., where the bed depth increases with distance from the terminus), terminus retreat can reduce basal and lateral resistive stresses and increases the net-pressure force on the near-vertical terminus face, inducing speedup [*Howat et al.*, 2008; *Nick et al.*, 2009]. Similarly, terminus advance can cause slowing. In addition to terminus position, input of surface melt to the bed and ensuing

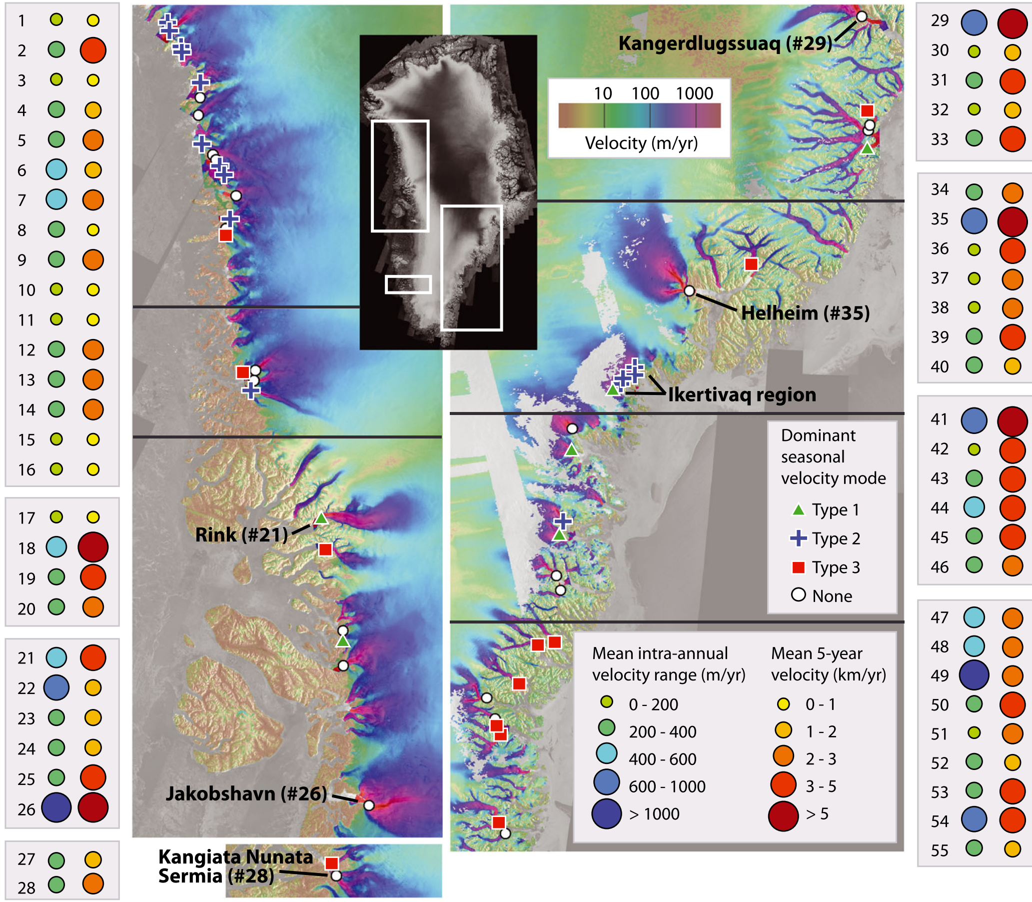

Figure 1. Mean intra-annual velocity range, 5 year mean velocity, and seasonal velocity mode for Greenland marine-terminating outlet glaciers. Center panels show the locations for the 55 study glaciers, with symbols indicating the dominant seasonal velocity mode. Background map shows RADARSAT mosaic of surface velocity. Side panels indicate the mean intra-annual velocity range (m/yr, blue-tone circles) and mean 5 year velocity (km/yr, red-tone circles) for each glacier (identified numerically) in north-to-south order corresponding to glaciers in center panels (divided into segments for easier reference).

evolution of the basal hydrological system can produce seasonal variation in speed [*Joughin et al.*, 2008c; *Banwell et al.*, 2013; *Hewitt*, 2013; *Sole et al.*, 2013; *Tedesco et al.*, 2013]. Early in the melt season, an inefficient system maintains relatively high water pressure, and additional meltwater input further raises water pressure, increasing ice velocity. With sufficient meltwater influx, however, the distributed system evolves into an efficient, channelized drainage network. Water pressure and speed then drop, even though melt rates may remain high [*Bartholomew et al.*, 2010]. Subglacial hydrology theory and observation suggests that it should take sustained (weeks) input of surface melt to the bed to produce a seasonal transition from an inefficient, distributed subglacial drainage system to an efficient, channelized network [*Schoof*, 2010]. Thus, changes in terminus position, meltwater availability, and subglacial environment and evolution may contribute to seasonal velocity fluctuations. Combining velocity, terminus, and runoff records for all study glaciers, we examine the influence of these potential controlling mechanisms across the ice sheet.

2. Methods

Interferometric synthetic aperture radar (InSAR) and speckle tracking techniques provide measurements of ice sheet surface velocity over expansive areas [*Joughin*, 2002; *Joughin et al.*, 2010]. Using TerraSAR-X radar data from the German Space Agency (DLR), we made roughly seasonal surface velocity measurements of 55 marine-terminating Greenland outlet glaciers (shown in Figure 1) over 5 years, from 2009 through 2013. Most

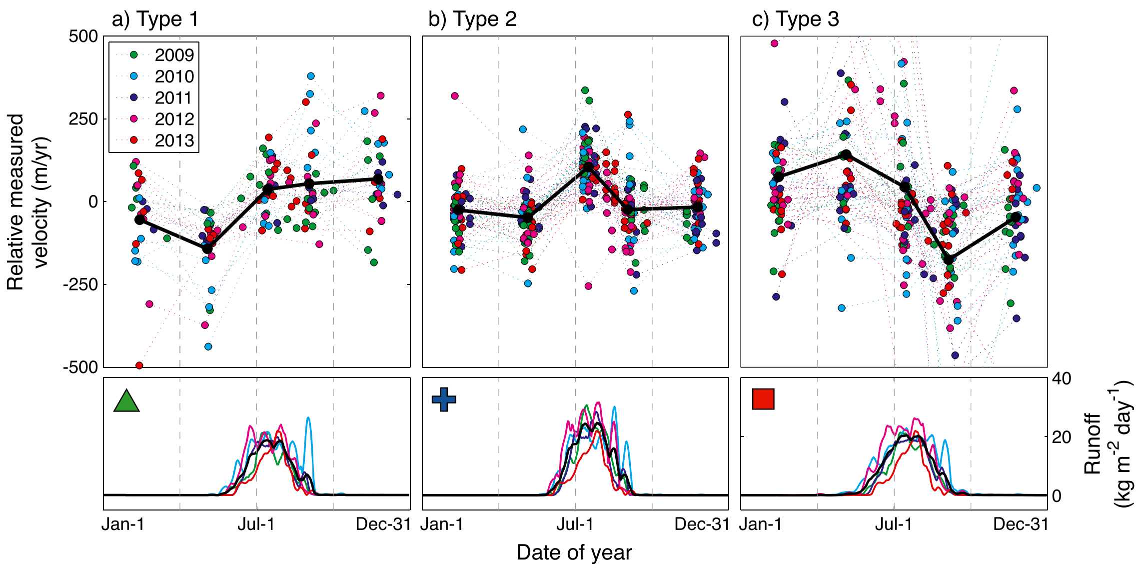

Figure 2. Marine-terminating Greenland outlet glaciers with distinct seasonal velocity modes and associated ice sheet runoff. Top row: Plots include all glaciers with dominant seasonal velocity modes for (a) type 1, (b) type 2, and (c) type 3 behavior (as shown in Figure 1 and discussed in text). Mean velocity pattern is indicated (thick black line). Bottom row: Smoothed daily runoff (kg/m^{2}d) from RACMO2.3 for 2009–2013 for glaciers with the designated dominant seasonal velocity mode. Mean runoff is included for each year (colored lines) as well as the 4 year mean runoff (black line).

glaciers were measured 3–6 times per year using 11 day or occasionally 22 day repeat TerraSAR-X images (the resulting measurement represents mean velocity during this period) with more frequent measurements on a few glaciers (e.g., Jakobshavn Isbræ, Helheim, and Kangerdlugssuaq) (Figures S1–S55). Measurements were taken at a fixed location roughly one half width from the terminus, with adjustments to minimize missing data and account for changing terminus position. Data are posted at 100 m intervals with true spatial resolution of ~300 m. Errors for fast-flowing ice are ~3% although relative accuracy is much better because errors are geometry dependent and a consistent viewing geometry was used for each glacier [*Joughin*, 2002; *Joughin et al*., 2010]. Comparison of GPS velocity measurements to TerraSAR-X velocities showed agreement consistent with this level of error [*Ahlstrøm et al*., 2013].

Daily ice sheet runoff data are from the Royal Netherlands Meteorological Institute (KNMI) regional atmospheric climate model RACMO2.3 [*van Meijgaard et al*., 2008; *Sasgen et al*., 2012; *Lenaerts et al*., 2013; *van Angelen et al*., 2013; *Van As et al*., 2014], which provides the most current model results, including coverage during 2009 through 2013. Runoff data are used to identify potential subglacial water availability and the timing of the seasonal melt cycle. Modeled runoff is defined as the liquid water flux (melt plus rain) that is not retained (e.g., refreezing in firn) at the surface of the ice sheet and thus may be available for drainage to the bed of the ice sheet. To avoid conflict with the ice mask edge, we sampled RACMO2.3 data at a point ~10 km up-glacier from each velocity measurement point. We applied a Savitzky-Golay filter [*Savitzky and Golay*, 1964] (using second degree polynomials) over a 15 day sliding window to smooth the daily measurements.

We developed a time series of glacier ice-front positions by digitizing each ice front using the TerraSAR-X radar mosaics, resulting in 6–12 measurements per year for most glaciers. For glaciers #1–16 in northwestern Greenland (Figure 1), we also included ice-front measurements made using Landsat 7 images during 2009–2012 [*Moon*, 2014]. Because analysis of the link between terminus and velocity fluctuations is limited by the sparsity of our velocity measurements, we chose not to add Landsat-derived measurements for other glaciers. Ice-front changes were calculated using the “box” method [*Moon and Joughin*, 2008], and errors from manual digitization are approximately equal to image pixel size (20 to 30 m) based on results from previous work [*Moon*, 2014].

3. Results

We began by examining the intra-annual velocity range (difference between minimum and maximum velocity during a year) to determine whether seasonal variation is influenced by mean glacier speed. Figure 1 shows the location, 5 year mean velocity, and mean intra-annual velocity range for each glacier. Velocity

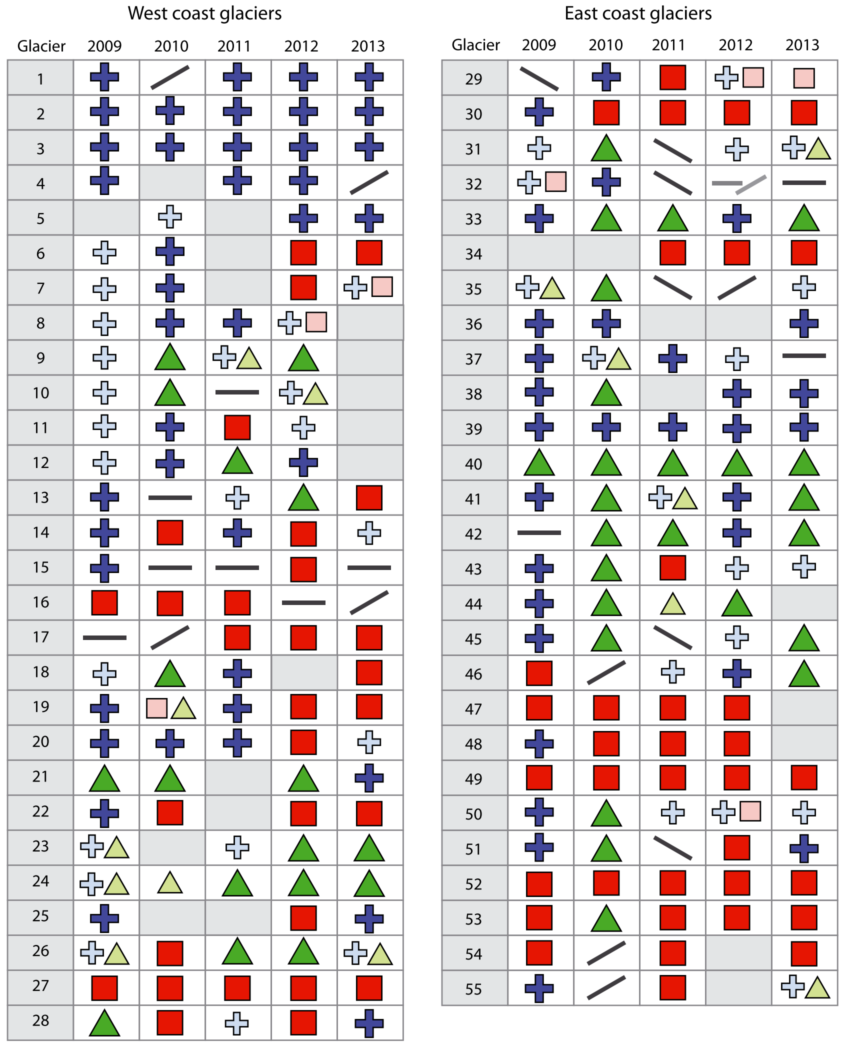

Figure 3. Seasonal velocity modes for Greenland outlet glaciers by year. Symbols designate the seasonal velocity pattern for each glacier for every year (triangle = type 1; cross = type 2; square = type 3), with straight lines indicating consistently accelerating, decelerating, or flat speeds (<50 m/yr range) during the year. Lighter, smaller symbols indicate that the designation is based on limited data or has components of two patterns. Lighter, smaller crosses (blue) may also indicate that there was a summer spike but a higher measured velocity in winter or late fall. Gray boxes indicate insufficient data for identifying patterns. (See Figures S1–S55 for velocity data for individual glaciers).

measurements for individual glaciers are shown in Figures S1–S55. There is a moderate correlation between the intra-annual range and mean speed ($r^2 = 0.44$) (Figure S56), with an overall mean range of 413 m/yr or 16% of the 5 year mean speed. Most of the glaciers flow at speeds of 1 to 5 km/yr with mean intra-annual velocity ranges between 150 and 500 m/yr. For the slowest glaciers (mean speed <1 km/yr), which are clustered in the northwest [*Moon et al.*, 2012], the intra-annual variation is consistently less than 250 m/yr. For the limited number of fastest-flowing (>5 km/yr) glaciers, which are located along the central west and southeast coasts, the intra-annual range always exceeds 500 m/yr (Figures 1 and S56). These results suggest some regional differences in intra-annual flow variability, and we explore this idea more closely by analyzing patterns of seasonal change.

For evaluation of seasonal variation, measured velocity was detrended (removing either a 5 year linear or quadratic trend, as indicated in Figures S1–S55) and broken out by year, with mean annual velocity subtracted for each individual year. To identify seasonal patterns, we initially examined all velocity data for every glacier to manually identify glaciers with consistent seasonal patterns for the full 5 year observation period. Glaciers with consistent behavior were grouped together based on pattern similarity; we identified three distinct seasonal velocity patterns. Using these patterns, we classified velocity behavior for each calendar year for every glacier. The dominant pattern for glaciers with the same pattern for at least three of the five observation years is indicated in Figure 1. Figure 2 shows the seasonal cycle of velocity and runoff for all glaciers with a dominant seasonal pattern in 3 of 5 years, for the three different velocity patterns. Figure 3 indicates the observed seasonal velocity pattern during each year for all of the glaciers studied.

We observed three distinct types of seasonal velocity patterns on marine-terminating Greenland glaciers, which we classify as types 1 through 3 (Figure 2, top row). Type 1 behavior is characterized by speedup between late spring (early May) and early summer (mid-July), with speed remaining high until late winter or early spring. With type 2 behavior, velocity is relatively stable from late summer through spring, with a strong early summer speedup and midsummer slowing. Winter speed is sometimes elevated compared to spring and fall, but in most cases remains lower than the summer peak (Figures 2b and 3). Type 3 behavior has a mid-summer slowdown leading to a pronounced late summer minimum, which rebounds over the winter. Along with these three patterns, we observed some years with steady speedup, deceleration, or no change (range <50 m/yr) (Figure 3).

Our results are limited by the temporal resolution of our velocity measurements. On average, we observe motion during five 11 day intervals per year. Rapid, large seasonal velocity changes can occur, especially early in the melt season [*Podrasky et al*., 2012; *Joughin et al*., 2013], and may not be sampled by our measurements. In particular, we may have missed an early season speedup in our type 3 observations. However, the classification of speed patterns would not be different if we did observe such an early-season speedup in that the difference between the patterns is well resolved by our observations.

4. Discussion

We observe strong correspondence between seasonal fluctuations in speed and terminus position for type 1 behavior. Examining time series of velocity and ice-front position for all glaciers, we identified glaciers for which terminus retreat coincides with speedup and advance with slowing. Synchronous seasonal changes in speed and ice-front position were previously observed on Rink Glacier (#21, Figure S21) [*Howat et al*., 2010] and are confirmed by our measurements. We also find a strong correspondence between seasonal velocity and terminus position throughout the 5 year record for Sermilik (#24, Figure S24) and Ulimaatikajik (#40, Figure S40). The velocity signal for some years (particularly 2010) also corresponds well to terminus changes for the other type 1 glaciers (#33, #42, and #44, Figures S33, S42, and S44). Comparison of seasonal velocity changes and the timing of meltwater runoff suggests that melt may play a role in the type 1 pattern, especially during spring to summer speedup. A distinguishing feature of type 1 behavior, however, is sustained speedup well past the end of the melt and runoff season (Figure 2a). These faster speeds through late summer and fall appear to be connected to terminus retreat. While only a few glaciers regularly exhibit type 1 behavior, the pattern does occur during isolated years for glaciers that are not dominantly type 1 when there is strong correspondence between terminus and velocity changes (e.g., Figure S18 during 2010). Jakobshavn Isbræ, where a seasonal link between terminus and velocity is well established [*Joughin et al*., 2008b, 2014], also has mixed or strong type 1 behavior in most years (#26 in Figure 3), though the magnitude of the seasonal velocity range on Jakobshavn differentiates it from other glaciers (Table S1). Together, these observations suggest that seasonal velocity changes for type 1 behavior are likely controlled primarily by ice-front position.

For observations of glaciers with type 2 and type 3 behavior, there does not appear to be a strong relationship between seasonal speed and ice-front position. Instead, for type 2 glaciers, clustered in the northwest and the Ikertivaq region in the southeast (glaciers #36–39, Figure 1), there is strong correspondence between speed and runoff (Figure 2b). Type 2 glaciers have a pronounced early summer speedup that coincides with the onset and increase in meltwater runoff, with relatively steady speeds the rest of the year. Examining the northwest and southeast type 2 clusters separately, including comparing velocity and runoff measurements during individual years, provides further evidence of synchronous changes in runoff and glacier speed during late summer (Figure S57). Late summer velocities in the northwest, mostly measured after the runoff season has ended, are similar to pre-summer speeds, while velocities measured in the Ikertivaq region during the tail end of the runoff season have not decreased to pre-summer speeds. During 2010, we also measure particularly high velocities on Ikertivaq region glaciers coincident with a late summer spike in runoff (Figure S57). The fact that runoff and velocity changes are well matched and we observe no mid- or late-season velocity low suggests that development of efficient channelized subglacial drainage is absent or limited for these glaciers.

By contrast with type 2, the type 3 pattern shows a decline in velocity during times of high runoff with a pronounced minimum during late summer, when runoff is low. This behavior is consistent with a seasonal switch from inefficient to efficient subglacial drainage. Most of our observations lack a strong early season peak that would be expected when the drainage system was still inefficient. Our sampling, however, is such that we miss most of the early melt season leading up to peak melt. Thus, we may simply have missed early peaks, which can be relatively short lived (days to weeks) [*Sole et al*., 2011; *Joughin et al*., 2013]. For example, continuous Global Positioning System (GPS) measurements on Kangiata Nunâta Sermia (#28, Figure S28) [*Ahlstrøm et al*., 2013], which coincide with our measurements during 2010, do show velocity peaks close to 1 June that we do not sample. Type 3 behavior is more often associated with a high intra-annual velocity range, both as measured (>600 m/yr) and as compared to mean velocity (>30%), than type 1 or type 2 behavior (Table S1, Figures 1 and S56), which may reflect the addition of the late-summer velocity minimum and contributes to the regional variation in intra-annual velocity range.

Prevalence of type 2 and type 3 seasonal behavior varies geographically (Figures 1 and 3). We suggest that the difference may be primarily determined by meltwater availability. The northwest region (predominantly type 2) has a relatively short melt season. By contrast, the melt season is longer and melt is considerably higher in the southeast, where we see most instances of type 3 behavior. There are exceptions in the southeast, such as the Ikertivaq region, where some glaciers exhibit type 2 behavior. In these cases, much of the surface melt may not reach the bed. For example, *Forster et al*. [2013] modeled expected liquid water content in the firn along the southeast coast and identified perennial firn aquifers using airborne radar. In the far southeast, where we observe many type 3 glaciers, they found high expected liquid water content but did not detect perennial firn aquifers, suggesting that the meltwater may be accessing the subglacial system. Perennial firn aquifers were found in the Ikertivaq region. Thus, in regions of abundant melt, the firn aquifers may produce type 2 behavior where it otherwise would not occur. Other factors (e.g., subglacial geology) may also contribute to the regional differences in seasonal behavior, but data are quite limited for the fast-flow regions we are examining and variation in meltwater availability may be sufficient to explain the seasonal patterns we observe.

Type 2 and type 3 behavior may represent end-members along a spectrum determined by subglacial conditions and water availability. Thus, with the elevation-dependent availability of surface runoff, we might expect a shift in behavior from type 3 in high-melt regions downstream to type 2 in low-melt areas upstream. Measurements by multiple groups on Kangiata Nunâta Sermia (#28) in 2010 allow us to examine this hypothesis. Our near-terminus seasonal velocity measurements agree well with continuous GPS measurements taken ~10 km further upstream [*Ahlstrøm et al*., 2013], and measurements 36 km upstream from the margin also match the type 3 pattern [*Sole et al*., 2011]. At 59 km upstream, however, there is almost no late summer slowdown and the pattern more closely resembles type 2 behavior [*Sole et al*., 2011]. These results are consistent with other recent modeling and limited observational results [*Hewitt*, 2013; *Meierbachtol et al*., 2013]. Unfortunately, data are not currently available to test this idea during other years at Kangiata Nunâta Sermia or for other locations.

We do observe year-to-year transitions in seasonal velocity patterns on many glaciers (Figure 3). These changes may provide an important indicator of differences in local conditions, such as changes in subglacial hydrology, unusual terminus behavior, or differences in timing and availability of runoff. For example, Igdlugdlip Sermia (#14, Figure S14) has type 2 behavior during 2009, 2011, and 2013 and type 3 behavior during 2010 and 2012, suggesting that efficient drainage may have developed during two of the five observation years. Thus, Igdlugdlip Sermia may provide a test glacier for further investigation of the development and sensitivity of the subglacial hydrologic system.

5. Conclusions

Our data present the first comprehensive ice sheet-wide seasonal velocity measurements of marine-terminating Greenland glaciers. We observe two types of seasonal velocity patterns that appear to be meltwater controlled, one with seasonal switching between inefficient and efficient subglacial drainage

networks and the other without. Apparently high sensitivity to terminus retreat on a few glaciers sustains faster summer velocities well beyond the end of the melt season. Our observations reveal differences in dominant velocity control mechanisms and highlight the importance of understanding spatiotemporal variability of subglacial meltwater availability.

Acknowledgments

Velocity data through 2012 are available through the MEaSUREs data site at the National Snow and Ice Data Center (nsidc.org/data/measures). Subsequent years will be added to the online database or are available via request from the authors. Runoff and terminus data are available via request from the authors. The TerraSAR-X data were provided by the German Space Agency (DLR), project HYD0754 and XTI_GLAC0400. Velocity products were processed under NASA MEaSUREs (NNX08AL98A). Analysis was funded by an NSF Graduate Research Fellowship (T.M.) and grant NSF ANT-0424589 (T.M. and I.J.). B.S. and M.U. were supported by NASA grant NNX13AP96G. M.B., W.B., and B.N. acknowledge support from the Netherlands Polar Program.

Julienne Stroeve thanks Shfaqat Khan and one anonymous reviewer for their assistance in evaluating this manuscript.

References

Ahlstrøm, A. P., S. B. Andersen, M. L. Andersen, H. Machguth, F. M. Nick, I. Joughin, C. H. Reijmer, R. van de Wal, J. P. Boncori, and J. E. Box (2013), Seasonal velocities of eight major marine-terminating outlet glaciers of the Greenland ice sheet from continuous in situ GPS instrument, *Earth Syst. Sci. Data*, *5*(2), doi:10.5194/essd-5-277-2013.

Banwell, A. F., I. C. Willis, and N. S. Arnold (2013), Modeling subglacial water routing at Paakitsoq, W Greenland, *J. Geophys. Res. Earth Surface*, *118*, 1282–1295, doi:10.1002/jgrf.20093.

Bartholomew, I., P. Nienow, D. Mair, A. Hubbard, M. A. King, and A. Sole (2010), Seasonal evolution of subglacial drainage and acceleration in a Greenland outlet glacier, *Nat. Geosci.*, *3*(6), 408–411, doi:10.1038/ngeo863.

Bevan, S. L., A. J. Luckman, and T. Murray (2012), Glacier dynamics over the last quarter of a century at Helheim, Kangerdlugssuaq and 14 other major Greenland outlet glaciers, *The Cryosphere*, *6*(5), 923–937, doi:10.5194/tc-6-923-2012.

Carr, J. R., C. R. Stokes, and A. Vieli (2013), Recent progress in understanding marine-terminating Arctic outlet glacier response to climatic and oceanic forcing: Twenty years of rapid change, *Prog. Phys. Geogr.*, *37*(4), 436–467, doi:10.1177/0309133313483163.

Enderlin, E. M., I. M. Howat, S. Jeong, M. J. Noh, J. H. Angelen, and M. R. Broeke (2014), An improved mass budget for the Greenland ice sheet, *Geophys. Res. Lett.*, *41*, 866–872, doi:10.1002/2013GL059010.

Forster, R. R., et al. (2013), Extensive liquid meltwater storage in firn within the Greenland ice sheet, *Nat. Geosci.*, *7*(12), 1–4, doi:10.1038/ngeo2043.

Hewitt, I. J. (2013), Seasonal changes in ice sheet motion due to melt water lubrication, *Earth Planet. Sci. Lett.*, *371–372*(C), 16–25, doi:10.1016/j.epsl.2013.04.022.

Howat, I. M., I. Joughin, M. Fahnestock, B. E. Smith, and T. A. Scambos (2008), Synchronous retreat and acceleration of southeast Greenland outlet glaciers 2000-06: Ice dynamics and coupling to climate, *J. Glaciol.*, *54*(187), 646–660.

Howat, I. M., J. E. Box, Y. Ahn, A. Herrington, and E. M. McFadden (2010), Seasonal variability in the dynamics of marine-terminating outlet glaciers in Greenland, *J. Glaciol.*, *56*(198), 601–613.

IPCC (2013), *Climate Change 2013: The Physical Science Basis*, *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by T. F. Stocker et al., Cambridge Univ. Press, Cambridge, U. K., and New York.

Joughin, I. (2002), Ice-sheet velocity mapping: A combined interferometric and speckle-tracking approach, *Ann. Glaciol.*, *34*, 195–201.

Joughin, I., I. Howat, R. B. Alley, G. Ekstrom, M. Fahnestock, T. Moon, M. Nettles, M. Truffer, and V. C. Tsai (2008a), Ice-front variation and tidewater behavior on Helheim and Kangerdlugssuaq Glaciers, Greenland, *J. Geophys. Res.*, *113*, F01004, doi:10.1029/2007JF000837.

Joughin, I., I. M. Howat, M. Fahnestock, B. Smith, W. Krabill, R. B. Alley, H. Stern, and M. Truffer (2008b), Continued evolution of Jakobshavn Isbrae following its rapid speedup, *J. Geophys. Res.*, *113*, F04006, doi:10.1029/2008JF001023.

Joughin, I., S. B. Das, M. A. King, B. E. Smith, I. M. Howat, and T. Moon (2008c), Seasonal speedup along the western flank of the Greenland Ice Sheet, *Science*, *320*(5877), 781–783, doi:10.1126/science.1153288.

Joughin, I., B. E. Smith, I. M. Howat, T. A. Scambos, and T. Moon (2010), Greenland flow variability from ice-sheet-wide velocity mapping, *J. Glaciol.*, *56*(197), 415–430.

Joughin, I., R. B. Alley, and D. M. Holland (2012), Ice-sheet response to oceanic forcing, *Science*, *338*(6111), 1172–1176, doi:10.1126/science.1226481.

Joughin, I., S. B. Das, G. E. Flowers, M. D. Behn, R. B. Alley, M. A. King, B. E. Smith, J. L. Bamber, M. R. Van Den Broeke, and J. H. van Angelen (2013), Influence of ice-sheet geometry and supraglacial lakes on seasonal ice-flow variability, *The Cryosphere*, *7*(4), 1185–1192, doi:10.5194/tc-7-1185-2013.

Joughin, I., B. E. Smith, D. E. Shean, and D. Floricioiu (2014), Brief Communication: Further summer speedup of Jakobshavn Isbræ, *The Cryosphere*, *8*(1), 209–214, doi:10.5194/tc-8-209-2014.

Khan, S. A., et al. (2014), Sustained mass loss of the northeast Greenland ice sheet triggered by regional warming, *Nat. Clim. Change*, *4*(4), 292–299, doi:10.1038/nclimate2161.

Lenaerts, J. T. M., J. H. van Angelen, M. R. van den Broeke, A. S. Gardner, B. Wouters, and E. van Meijgaard (2013), Irreversible mass loss of Canadian Arctic Archipelago glaciers, *Geophys. Res. Lett.*, *40*, 870–874, doi:10.1002/grl.50214.

Meierbachtol, T., J. Harper, and N. Humphrey (2013), Basal drainage system response to increasing surface melt on the Greenland ice sheet, *Science*, *341*(6147), 777–779, doi:10.1126/science.1235905.

Moon, T. (2014), Greenland outlet glacier behavior during the 21st century: Understanding velocities and environmental factors, PhD thesis, Earth and Space Sciences, Univ. of Washington, Seattle, Wash.

Moon, T., and I. Joughin (2008), Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007, *J. Geophys. Res.*, *113*, F02022, doi:10.1029/2007JF000927.

Moon, T., I. Joughin, B. Smith, and I. Howat (2012), 21st-century evolution of Greenland outlet glacier velocities, *Science*, *336*(6081), 576–578, doi:10.1126/science.1219985.

Nick, F. M., A. Vieli, I. M. Howat, and I. Joughin (2009), Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus, *Nat. Geosci.*, *2*(2), 110–114, doi:10.1038/ngeo394.

Podrasky, D., M. Truffer, M. Fahnestock, J. M. Amundson, R. Cassotto, and I. Joughin (2012), Outlet glacier response to forcing over hourly to interannual timescales, Jakobshavn Isbræ, Greenland, *J. Glaciol.*, *58*(212), 1212–1226, doi:10.3189/2012JoG12J065.

Rennermalm, A. K., et al. (2013), Understanding Greenland ice sheet hydrology using an integrated multi-scale approach, *Environ. Res. Lett.*, *8*(1), 015017, doi:10.1088/1748-9326/8/1/015017.

Sasgen, I., M. Van Den Broeke, J. L. Bamber, E. Rignot, L. S. Sørensen, B. Wouters, Z. Martinec, I. Velicogna, and S. B. Simonsen (2012), Timing and origin of recent regional ice-mass loss in Greenland, *Earth Planet. Sci. Lett.*, *333*, 293–303, doi:10.1016/j.epsl.2012.03.033.

Savitzky, A., and M. J. Golay (1964), Smoothing and differentiation of data by simplified least squares procedures, *Anal. Chem.*, *36*(8), 1627–1639.

Schoof, C. (2010), Ice-sheet acceleration driven by melt supply variability, *Nature*, *468*(7325), 803–806, doi:10.1038/nature09618.

Shepherd, A., et al. (2012), A reconciled estimate of ice-sheet mass balance, *Science*, *338*(6111), 1183–1189, doi:10.1126/science.1228102.

10.1002/2014GL061836

Sole, A. J., D. W. F. Mair, P. W. Nienow, I. D. Bartholomew, M. A. King, M. J. Burke, and I. Joughin (2011), Seasonal speedup of a Greenland marine-terminating outlet glacier forced by surface melt–induced changes in subglacial hydrology, *J. Geophys. Res.*, *116*, F03014, doi:10.1029/2010JF001948.

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.

Straneo, F., and P. Heimbach (2013), North Atlantic warming and the retreat of Greenland's outlet glaciers, *Nature*, *504*(7478), 36–43, doi:10.1038/nature12854.

Tedesco M., I. C. Willis, M. J. Hoffman, A. F. Banwell, P. Alexander, and N. S. Arnold (2013), Ice dynamic response to two modes of surface lake drainage on the Greenland ice sheet, *Environ. Res. Lett.*, *8*(3), 034007, doi:10.1088/1748-9326/8/3/034007.

van Angelen, J. H., M. van den Broeke, B. Wouters, and J. T. M. Lenaerts (2013), Contemporary (1960–2012) evolution of the climate and surface mass balance of the Greenland ice sheet, *Surv. Geophys.*, *35*, 1155–1174, doi:10.1007/s10712-013-9261-z.

van As, D., et al. (2014), Increasing meltwater discharge from the Nuuk region of the Greenland ice sheet and implications for mass balance (1960–2012), *J. Glaciol.*, *60*(220), 314–322, doi:10.3189/2014JoG13J065.

van Meijgaard, E., L. H. van Ulft, W. J. van de Berg, F. C. Bosveld, B. van den Hurk, G. Lenderink, and A. P. Siebesma (2008), The KNMI regional atmospheric climate model RACMO version 2.1, *KNMI Tech. Rep*. *302*, 43 pp., Royal Netherlands Met. Inst., De Bilt, Netherlands.