# Greenland outlet glacier behavior during the 21st century: Understanding velocities and environmental factors

Twila Moon

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Reading Committee:

Ian R. Joughin, Chair

Howard B. Conway

Eric J. Steig

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**Abstract**

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Understanding velocities and environmental factors

Twila Moon

Chair of the Supervisory Committee:

Dr. Ian R. Joughin
Applied Physics Laboratory

Outlet glacier ice dynamics, including ice-flow speed, play a key role in determining Greenland Ice Sheet mass loss, which is a significant contributor to global sea-level rise. Mass loss from the Greenland Ice Sheet increased significantly over the last several decades and current mass losses of 260-380 Gt ice/yr contribute 0.7-1.1 mm/yr to global sea-level rise (~10%). Understanding the potentially complex interactions among glacier, ocean, and climate, however, remains a challenge and limits certainty in modeling and predicting future ice sheet behavior and associated risks to society. This thesis focuses on understanding the seasonal to interannual scale changes in outlet glacier velocity across the Greenland Ice Sheet and how velocity fluctuations are connected to other elements of the ice sheet-ocean-atmosphere system.

***1) Interannual velocity patterns***

Earlier observations on several of Greenland's outlet glaciers, starting near the turn of the 21st century, indicated rapid (annual-scale) and large (>100%) increases in glacier velocity. Combining data from several satellites, we produce a decade-long (2000 to 2010) record

documenting the ongoing velocity evolution of nearly all (200+) of Greenland's major outlet glaciers, revealing complex spatial and temporal patterns. Changes on fast-flow marine-terminating glaciers contrast with steady velocities on ice-shelf–terminating glaciers and slow speeds on land-terminating glaciers. Regionally, glaciers in the northwest accelerated steadily, with more variability in the southeast and relatively steady flow elsewhere. Intraregional variability shows a complex response to regional and local forcing. Observed acceleration indicates that sea level rise from Greenland may fall well below earlier proposed upper bounds.

***2) Seasonal velocity patterns***

Greenland mass loss includes runoff of surface melt and ice discharge via marine-terminating outlet glaciers, the latter now making up a third to a half of total ice loss. 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. Research on a few Greenland glaciers also shows that speed varies seasonally. However, for many regions of the ice sheet, including wide swaths of the west, northwest, and southeast coasts where ice loss is increasing most rapidly, there are few or no records of seasonal velocity variation. We present 5-year records of seasonal velocity measurements for 55 glaciers distributed around the ice sheet margin. We find 3 distinct seasonal velocity patterns. The different patterns indicate varying glacier sensitivity to ice-front (terminus) position and likely regional differences in basal hydrology in which some subglacial systems do transition seasonally from inefficient, distributed hydrologic networks to efficient, channelized drainage, while others do not. Our findings highlight the need for modeling and observation of diverse glacier systems in order to understand the full spectrum of ice-sheet dynamics.

### *3) Seasonal to interannual glacier and sea ice behavior and interaction*

Focusing on 16 northwestern Greenland glaciers during 2009-2012, we examine terminus position, sea ice and ice mélange conditions, seasonal velocity changes, topography, and climate, with extended 1999-2012 records for 4 glaciers. There is a strong correlation between near-terminus sea ice/mélange conditions and terminus position. In several cases, late-forming and inconsistent sea ice/mélange may induce sustained retreat. For all of the 13-year records and most of the 4-year records, sustained, multi-year retreat is accompanied by velocity increase. Seasonal speedup, which is observed across the region, may, however, be more heavily influenced by melt interacting with the subglacial hydrologic system than seasonal terminus variation. Projections of continued warming and longer ice-free periods around Greenland suggest that notable retreat over wide areas may continue. Sustained retreat is likely to be associated with multi-year speedup, though both processes are modulated by local topography. The timing of seasonal ice dynamics patterns may also shift.

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# Chapter 1: Introduction to Greenland Ice Sheet Dynamics and Climate

The Greenland Ice Sheet is one of three ice sheets on Earth, all of which act as reservoirs for fresh water and each of which has the potential to raise sea level from many centimeters to many meters over the coming decades to millennia. The rate of ice loss from the Greenland Ice Sheet has accelerated over the last couple of decades and Greenland currently contributes 0.7-1.1 mm/yr to sea-level rise (260-380 Gt/ice per year) [*Shepherd et al.*, 2012; *Enderlin et al.*, 2014]. Determining the magnitude of Greenland Ice Sheet mass loss expected over the coming decades is critical for adaptation and mitigation planning efforts worldwide [*IPCC*, 2013b]. Predicting the potential rate and limits of future mass loss in turn requires a clear understanding of ice sheet dynamics and how the ice sheet is coupled to the climate system [*Alley and Joughin*, 2012].

## 1.1 Mass loss from the Greenland Ice Sheet

Mass loss from the Greenland Ice Sheet falls under two broad categories: decreasing surface mass balance, primarily through increased melt, and increasing ice discharge. Surface mass balance is the net balance between accumulation through snowfall and ablation due to melt and runoff. Ice discharge is the loss of ice through calving of icebergs, which is connected to the dynamics of the ice sheet and requires an understanding of ice velocity and thickness. Roughly a third to a half of Greenland ice loss is due to discharge through iceberg calving at the ice-ocean interface, as opposed to *in situ* surface melt [*Shepherd et al.*, 2012; *Enderlin et al.*, 2014]. Glacier velocity, as well as ice thickness, terminus advance and retreat, and the mechanisms controlling their variability, must be understood to calculate and predict ice sheet discharge. Thus, characterization and understanding of ice sheet velocity contributes both to exploring the processes controlling ice dynamics and predicting future mass loss and associated sea-level rise via modeling.

The research presented in this thesis is an effort to improve understanding of ice flow for the Greenland Ice Sheet and also understand how ice flow behavior is connected to other slow- and fast-changing components of the ice-sheet-ocean-climate system. This work, in part, is motivated by a critical need identified by the Intergovernmental Panel on Climate Change (IPCC), which is tasked with reviewing and assessing the international scope of research on climate change, including the physical science driving climate change, potential future changes in climate, and adaptation and mitigation options. In 2007, the IPCC released a report outlining predictions for global changes related to climate change [*IPCC*, 2007b]. Within this report, the IPCC attempted to provide predictions for sea level rise up to 2100. The report, however, noted: "Dynamical processes related to ice flow not included in current models but suggested by recent observations could increase the vulnerability of the ice sheets to warming, increasing future sea level rise. Understanding of these processes is limited and there is no consensus on their magnitude" [*IPCC*, 2007b]. Through the efforts of the larger glaciology community, including the work presented here, substantial progress has already been made in understanding ice flow and is reflected in the most recent IPCC report, released in 2013, which shows higher confidence in understanding ice sheet dynamics and projecting future sea-level rise [*IPCC*, 2013b].

## 1.2 Measuring glacier velocity

Early glaciological ideas regarding ice sheets suggested that ice sheet velocities were primarily driven by ice sheet deformation under the force of gravity and changed slowly over time based on multiyear changes in loss and accumulation of interior ice sheet mass. Direct measurements of ice velocity for the Greenland Ice Sheet were also limited. Development of remote sensing techniques to use satellite observations to measure ice surface velocity provided an important step toward improved understanding. Techniques developed in the 1980's provided the first satellite image-based observations of ice sheet velocity through image co-registration [*Lucchitta and Ferguson*, 1986]. Advances in these co-registration techniques in the early 1990's allowed for velocity measurements in ice sheet regions away from visible bedrock. In the later 1990's, a new remote sensing technique using interferometric synthetic aperture radar allowed for ice velocity measurements over wide areas regardless of cloud conditions [*Joughin et al.*, 1995; 1998]. Throughout this period, there was little indication that ice sheet velocities might change over timescales less than decades or centuries because most observations provided only single snapshots of ice sheet velocity. In the mid-2000's, however, repeat observations of Greenland outlet glacier velocities showed that large and rapid changes do occur on the ice sheet [*Joughin et al.*, 2004; *Howat et al.*, 2005; 2007]. These discoveries revealed that the Greenland Ice Sheet may be much more sensitive to climate change than previously assumed and energized a community effort to better understand the mechanisms governing ice sheet mass loss on short (seasonal to decadal) timescales, including the work presented here.

## 1.3 Environmental factors connected to ice flow speed

Greenland outlet glaciers function as part of a connected ice-sheet-ocean-climate system. Within this system, a range of local and regional factors likely affects individual glacier variability. These include, for example: local and regional climate; ice-sheet bed geometry and fjord bathymetry; characteristics of near-terminus sea ice or ice mélange (a combination of icebergs, bergy bits, and sometimes sea ice); small- and large-scale variability in ocean water properties and circulation; and the features of the supraglacial to subglacial hydrologic environment (Fig. 1.1). Many of these factors can be classified as either mainly affecting the glacier terminus or the glacial hydrologic system, both of which may play dominant roles in controlling ice velocity.

### *1.3.1 At- or near-terminus changes*

The importance of the local environment for determining ice-flow speeds is in part due to the potentially high sensitivity of outlet glaciers to changes at the glacier terminus. Observations, modeling, and theory support the hypothesis that changes in ice-front position can have notable affects on glacier velocity [e.g., *Joughin et al.*, 2008b; *Nick et al.*, 2009; *Podrasky et al.*, 2012]. Ice flow speeds are expected to increase in response to terminus retreat through a combined reduction in resistive stress and increase in ice thickness as the calving front retreats into deeper water. To maintain force balance, basal traction must increase, which occurs through ice-flow speedup. Because reverse-slope beds are common on Greenland's largest glaciers it is often assumed that as most glaciers in Greenland retreat their termini are moving into deeper water and thus speed is expected to increase.

Modulations in terminus position are not the result of a single, simple process. Instead, terminus change may be affected by a variety of mechanisms. Formation and breakup of ice mélange and sea ice at the glacier terminus may in part control the timing and length of the calving season by suppressing or allowing calving, respectively (Fig. 1.1). For example, observations of Jakobshavn Isbræ, one of Greenland's highest discharge glaciers, show that its velocity is significantly modified by terminus advance and retreat, which may in turn be largely controlled by changes in the ice mélange within the Jakobshavn Fjord [*Joughin et al.*, 2008b; *Amundson and Truffer*, 2010]. Another mechanism by which ocean conditions can influence terminus position is through subsurface melt of the terminus face that may undercut or thin the terminus, allowing for increased calving (Fig. 1.1). Summer subsurface melt rates of up to several meters per day have been observed on some Greenland glaciers [e.g., *Rignot et al.*, 2010a; *Enderlin and Howat*, 2013] and broad patterns of retreat, for example in the southeast, as well as the timing of rapid retreat on Jakobshavn have been connected to warming ocean waters [e.g., *Holland et al.*, 2008; *Rignot et al.*, 2012]. Ice sheet bed topography and fjord bathymetry also influence near-terminus ocean circulation patterns and terminus stability (Fig. 1.1). For example, the presence of deep submarine troughs for many of Greenland's largest-discharge glaciers likely plays an important role in allowing warm subsurface Atlantic water to interact with the ice sheet [*Straneo et al.*, 2012; *Sutherland et al.*, 2013]. Topography under and near the terminus can also include sills or over-deepenings that can slow or speed terminus retreat, respectively [*Joughin et al.*, 2008a; *Nick et al.*, 2010].

### *1.3.2 Glacial hydrologic system*

Along with changes at the glacier terminus, changes in the supraglacial to subglacial hydrologic system have also been linked to velocity fluctuations (Fig. 1.1). In the mid-2000's, observations revealed that surface meltwater on the Greenland Ice Sheet was likely migrating to the ice-bed interface and was associated with seasonal speedup [*Zwally et al.*, 2006]. Subsequent observations showed that summer meltwater can move to the base of the ice sheet via extensive meltwater stream systems and also from drainage of surface lakes [*Das et al.*, 2008; *Legleiter et al.*, 2014]. Speedup associated with subglacial meltwater input has been observed on both marine- and land-terminating regions of the Greenland Ice Sheet [*Joughin et al.*, 2008c; *Bartholomew et al.*, 2011; *Sole et al.*, 2011]. Understanding of the characteristics and evolution of the Greenland Ice Sheet subglacial system, however, continues to evolve via observation and modeling efforts [e.g., *Hewitt*, 2013; *Meierbachtol et al.*, 2013; *Werder et al.*, 2013; *Hoffman* *and Price*, 2014]. Some of the results from the seasonal velocity studies presented here are poised to help inform the evolving picture of ice sheet hydrology and its links to ice sheet velocity.

## 1.4 Improving understanding of Greenland glacier velocities

In light of the substantial contribution that the Greenland Ice Sheet makes to current sea-level rise and its potential future contribution [*Shepherd et al.*, 2012; *IPCC*, 2013b; *Enderlin et al.*, 2014], research on the dynamics of the Greenland Ice Sheet and their connection to environmental forcing has increased over the last decade. Progress has been made on both fronts and the work presented here contributes to these advances. With this research, we characterize outlet glacier velocities on seasonal to interannual timescales and for all regions of the ice sheet. We develop and incorporate multiple other datasets, including time series of terminus position, sea ice and ice mélange conditions, and modeled ice sheet surface runoff, to understand how velocity patterns are shaped by various environmental components. Finally, we use these results to examine the local and regional differences and similarities in ice dynamics and what these differences imply for the ice sheet's response to current and future warming. These findings will be useful for informing further observation and modeling research.

## 1.5 Summary

Mass loss from the Greenland Ice Sheet plays a significant role in current sea-level rise and its contribution may accelerate in the future [*IPCC*, 2013b]. Predicting future mass loss, however, requires an understanding of ice dynamics, including ice velocity, and how it is connected to other environmental components. Ice discharge, which makes up roughly one third to one half of current Greenland mass losses is largely determined by outlet glacier velocity

[*Shepherd et al.*, 2012; *Enderlin et al.*, 2014]. Velocity, in turn, reacts to a number of environmental conditions and is perhaps most responsive to changes at the glacier terminus and ice-bed interface. Here, we combine surface velocity measurements with other datasets to improve our understanding of the spatial and temporal characteristics of Greenland ice flow and how the various components of the ice-sheet-ocean-climate system are connected. In Chapter 2, we look at annual velocity measurements from 2000 and each year from 2005 to 2010, which reveal a substantial increase in mean regional velocities in the northwest and southeast over the decade. Along with notable regional differences in velocity behavior, the decade-long velocity record also reveals significant velocity variations on individual glaciers from year to year and from glacier to glacier within a region. In Chapter 3, seasonal velocity measurements from around the Greenland coast indicate that some glaciers have a strong sensitivity to terminus position, while others appear more responsive to subglacial hydrological changes. Furthermore, those glaciers apparently most responsive to subglacial hydrology exhibit 2 distinct seasonal velocity patterns, which may be primarily determined by water availability. In Chapter 4, we focus on 16 northwest Greenland glaciers and find that seasonal changes in ice mélange characteristics correspond to terminus advance and retreat, while seasonal velocity appears sensitive to seasonal runoff. On an interannual scale, sustained retreat may be linked to longer sea-ice-free periods, also resulting in multi-year speedup. Finally, Chapter 5 summarizes the primary findings from the previous chapters and provides some perspective on future research needs.

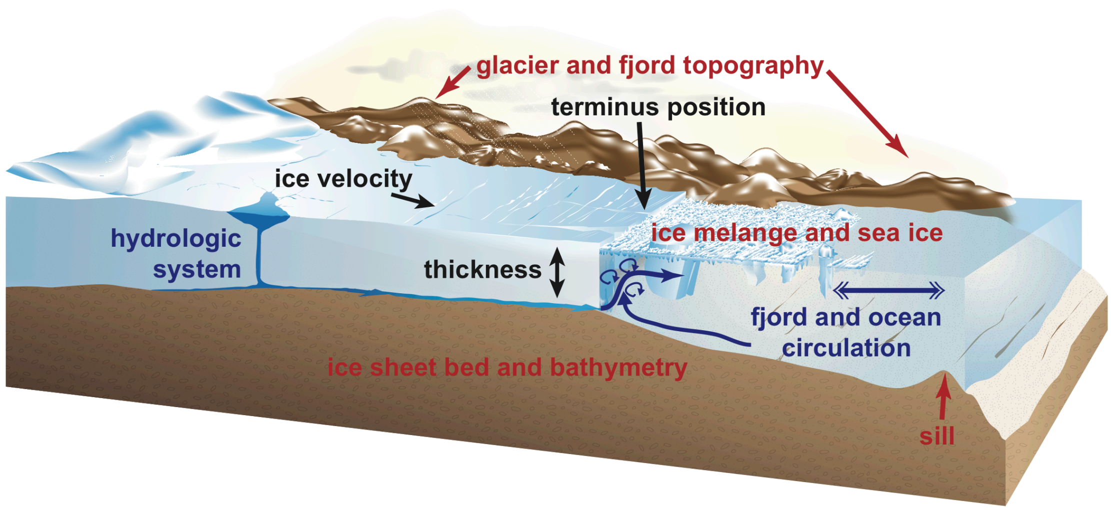


Figure 1.1 – Diagram of a marine-terminating Greenland outlet glacier (without floating ice tongue), showing elements contributing to iceberg discharge (black), the hydrologic and oceanic systems (blue), and other factors influencing ice dynamics (red). Background image from Straneo et al. [2013b].

# Chapter 2: Patterns of Interannual Velocity Change

Chapter 2, in full, is a reprint of "21st century evolution of Greenland outlet glacier velocities" authored by T. Moon, I. Joughin, B.E. Smith, and I. Howat. This is the author's version of the work. It is posted here by permission of the AAAS for personal use, not for redistribution. The definitive version was published in *Science* **336**, 576 (2012) doi: 10.1126/science.1219985. The dissertation author was the primary investigator and author of this paper.

## 2.1 Abstract

Earlier observations on several of Greenland's outlet glaciers, starting near the turn of the 21st century, indicated rapid (annual-scale) and large (>100%) increases in glacier velocity. Combining data from several satellites, we produce a decade-long (2000-2010) record documenting the ongoing velocity evolution of nearly all (200+) of Greenland's major outlet glaciers, revealing complex spatial and temporal patterns. Changes on fast-flow marine-terminating glaciers contrast with steady velocities on ice shelf-terminating glaciers and slow speeds on land-terminating glaciers. Regionally, glaciers in the northwest accelerated steadily, with more variability in the southeast and relatively steady flow elsewhere. Intra-regional variability shows a complex response to regional and local forcing. Observed acceleration indicates that sea level rise from Greenland may fall well below proposed upper bounds.

## 2.2 21st century evolution of Greenland outlet glacier velocities

Changes in glacier dynamics contribute to roughly half of the Greenland Ice Sheet's current mass loss (~250 Gt/yr equivalent to 0.6 mm/yr sea level rise) [*Van Den Broeke et al.*, 2009; *Rignot et al.*, 2011], in large part through thinning and increased calving as glaciers have sped up. Large changes in ice dynamics have been observed [*Howat et al.*, 2007], but were not accounted for in early models and led to the inability to quantify uncertainty of 21st century sea level rise in the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment [*IPCC*, 2007a]. While multi-glacier speedups have been linked to recent warming in Greenland [*Howat et al.*, 2008; *Van De Wal et al.*, 2008; *Zwally et al.*, 2011], the exact connection to climate change is poorly known, but may be related to processes controlled by ice-ocean interaction [*Holland et al.*, 2008; *Rignot et al.*, 2010a; *Andresen et al.*, 2011]. A firm understanding of the processes driving recent change, which is needed to improve predictions of sea level rise, requires a better characterization of the temporal and spatial patterns of ice flow across the ice sheet.

Despite the need for comprehensive data, recent studies of velocity in Greenland are limited in spatial and temporal resolution. For Jakobshavn Isbræ, Helheim Gletscher, and Kangerdlugssuaq Gletscher, three of Greenland's fastest outlet glaciers, velocity is relatively well documented [*Howat et al.*, 2007; *Joughin et al.*, 2008c; *Howat et al.*, 2011]. For the majority of Greenland's other 200+ outlet glaciers, however, observation has been limited to ~5-year sampling on an ice-sheet-wide scale [*Rignot and Kanagaratnam*, 2006; *Joughin et al.*, 2010] or smaller regions with more frequent sampling [*Howat et al.*, 2008]. Where comprehensive records exist, they have been used to focus on aggregate discharge rather than regional variability [*Rignot et al.*, 2011]. We present a decade-long record, with annual sampling for the latter half, to examine decadal scale trends and regional and local interannual variation, and to inform predictions of sea level rise.

To create this record we produced velocity maps for winter 2000/01 (referred to as 2000) and annually for each winter from 2005/06 through 2010/11 (referred to using the earlier year for the map), using synthetic aperture radar data from the Canadian Space Agency's RADARSAT-1, German TerraSAR-X, and Japanese Advanced Land Observation Satellite (ALOS) (Table A1). We use a combination of speckle-tracking and interferometric algorithms to estimate ice-flow velocity [*Joughin*, 2002; *Joughin et al.*, 2010]. Coverage for each year is almost complete, with some unavoidable gaps, primarily in the south, due to satellite acquisition limits.

Of the 206 largest Greenland outlet glaciers, 178 have adequate temporal coverage for 2000-2005 and 195 have sufficient data for 2005-2010 (Fig. 2.1) (Appendix A). We divide these glaciers into several categories. First, we identify land-terminating, ice shelf-terminating (ice shelf >10 km long), and low velocity marine-terminating (mean velocity <200 m/yr) glaciers (55 total). Next, glaciers with highly variable behavior are separated to avoid misrepresenting large variations as consistent trends (Appendix A). This includes glaciers such as Harald Moltke Bræ (Fig. A1), where apparent surge behavior produces erratic changes [*Mock*, 1966]. The final group consists of fast-flow marine-terminating glaciers we fit with linear regressions for all available data for 2000-2005 (111 glaciers) and 2005-2010 (123 glaciers) to evaluate trends and fill data gaps (Fig. A2-A3).

Our record reveals the complexity of Greenland's ice flow. Greenland's largest land-terminating glaciers are located primarily along the southwest coast, with a few in the northeast (Fig. 2.1). Nearly all flow at peak velocities between 10 and 100 m/yr, so that 10-30 m/yr annual changes produce large long-term trends (>15% change over 5 years). Most (70%) of the land-terminating glaciers with a notable trend slowed during 2005-2010 - a continuing trend for half of them. The scale of these changes, however, is close to the measurement error and seasonal variability [*Joughin et al.*, 2008c] and orders of magnitude smaller than changes seen on many fast-flowing glaciers. The one outlier, Frederikshab Isblink (Fig. A1), has a large lobe-shaped terminus that is primarily land-terminating, but with one segment of lake-terminating ice front. The velocity field suggests that this segment helps the glacier maintain a higher peak velocity (~270 m/yr) than other land-terminating glaciers, and hints at the importance of a calving terminus in maintaining fast ice flow.

Ice-shelf terminating glaciers (Fig. 2.1) have mean velocities (300-1670 m/yr) that are generally slower than other marine-terminating glaciers (total mean: 1890 m/yr), but most show negligible change for 2000-2010. The most notable change occurred on Hagen Bræ (from 50 m/yr in 2000 to 650 m/yr in 2007), a previously identified surge-type glacier [*Rignot et al.*, 2001].

Surge-type glaciers occur mostly in the northwest, north, and east [*Rignot et al.*, 2001; *Jiskoot et al.*, 2003]. In several cases, one- or two-year velocity changes suggest surge-type behavior, as observed on Harald Moltke Bræ (high speed in 2005), where surges have been recorded before, and Adolf Hoel Gletscher (low speed in 2007) (Fig. A1) and Kangilerngata sermia (low speed in 2005), where earlier surges have not been recorded. Other glaciers where surges have been observed previously, including Storstrommen and L. Bistrup Bræ [*Rignot et al.*, 2001] and Sortebræ [*Murray et al.*, 2002], maintained quiescent speeds over the last decade.

Most glaciers in east Greenland are marine-terminating, but have substantially slower mean velocities (1040 m/yr) relative to southeast (2830 m/yr) or northwest (1630 m/yr) marine-terminating glaciers. This is consistent with the lower regional discharge from this low accumulation area [*Box*, 2005]. As a group, eastern glaciers showed only negligible changes from 2000-2010. The low decadal-scale variability may be related to colder surface and subsurface ocean temperatures north of ~69°N [*Seale et al.*, 2011]. Of the few glaciers where we did detect a trend, at least half were slowing in each period (Fig. 2.1). The predominance of surge-type glaciers in the east [*Jiskoot et al.*, 2003] also suggests that the few notable trends may result from surge-related dynamics, which represent velocity changes that are not necessarily linked to climate [*Kamb et al.*, 1985; *Murray et al.*, 2003].

Fast-flow marine-terminating glaciers are the dominant type in the northwest, and regional speed increased there by 8% from 2000 to 2005 (Fig. 2.2). This was followed by a larger increase (18%) from 2005 to 2010, with most of the speedup during 2007-2010 (14%). This trend results from a number of glaciers speeding up and is not driven by the acceleration of any particular glacier (Appendix A). Despite the overall increase, however, there is not a uniform pattern of synchronous intraregional acceleration (Fig. A2). A third of northwest glaciers steadily increased over the whole decade, while ~15% slowed from 2000-2005 and then accelerated substantially from 2005-2010. Another third of the glaciers showed no trend and a quarter of the region's glaciers slowed over the decade (Fig. 2.1).

Greenland's southeast sector also has a high concentration of marine-terminating glaciers. Satellite coverage is more limited in this region, allowing us to sample 35 of 47 glaciers for the whole decade (Fig. 2.1). Many (43%) of these glaciers sped up substantially over the first half of the decade, but most did not maintain their rate of acceleration to 2010 and a third dropped below their 2005 speed. Across the region, a quarter of the glaciers slowed >15% from 2005 to 2010 (none did during 2000-2005). As a result, the southeast's mean velocity in 2010 (3120 m/yr) was less than 200 m/yr higher than its 2005 mean (2980 m/yr) (Fig. 2.2); the result of a 2005-2006 slowdown followed by a sluggish 2006-2010 speedup (50-110 m/yr average annual speedup). The pattern is similar when excluding the three fastest 2010 glaciers, though the annual speedup after 2005 is lower (20-60 m/yr average annual speedup). Like the northwest, however, the regional trend in the southeast does not describe most individual glaciers (Fig. A3). Instead, large speedups on many glaciers during 2005-2010 are balanced by considerable slowing on others (Fig. 2.1).

Despite some consistency in regional trends, the data show a remarkable degree of overall variability. Substantial acceleration (28%) in the southeast and on Jakobshavn Isbræ (32%) from 2000-2005 garnered much attention [*Joughin et al.*, 2004; *Rignot and Kanagaratnam*, 2006; *Howat et al.*, 2008] and raised concern about the climate sensitivity of the Greenland Ice Sheet, particularly since these changes were not included in IPCC sea level rise predictions [*IPCC*, 2007a]. Subsequent studies found acceleration was not sustained on the southeast's largest glaciers, but continued on Jakobshavn [*Howat et al.*, 2007]. Our expanded record shows these patterns are truly region-wide: early acceleration in the southeast decreased, with little change from 2005-2010, while the northwest on net maintained relatively steady acceleration throughout the decade. As a result, 2000-2010 acceleration in the northwest (28%) is comparable to the southeast (34%).

Differences in the regional velocity patterns for the northwest and southeast may be connected to ice sheet environment; many northwest glaciers are embedded within the surrounding ice sheet so that strongly convergent flow may limit rapid thinning, while southeast glaciers tend to flow through long fjords where along-flow stretching can produce rapid thinning as a glacier speeds up, potentially creating faster and larger fluctuations in speed [*Howat et al.*, 2007]. Ocean water characteristics may also affect regional trends. Both southeast and northwest glaciers respond to changes in warm North Atlantic waters, but geography and atmospheric and ocean circulation patterns control when and how these warm waters reach the separate sectors [*Holland et al.*, 2008; *Murray et al.*, 2010; *Straneo et al.*, 2010].

Although ocean and climate factors seem to exert a regional influence [*Howat et al.*, 2008; *Murray et al.*, 2010; *Seale et al.*, 2011], the effect on any particular glacier is highly variable and may be primarily affected by a wide range of local factors [*Howat et al.*, 2005; *Nick et al.*, 2012]. We observe many instances of asynchronous behavior on neighboring glaciers on annual (Fig. A2-A3) and decadal (Fig. 2.1) time scales. Influencing factors likely include fjord, glacier, and bed geometry [*Howat et al.*, 2007]; local climate [*Shepherd et al.*, 2009]; and small-scale ocean water flow and terminus sea ice conditions [*Amundson et al.*, 2010; *Straneo et al.*, 2011]. The scale of many of Greenland's glaciers (<5 km width) suggests that high-resolution models with detailed topography and local conditions may be necessary to resolve this complex behavior; a challenge that remains for individual glacier to full ice-sheet simulations. Despite the extent of our observations, this remains a glaciologically short record and efforts in modeling and statistical extrapolation will benefit as the period of observation lengthens.

Finally, our observations speak to recent work on sea level rise. Earlier research [*Pfeffer et al.*, 2008] used a kinematic approach to estimate upper bounds of 0.8 to 2.0 m for 21$^{st}$ century sea level rise. In Greenland, this work assumed ice-sheet-wide doubling of glacier speeds (low-end scenario) or an order of magnitude increase in speeds (high-end scenario) from 2000 to 2010. Our wide sampling of actual 2000-2010 changes show that glacier acceleration across the ice sheet remains far below these estimates, suggesting that sea level rise associated with Greenland glacier dynamics remains well below the low-end scenario (9.3 cm by 2100) at present. Continued acceleration, however, may cause sea level rise to approach the low-end limit by this century's end. Our sampling of a large population of glaciers, many of which have sustained considerable thinning and retreat, suggests little potential for the type of widespread extreme (i.e., order of magnitude) acceleration represented in the high-end scenario (46.7 cm by 2100). Our result is consistent with findings from recent numerical flow models [*Price et al.*, 2011].

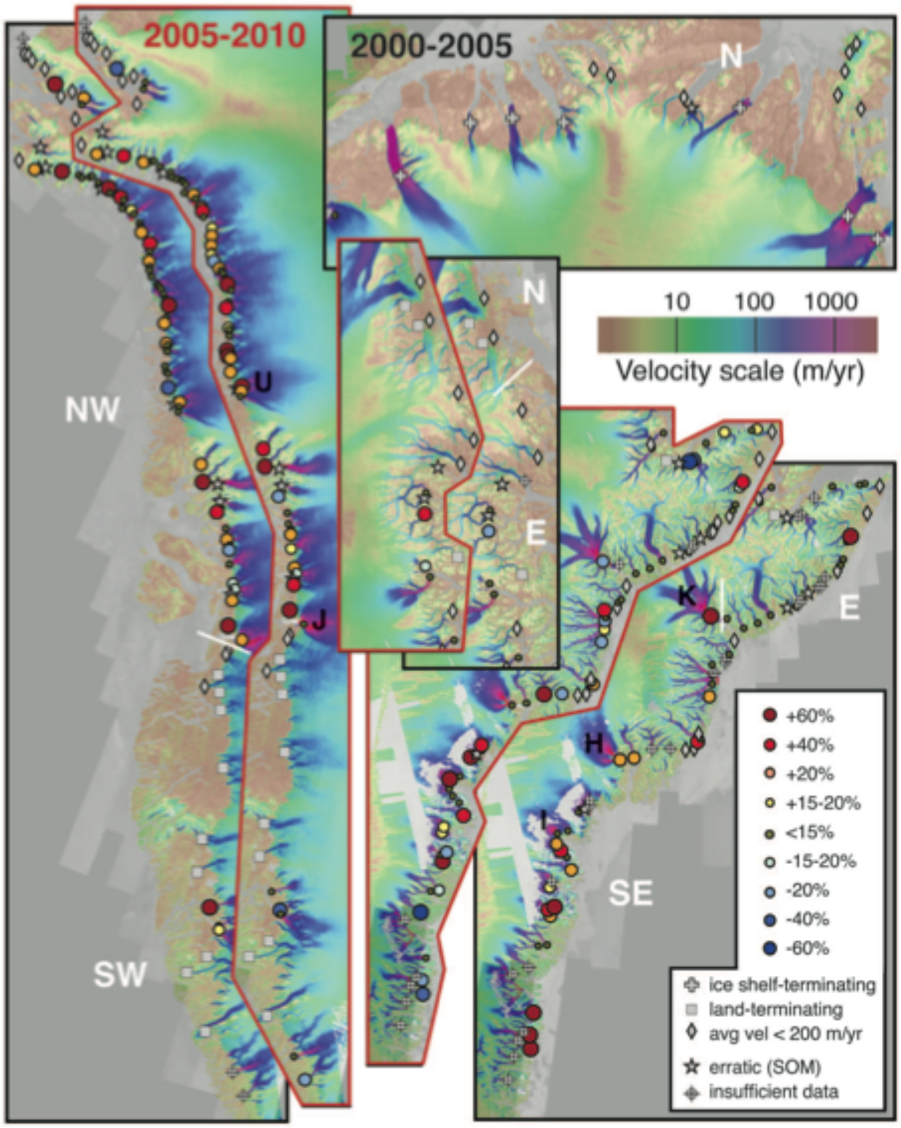


Figure 2.1 – Outlet glacier categories and rates of velocity change (% change from beginning of 5-year period). Black-outlined images show 2000-2005 results and red-outlined images are 2005-2010 results. The background velocity map for both periods is a 2007-2010 composite, with the 5 ice sheet regions indicated: north (N), northwest (NW), southwest (SW), southeast (SE), and east (E). There was no change for the north during 2005-2010. Jakobshavn (J), Upernavik North (U), Helheim (H), Kangerdlugssuaq (K), and Ikeq Fjord (I) glaciers are indicated.

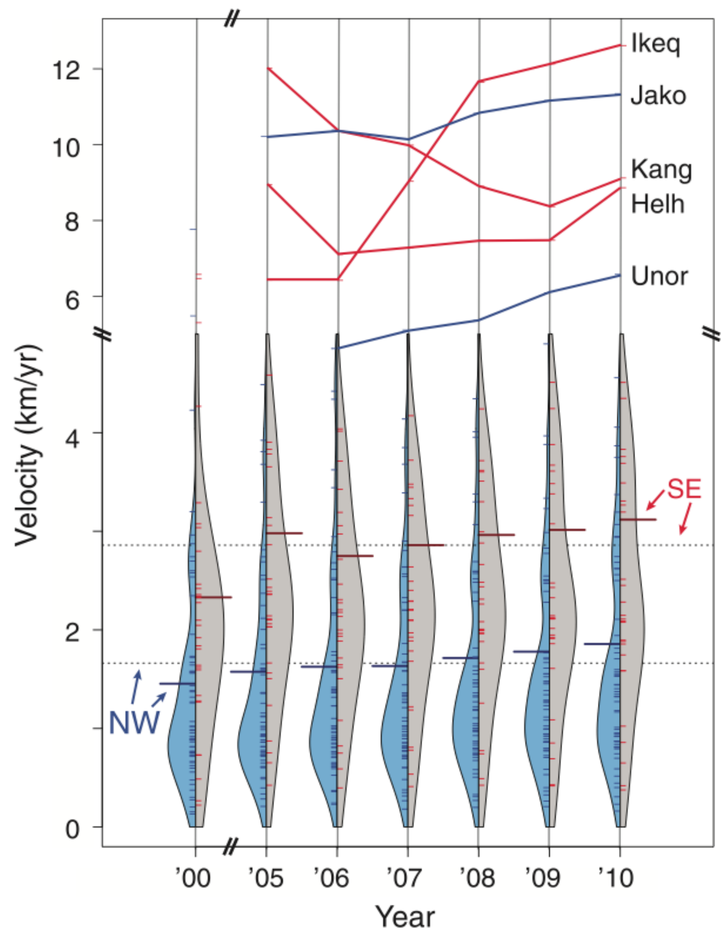


Figure 2.2 – Bottom: distribution of glacier speeds (short ticks), smoothed speed density (colored bars) and mean speeds (long ticks) for seven years' data. The northwest region is shown in blue (left side) and southeast region in grey/red (right side). Dashed black lines indicate regional mean speed over the entire decade (top for southeast, bottom for northwest). Only glaciers with sufficient data for both 2000-2005 and 2005-2010 are included. Top: velocity plots for Jakobshavn (Jako), Upernavik North (Unor), Kangerdlugssuaq (Kang), Helheim (Helh), and Ikeq Fjord (Ikeq).

# Chapter 3: Patterns of Seasonal Velocity Change

Chapter 3, in full, is currently being prepared for publication as "Distinct patterns of seasonal Greenland glacier velocity from ice-sheet-wide analysis" authored by T. Moon, I. Joughin, B.E. Smith, and M. Usher. The dissertation author was the primary investigator and author of this paper.

## 3.1 Distinct patterns of seasonal Greenland glacier velocity from ice-sheet-wide analysis

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] contribute 0.7-1.1 mm/yr to global sea-level rise (~10%) [*IPCC*, 2013a]. Greenland mass loss includes runoff of surface melt and ice discharge via marine-terminating outlet glaciers, the latter 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 few Greenland glaciers also shows that speed varies seasonally [*Joughin et al.*, 2008c; *Howat et al.*, 2010; *Ahlstrøm et al.*, 2013; *Joughin et al.*, 2014]. However, for many regions of the ice sheet, including wide swaths of the west, northwest, and southeast coasts where ice loss is increasing most rapidly, there are few or no records of seasonal velocity variation. Here we present 5-year records of seasonal velocity measurements for 55 glaciers distributed around the ice sheet margin. We find 3 distinct seasonal velocity patterns. The different patterns indicate varying glacier sensitivity to ice-front (terminus) position and likely regional differences in basal hydrology in which some subglacial systems do transition seasonally from inefficient, distributed hydrologic networks to efficient, channelized drainage, while others do not. Our findings highlight the need for modeling and observation of diverse glacier systems in order to understand the full spectrum of ice-sheet dynamics.

With continued warming projected across the Arctic, understanding the behavior of the Greenland Ice Sheet and the links among ice sheet, climate, and ocean is necessary to improve predictions of ice mass loss and to assess the associated risks to society [*Joughin et al.*, 2012b; *IPCC*, 2013a; *Straneo et al.*, 2013b]. Ice-flow speed plays a dominant role in determining ice discharge. Velocity fluctuations may occur as a response to changes in the subglacial hydrologic network modulated by surface melt [*Joughin et al.*, 2008c; *Banwell et al.*, 2013; *Hewitt*, 2013; *Sole et al.*, 2013] and/or to changes in ice-front position [*Howat et al.*, 2008; *Joughin et al.*, 2008a; 2008b; *Nick et al.*, 2009]. Thus, ice velocity integrates the behavior and characteristics of several key components of the ice-sheet-ocean-climate system: subglacial environment, surface melt and runoff, and ice-ocean interaction at the terminus. As a result, 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 (e.g., oceanographic and topographic).

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 measured surface velocities seasonally (3 to 6 times per year) for 55 marine-terminating Greenland glaciers across the west, northwest, southeast, and southwest coasts from 2009 to 2013 (Methods). Fig. 3.1 shows the location, 5-year mean velocity, and mean intra-annual velocity range (difference between minimum and maximum velocity during a year) for each glacier. Velocity measurements for individual glaciers are available in Figs. B1-B55.

First, we examined the intra-annual velocity range to determine whether its magnitude and variability is influenced by mean glacier speed. The majority of glaciers flow between 1 and 5 km/yr with mean intra-annual velocity ranges between 150 and 500 m/yr. The average intra-annual velocity range is 413 m/yr or 16% of the 5-yr mean speed. We found moderate correlation between the intra-annual range and mean velocity ($r^2=0.44$) (Fig. B56). Intra-annual velocities on slower glaciers (mean speed <1 km/yr) did not vary more than 250 m/yr, while the fastest-flowing glaciers (>5 km/yr) have mean intra-annual velocity ranges exceeding 500 m/yr (Fig. 3.1). The slowest-moving glaciers (<1 km/yr) are clustered in the northwest [*Moon et al.*, 2012] and this region overall has the smallest mean intra-annual velocity range, with larger ranges along the central west and southwest coast (Fig. 3.1). The southeast also has a higher concentration of glaciers with a low velocity range (<200 m/yr) in the northern half of the region than the southern half. These results suggest some regional variability in intra-annual flow variability and we explore this idea more closely by analyzing patterns of seasonal change.

We observed 3 prominent seasonal velocity patterns on marine-terminating Greenland glaciers, which we classify as types 1 through 3 (Fig. 3.2, top row). Glaciers with a consistent seasonal pattern during 3 or more years are indicated in Fig. 3.1 and annual behavior for all glaciers is presented in Fig. 3.3. Type-1 behavior is characterized by speedup between late spring (early May) and early summer (mid-July), with speed remaining high until winter (mid-February) or early spring. With type-2 behavior there is a strong early summer speedup with lower, similar velocities in spring, late summer (early September), and fall (late November). Winter speed sometimes is elevated compared to spring and fall, but in most cases remains lower than the summer peak (Figs. 3.2b and 3.3). Type-3 behavior has a mid-summer slowdown leading to a pronounced late summer minimum, which rebounds over the winter. Along with these 3 patterns, we observed some years with steady speedup, deceleration, or no change (range < 50 m/yr) (Fig. 3.3).

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 resolved by our measurements. In particular, we may have missed an early season speedup in our type-3 observations. The robustness of the 3 distinct velocity patterns across many glaciers during 2009-2013, however, suggests that we are observing real differences in glacier behavior.

Theory, modeling, and observations of some glaciers show that both ice-front fluctuations and modifications in subglacial hydrology can influence glacier velocity. Assuming a reverse-slope bed, retreat changes the resistive stresses and the pressure boundary condition on the near-vertical terminus face, inducing speedup, while advance can cause slowing [*Howat et al.*, 2008; *Nick et al.*, 2009]. Subglacial hydrology theory suggests a seasonal transition from an inefficient, distributed subglacial drainage system to an efficient, channelized network [*Schoof*, 2010]. An inefficient system maintains higher water pressure and additional meltwater input further raises water pressure, increasing ice velocity. In this way, a distributed network fosters synchronous changes in water pressure and flow speed. As meltwater influx continues to rise, however, the distributed system evolves into an efficient, channelized drainage network. Water pressure and speed then drop, even though melt rates might remain high [*Bartholomew et al.*, 2010].

Seasonal velocity changes for type-1 behavior appear to be controlled primarily by ice-front position. Synchronous changes in speed and ice-front position were previously observed on Jakobshavn Isbræ (Fig. B26) [*Joughin et al.*, 2008b; 2014] and Rink Glacier (Fig. B21) [*Howat et al.*, 2010] and are confirmed by our measurements. Along with Rink Glacier, more than 40% of the velocity behavior for glaciers #24 and #40 is connected to terminus fluctuations based on a simple linear regression for 2009-2013 (Table B1). The type-1 velocity signal for some years (particularly 2010) appears to be strongly linked to terminus changes for glaciers #42 and #44 as well (Figs. B42 and B44). We hypothesize that type-1 behavior is due to a combination of melt and terminus retreat, with the latter producing sustained speedup through early winter (Fig. 3.2a). Thus, most glaciers with consistently strong seasonal sensitivity to ice-front changes have dominant type-1 behavior and the pattern occurs during single years for other glaciers with apparently strong correspondence between terminus and velocity changes (e.g., Fig. B18 during 2010).

Observations from glaciers with type-2 and type-3 behavior do not appear to have a strong connection between seasonal speed and ice-front position. For type-2 glaciers, clustered in the northwest and the Ikertivaq region in the southeast (Fig. 3.1), the correspondence between speed and runoff suggests a distributed, inefficient subglacial system exists throughout the year (Fig. 3.2b). Examining the northwest and southeast type-2 clusters separately provides further evidence of the synchronous changes in runoff and glacier speed. For northwest type-2 glaciers, velocity slowed to pre-summer speeds by late summer, matching the short, high-magnitude runoff season for the region, while type-2 glaciers in the Ikertivaq region decelerated more slowly, in line with the extended runoff season (Fig. B57).

By contrast with type 2, glaciers classified as type-3 behavior show a decline in velocity during times of high melt with a pronounced minimum during late summer periods of low melt. 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 (weeks) [*Sole et al.*, 2011; *Joughin et al.*, 2013]. For example, continuous Global Positioning System (GPS) measurements on Kangiata Nunata Sermia (#28, Fig. B28) [*Ahlstrøm et al.*, 2013], which coincide with our measurements during 2010, do show velocity peaks close to June 1 that we do not sample. Type-3 behavior is more commonly 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 B1, Figs. 3.1 and B56), which may reflect the addition of the late-summer velocity minimum.

Variation in the prevalence of type-2 and type-3 seasonal behavior is strongly geographically controlled (Figs. 3.1 and 3.3). We suggest that the difference is primarily determined by water availability. The northwest region (type 2) has shorter melt seasons than areas farther south on either coast. Melt is far greater in the southeast, where we do see most type-3 behavior. Where we observe type-2 behavior in the Ikertivaq region, much of the melt may not reach the bed. 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 available to the subglacial system. In the Ikertivaq region, however, they detected many areas with perennial firn aquifers, which may limit subglacial meltwater influx. Forster et al. [*Forster et al.*, 2013] hypothesized that perennial firn aquifers might be associated with different ice dynamic regimes; our observations provide evidence that ice dynamics – and likely the related supraglacial to subglacial hydrologic system – are indeed different in these regions. Differences in hydraulic gradient and subglacial geology may also play a role in determining type-2 and type-3 behavior, but further evaluation of these links is data limited for the broad scale of our analysis.

Type-2 and type-3 behavior may represent end members across a spectrum determined by subglacial conditions and water availability. Thus, elevation dependent availability of surface melt may also create a shift from channelized flow downstream for type-3 glaciers to a distributed network upstream (type-2 behavior). Measurements by multiple groups on Kangiata Nunata Sermia (#28) in 2010 allow us to test this hypothesis. Our near-terminus seasonal velocity measurements agree well with continuous GPS measurements taken ~10 km further upstream [*Ahlstrøm et al.*, 2013], with the pattern also matching measurements 36 km upstream from the margin [*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 is not currently available for testing this idea during other years at Kangiata Nunata Sermia or for other locations.

Our data present the first comprehensive ice-sheet-wide seasonal velocity measurements of marine-terminating Greenland glaciers. The results indicate strong sensitivity to terminus fluctuations for some glaciers, which often produces relatively high late-summer velocities. Seasonal speeds on most glaciers, however, are likely controlled by subglacial water availability, with seasonal switching between distributed and channelized systems for some glaciers and no such evolution on others. These differences in individual and regional glacier systems have important implications for the broad applicability of research on ice-ocean interaction, subglacial modeling, and predicting the effects of continued warming across the Greenland Ice Sheet.

## 3.2 Methods

Applying interferometric algorithms and speckle tracking to synthetic aperture radar (SAR) data from the German Space Agency's (DLR) TerraSar-X satellite we made roughly seasonal surface velocity measurements of 55 Greenland outlet glaciers [*Joughin*, 2002; *Joughin et al.*, 2010]. Most 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) (Figs. B1-B55). 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 consistent geometry is applied to each glacier. Comparison of GPS velocity measurements to TerraSAR-X velocities showed agreement consistent with this level of error [*Ahlstrøm et al.*, 2013]. To identify seasonal patterns, we initially examined all velocity data for every glacier to identify glaciers with consistent seasonal patterns for the full 5-year observation period. Glaciers with consistent behavior were grouped together based on pattern similarity. Using these patterns, we classified each year for every glacier (Fig. 3.3). Glaciers with the same pattern for at least 3 of the 5 observation years are indicated in Fig. 3.1 and included in Fig. 3.2.

Daily ice sheet runoff data are from the Royal Netherlands Meteorological Institute (KNMI) regional atmospheric climate model RACMO2 [*van Meijgaard et al.*, 2008]. To avoid conflict with the ice mask edge, we sampled RACMO2 data ~10 km up-glacier from the velocity measurements. We applied a Savitzky-Golay filter [*Savitzky and Golay*, 1964] (using 2$^{nd}$ degree polynomials) over a 15-day sliding window to smooth the daily measurements. Filtered values below the original data minimum were set to equal the raw data minimum.

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, we also included ice-front measurements made using Landsat 7 images during 2009-2012 (Moon et al., submitted). Because analysis 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 resolution (20 m) based on results from previous work (Moon et al., submitted).

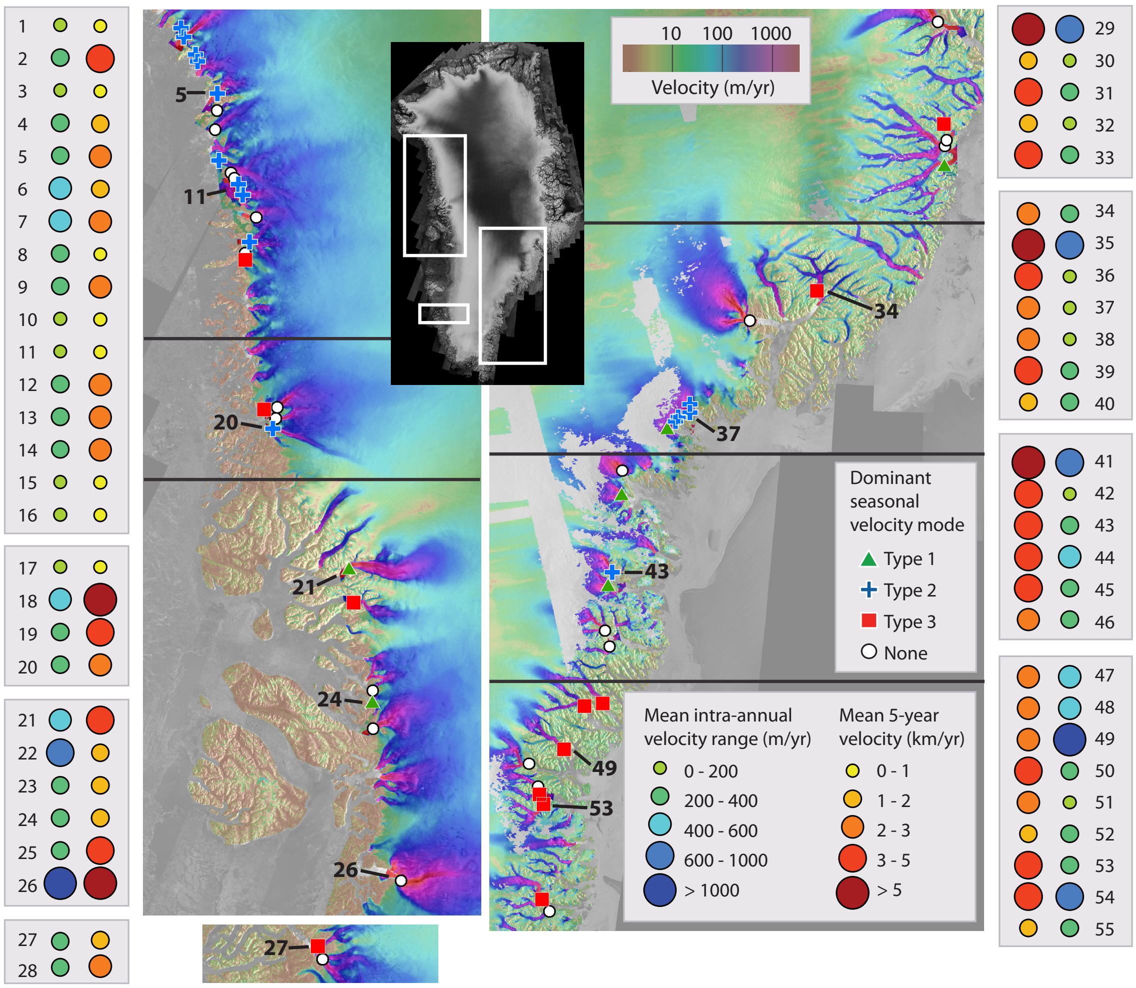


Figure 3.1 – Mean intra-annual velocity range, 5-year mean velocity, and seasonal velocity mode for Greenland marine-terminating outlet glaciers. Center panels show the locations for the 55 study glaciers, with symbols indicating the dominant seasonal velocity mode. Background map shows RADARSAT mosaic 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).

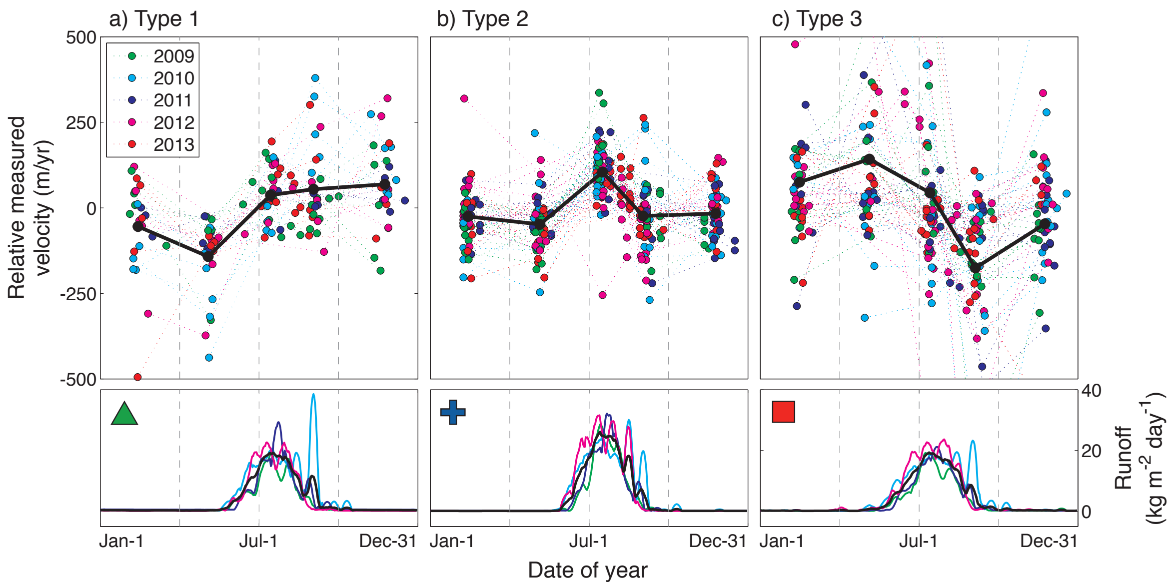


Figure 3.2 – Glaciers with distinct seasonal velocity modes and associated ice sheet runoff for marine-terminating Greenland outlet glaciers. Top row: Plots include all glaciers with dominant seasonal velocity modes for a) type 1, b) type 2, and c) type 3 behavior (as shown in Fig. 3.1). Measured velocity (m/yr) is detrended (removing either linear or quadratic trend, as indicated in Figs. B1-B55), divided by year with mean annual velocity subtracted for that year, and plotted on a 1-Jan to 31-Dec scale. Mean velocity pattern is indicated (thick black line). Bottom row: Smoothed daily runoff (kg/m$^2$d) from RACMO2 for 2009-2012 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).

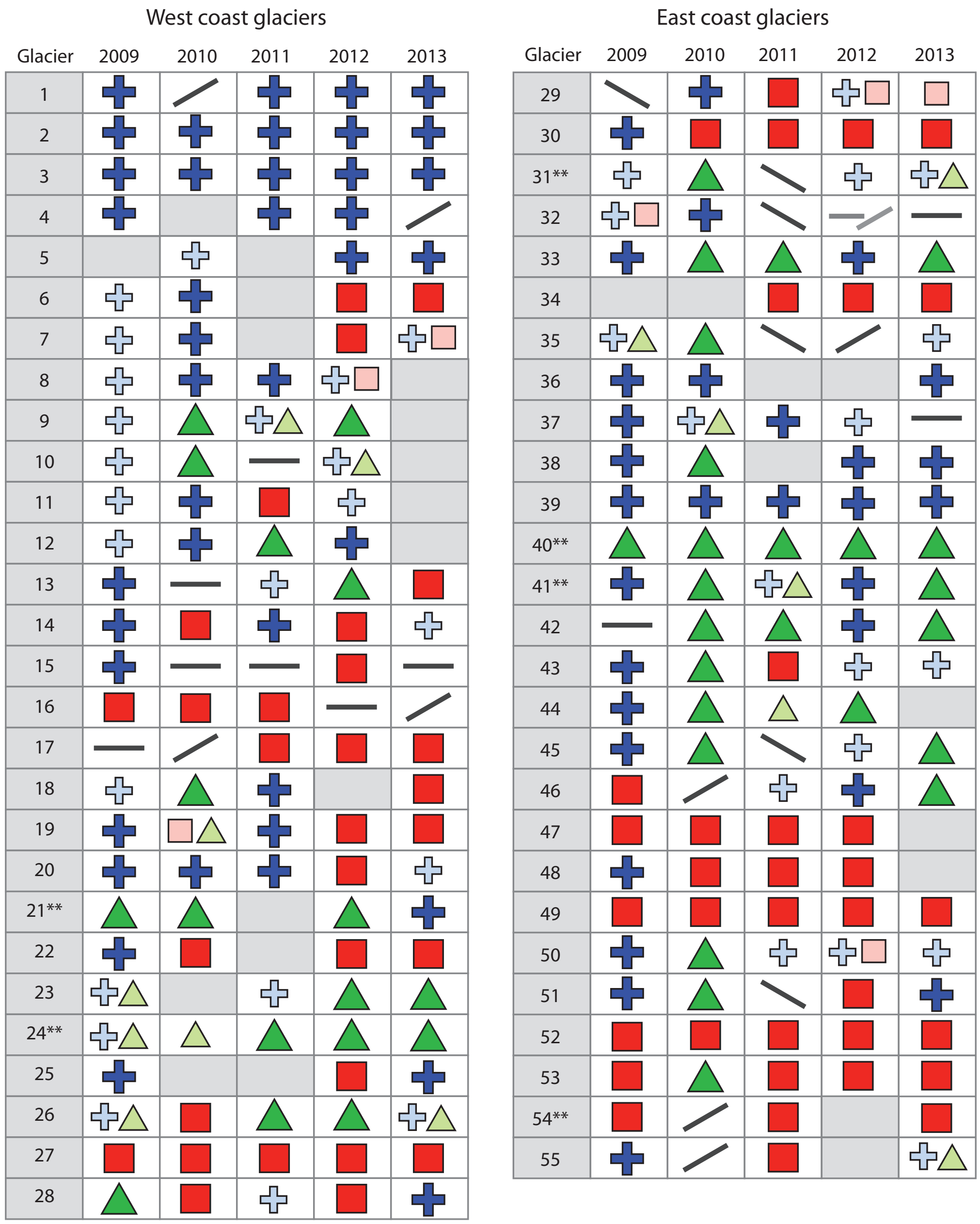


Figure 3.3 – Seasonal velocity modes for Greenland outlet glaciers by year. Symbols designate the seasonal velocity pattern for each glacier for every year (triangle = type 1; cross = type 2; square = type 3), with straight lines indicate consistently accelerating, decelerating, or flat speeds (<50 m/yr change) during the year. Lighter, smaller symbols indicate that the designation is based on limited data or has components of 2 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 pattern. Patterns were identified based only on measurements taken within each calendar year. Glaciers for which the terminus is associated with >40% of the change in velocity based on simple linear regression (with inverse correlation) are indicated (**). (See Figs. B1-B55 for velocity data for individual glaciers).

# Chapter 4: Seasonal to Multi-Year Sea Ice/Ice Mélange and Glacier Terminus Position and Velocity in Northwest Greenland

Chapter 4, in full, has been submitted for publication as "Seasonal to multi-year sea ice/ice mélange and glacier terminus position and velocity in northwest Greenland" authored by T. Moon, I. Joughin, and B.E. Smith. The dissertation author was the primary investigator and author of this paper.

## 4.1 Abstract

Focusing on 16 northwestern Greenland glaciers during 2009-2012, we examined terminus position, sea ice and ice mélange conditions, and seasonal velocity changes, with extended 1999-2012 records for 4 glaciers. There is a strong correspondence between seasonal near-terminus sea-ice/mélange conditions and terminus position. Extended sea-ice-free periods and reduced rigid mélange also appear to induce multi-year terminus retreat. For all of the 13-year records and most of the 4-year records, sustained multi-year retreat was accompanied by interannual velocity increases. Seasonal speedup across the region coincided with the onset of spring runoff and seasonal terminus retreat, suggesting that melt interacting with the subglacial hydrologic system and seasonal terminus variation may both influence seasonal velocity. Projections of continued warming and longer sea-ice-free periods around Greenland indicate that notable retreat over wide areas may continue. This sustained retreat likely will contribute to multi-year speedup. Longer melt seasons and earlier breakup of mélange may also alter the timing of seasonal ice-dynamic patterns.

## 4.2 Introduction

Ice loss from the Greenland Ice Sheet is an important component of global sea-level rise, with current mass losses of 260-380 Gt ice/yr (contributing ~0.7-1.1 mm/yr to sea level) [*Shepherd et al.*, 2012; *Enderlin et al.*, 2014]. Mass loss has accelerated over the last several decades [*Allison et al.*, 2009; *Rignot et al.*, 2011; *Shepherd et al.*, 2012; *Enderlin et al.*, 2014] and climate models contributing to the Intergovernmental Panel on Climate Change Fifth Assessment project ~1.5-6°C of additional warming for Greenland by 2100 using a range of forcing scenarios (representing 2.6-8.5 W/m$^2$ radiative forcing by 2100 relative to pre-industrial conditions) [*IPCC*, 2013b]. Roughly a third to a half of Greenland's mass loss is due to ice discharge from marine-terminating outlet glaciers, as opposed to loss through *in situ* melt [*Van Den Broeke et al.*, 2009; *Rignot et al.*, 2011; *Enderlin et al.*, 2014]. Predicting future ice discharge is critical for understanding the potential magnitude and timing of sea-level rise, but remains difficult in part because we do not have a complete understanding of how outlet glacier dynamics interact with and are influenced by other elements of the earth system, including the ocean, atmosphere, and geology [*Joughin et al.*, 2012b; *Straneo et al.*, 2013a]. The complexity of outlet glacier systems and the likelihood that the influence of different components (e.g., topography, fjord circulation, surface melt) varies from glacier to glacier and from year to year exacerbates the challenge. Despite this difficulty, theory, observation, and modeling have identified several key mechanisms that appear to control changes in outlet glacier behavior, particularly at the terminus:

- Rigid sea ice and ice mélange (a mixture of sea ice and icebergs) appear to suppress calving at the glacier terminus, allowing for terminus advance [*Joughin et al.*, 2008b; *Amundson et al.*, 2010].

- Terminus advance, retreat, or thinning influences velocity by changing the resistive stress caused by contact with the fjord walls and/or glacier bed [*Howat et al.*, 2005; *Pfeffer*, 2007; *Howat et al.*, 2008].
- Warming subsurface ocean water and/or increased subglacial runoff may increase below-surface ice melt at the terminus, affecting terminus stability [*Holland et al.*, 2008; *Rignot et al.*, 2010b; *Motyka et al.*, 2011; *Sciascia et al.*, 2013].
- The position of the terminus relative to basal topography (e.g., over-deepening or sills) influences rates of retreat for a given forcing [e.g., *Oerlemans and Nick*, 2005].

We focus primarily on the first two mechanisms, examining seasonal-to-interannual sea-ice and ice mélange conditions, terminus position, and ice-flow speed. Surface mass balance (e.g., summer runoff) is considered in a more limited context.

To examine glaciers with similar climate variability, we focused on 16 marine-terminating glaciers in northwest Greenland (Fig. 4.1). We chose this region because it includes glaciers with characteristics that vary across multiple scales, including mean-annual velocity, bed depth [*Allen*, 2013], and fjord setting. Also, results from previous studies found varied relationships between dynamics and environmental factors in west/northwest Greenland [*Howat et al.*, 2010; *McFadden et al.*, 2011; *Carr et al.*, 2013a], so continued work in the area is well justified. A useful feature of the study region is that it spans a transition zone at Melville Bay, north of which relatively high winter sea-ice concentrations remain longer into spring than in other regions along the west coast (e.g., sea ice fraction (SIF) in Fig. 4.1). This contrast allows for a better evaluation of how sea ice and mélange may influence outlet-glacier behavior. To observe multiple timescales, this study included two parts: 1) a primary focus on seasonal and short multi-year changes for all 16 glaciers from 2009 through 2012, and 2) a more extensive record for 4 glaciers from late 1999 through 2012.

## 4.3 Methods

We used a variety of datasets to create seasonal-scale records of ice-flow velocities, terminus positions, and near-terminus mélange conditions for 16 northwest outlet glaciers from 2009 to 2012. Our analysis also incorporated modeled results for runoff and air temperature. Finally, for 4 glaciers we extended our terminus position and mélange record to 1999 using additional satellite imagery.

### *4.3.1 Seasonal velocity*

Using a combination of speckle tracking and interferometric algorithms applied to synthetic aperture radar (SAR) data from the German Space Agency's (DLR) TerraSAR-X satellite [*Joughin*, 2002; *Joughin et al.*, 2010], we measured ice-flow velocity with roughly once-per-season sampling for each glacier during 2009-2012, with a range of three to five velocity measurements per year (except for G3, which was only measured twice during 2010). Each velocity measurement was made using a pair of 11-day or occasionally 22-day repeat TerraSAR-X images and represents the average near-terminus speed during the period between image acquisitions. The timing for velocity measurements is roughly mid-February, early May, mid-July, early September, and late November. We define winter as January-March, spring as April-June, summer as July-September, and fall as October-December. The data are posted at 100-m intervals but the true spatial resolution is ~300 m. Errors for fast-flowing ice are ~3%, though relative accuracy (precision) is substantially better because errors are geometry dependent and the map for each glacier was created using a consistent viewing geometry. While the measurements provide a roughly seasonal look at velocity changes, our observations do not capture variations in speed between measurements, and may not measure each glacier's annual minimum and maximum velocity.

### *4.3.2 Terminus position*

We used the "box method" to measure glacier terminus position [*Moon and Joughin*, 2008]. First, each glacier was assigned an approximate outline to delineate its edges, including bends in the glacier shape. An arbitrary reference line positioned well upstream of the terminus closes the "box". To determine terminus length relative to the stationary up-glacier reference line, each terminus was digitized and the area within the box, as delineated by the digitized front, was divided by the corresponding glacier width (calculated as a straight line between the two intersecting points of the digitized front and the reference box).

Using the TerraSAR-X (20-m resolution) image pairs, we measured two terminus positions that are nearly coincident with each velocity measurement. To produce a more complete record we also used visible band images (30-m resolution) from the Landsat 7 Enhanced Thematic Mapper Plus (ETM+). Retreat was calculated relative to the first measurement for each glacier, all of which were acquired between 29 January and 5 February 2009 (except G6, first measured 26 March 2009). To examine cumulative terminus change, we linearly interpolated the terminus measurements to a weekly timescale.

Errors in manual terminus digitization were assessed by repeat digitization of TerraSAR-X and Landsat 7 images. We digitized the termini of several glaciers 10 times each in the same images, yielding root mean squared (RMS) digitization errors of 24 m and 25 m for TerraSAR-X and Landsat, respectively. For both TerraSAR-X and Landsat images, errors are similar to image resolution. Based on the manual digitization error, we define significant terminus changes as those greater than 50 m (i.e., >2σ). An additional source of potential error is image gaps from the failure (31 May 2003) of the Landsat 7 Scan Line Corrector (SLC) (e.g., Fig. 4.2). To minimize potential errors from SLC gaps, glacier terminus position was digitized in areas with image gaps only if: 1) the gaps ran approximately perpendicular to the ice front or the gap areas were unlikely to include irregular terminus regions, as judged by looking at other near-time glacier images, and 2) gaps were relatively narrow (closer to the center of the Landsat 7 image).

### *4.3.3 Mélange condition*

We used multiple methods for assessing the sea-ice concentration and potential rigidity of the near-terminus sea ice and/or ice mélange for each glacier. Sea ice (frozen seawater) and ice mélange (a mixture of sea ice and icebergs) are often discussed separately, however, remote sensing measurements of sea-ice concentration to not distinguish between them. We also assess sea ice and mélange together and, to simplify terminology, we will refer to all ice seaward of the terminus as "mélange", though in some instances it may be entirely sea ice.

Our primary dataset on mélange conditions combines results from TerraSAR-X velocities with TerraSAR-X and Landsat images. The TerraSAR-X velocity measurements provided a robust method for determining the potential for rigid near-terminus mélange behavior using speckle tracking: if we were able to use speckle-tracking methods to measure velocity in front of the terminus, it indicated that the mélange was rigid or nearly rigid over the period [*Joughin et al.*, 2008b]. Because of the limited number of TerraSAR-X velocity measurements, however, this method provided limited data points. The majority of our data to assess rigid or near-rigid mélange behavior used visual analysis of individual TerraSAR-X and Landsat images. In every image, the near-terminus region for each glacier was classified as likely rigid (rigid), potentially rigid (mixed), unlikely rigid (open), or indeterminate (no data or cloudy, which is not included in figures) (Fig. 4.2). To be classified as “rigid” a region must have complete or near-complete mélange cover and/or comparison with near-time images indicating little relative deformation of the mélange. When we observed open water or extensive motion as compared to other near-time images, we classified the data as “open”. Areas with substantial ice cover but also extensive fracture, or areas with less mélange but also little relative motion in near-time comparable images, were classified as “mixed”.

Results from visual analysis are limited by image resolution and can be affected by errors in interpretation. We evaluated the consistency of visual analysis by comparing the TerraSAR-X velocity observations of rigid mélange (85 in total) with the visual analysis results. Visual analysis creates 2 near coincident observations for each TerraSAR-X velocity measurement. Visual analysis agreed fully with velocity-measured rigidity 72% of the time, with partial agreement (1 rigid observation, 1 mixed observation) an additional 19% of the time, providing relatively high confidence in visual analysis results.

To examine local-to-regional mélange conditions on a daily scale for the full 2009-2012 period, we used sea ice fraction (SIF) (i.e., fractional coverage of a grid cell by sea ice) data from the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system, which uses satellite data from the Group for High Resolution Sea Surface Temperature (GHRSST) along with in-situ observations to determine daily SIF with ~5 km resolution [*Donlon et al.*, 2012]. We sampled SIF as close to the glacier terminus as possible (typically within 5-15 km). Due to the limited resolution of the SIF records and because near-coast accuracy may be affected by the land-ocean interface, we used the SIF data to analyze broad regional mélange patterns rather than to determine mélange conditions at the terminus.

### 4.3.4 *Ice sheet meltwater runoff*

Daily runoff data for 2009-2012 are from the Royal Netherlands Meteorological Institute (KNMI) Regional Atmospheric Climate Model v2 (RACMO2) [*van Meijgaard et al.*, 2008]. When compared with observations RACMO2 has a 14% uncertainty for ice sheet integrated surface mass balance [*Ettema et al.*, 2009]. RACMO2 data were sampled at locations ~10 km up-glacier from the velocity measurements to avoid conflicts with the ice mask edge (Fig. 4.1).

### 4.3.5 *Extended glacier records*

We focused on four glaciers (G7, HA, SV, and G1) to construct a longer-term record of terminus position and mélange condition. We used the visual analysis methods described above with Landsat images from late 1999 through 2008 to extend the record for each of these glaciers to 13 years. To examine the link between terminus position and velocity, we compared the terminus position results with annual winter velocity measurements for 2000/01 and 2005/06-2008/09 from SAR data from TerraSAR-X, the Japanese Advanced Land Observation Satellite (ALOS), and the Canadian Space Agency's RADARSAT-1 [*Joughin et al.*, 2010; *Moon et al.*, 2012].

## 4.4 Results

Using the data and techniques described above, we analyzed individual patterns of ice-flow velocity and terminus position and the links among velocity, terminus position, and mélange condition. Figure 3 shows the 2009-2012 velocities, terminus positions, and mélange conditions for all glaciers, providing seasonal and interannual detail, and Table 1 lists some key measurements for each glacier. Together, our results reveal strong seasonal patterns and connections between glacial and sea surface changes.

### *4.4.1 Velocity patterns*

Our study group includes glaciers with 2009-2012 mean velocities ranging from 265 m/yr (G7) to 3378 m/yr (KO), with both increasing and decreasing velocity trends over the 4-year record (Table 4.1). The largest increasing velocity trends are for G4, HA, AG, and G3 (112-253 m/yr$^2$). Four other glaciers also have increasing velocity trends greater than 20 m/yr$^2$. Decreasing velocity trends are generally smaller; only G6 and IGD slow at rates exceeding 20 m/yr$^2$. Interannual trends on the remaining 6 glaciers are comparable to measurement error.

A valuable result of our study is gaining a seasonal-scale record of velocity patterns. The largest seasonal velocity changes generally occurred during a spring-to-summer speedup and mid-to-late summer deceleration. Measurements in roughly early May and mid-July allowed for comparison of spring and summer velocities for most glaciers (Fig. 4.3). (For SV, G4, and G5 during 2012, we compare mid-February to mid-July). Our measurements indicate a strong seasonal pattern of speedup from spring to summer; glaciers sped up for ~88% (56 of 64) of spring-to-summer measurements. With few exceptions, the spring-to-summer speedup was the largest velocity increase during the year. Spring-to-summer velocity increases ranged from 1% to 38% (11% mean) of the 4-year mean velocity, with a mean speedup of 151 m/yr (calculated with 4-year mean velocity trend removed from data). In many cases the subsequent summer-to-fall slowing was also the largest slowdown during the year, but more exceptions existed for this case. For example, HA had notable speedup every spring during the record, but little subsequent slowing in 2009-2011 and delayed winter slowing in the beginning of 2012 (Fig. 4.3).

Eight instances of spring-to-summer slowdown occurred for the 4 southernmost glaciers during 2010 (AG, IGD, G8), 2011 (G7, G8), and 2012 (IGD, G7, G8). In all but one case (IGD in 2012), however, these glaciers sped up during the preceding winter-to-spring measurement period. Due to the limited temporal sampling of the velocity data, we cannot determine if speedup continued after early May in these 7 cases. When spring speedup occurs, it is often followed by a large slowdown. The mid-July observations may not sample peak summer velocities, failing to reveal continued early May to early July speedup.

### *4.4.2 Terminus change*

Using the Landsat and TerraSAR-X datasets from 2009 to 2012, we produced an average of 88 terminus measurements for each glacier. In addition to Figure 4.3, Figure 4.4a shows the complete terminus records for every individual glacier. Measurement density is higher during spring and summer quarters, particularly during late 2009 to early 2010, with more even coverage in later years. All 16 glaciers retreated between the first and last measurements, but overall retreat was dominated by changes at G1 and AG, with retreat >1 km also observed on SV, G4, G5, and HA (Table 4.1 and Fig. 4.4a). Figure 4.4b uses weekly-interpolated terminus data to show the cumulative terminus change. These data emphasize the strong seasonal signal of advance and retreat for all years, which is also apparent in individual glacier records (Fig. 4.3). Both 2009 and 2012 (and potentially 2010, but this is data limited) have a longer, more continuous winter through spring advance, but all years have a sharp retreat beginning at about the onset of summer quarter (July). We find a mean annual difference between measured maximum and minimum terminus positions of 590 m. Looking only at the glaciers also studied by Carr et al. [2013a], the mean annual variation is 525 m, somewhat larger than the 400 m range they found for 2004-2010.

### *4.4.3 Mélange condition and terminus change*

Along with velocity and terminus data, Figure 4.5 shows daily runoff from RACMO2, daily SIF, and mélange conditions based on visual analysis and velocity-measured rigidity. To capture the range in magnitude and timing of the environmental changes, we display data from the second most northern (KO) and most southern (G8) glaciers. Timing for the onset of runoff is similar across the region, but total runoff decreases as latitude increases. In contrast, spring breakup of mélange (both from daily SIF and visual analysis) is approximately 3 weeks earlier in the south than the north.

One aim of our study was to examine terminus behavior associated with different mélange conditions. To maximize confidence that we were examining terminus change during periods of specific mélange conditions, we only examined periods for which: 1) the observed mélange condition, as recorded in our analysis dataset, continued for at least 2 weeks, and 2) more than 2 terminus position measurements were made during the interval. We assumed that if two observations were made of the same mélange condition then that condition was maintained between observations. This method successfully captured summer open water and winter rigid mélange periods (e.g., Fig. 4.3 and Fig. 4.5d).

Using the above criteria, we captured between 5 and 11 mélange/terminus observation intervals for each glacier during 2009-2012, with an average of 8 intervals per glacier (135 total intervals for all glaciers) (e.g., Fig. 4.5d). Most commonly, we recorded one period with open conditions and one with rigid conditions each year (the complete dataset includes 59 open periods, 12 mixed periods, and 64 rigid periods). Figure 4.6 summarizes the terminus changes measured during observation windows for each mélange type. On average, the observation windows cover ~50% of each year, so additional changes in terminus position occurring during the remainder of the year are not shown in Figure 4.6. We find a general correspondence between mélange condition and terminus advance or retreat. During open conditions (average length of 73 days) retreat dominated (retreat > 50 m during 73% of open periods), with a mean retreat of 260 m. There were only 4 instances (~7% of open periods) of advance more than 50 m during open conditions. In contrast, rigid conditions coincided with terminus advance greater than 50 m during 56% of the time. During 47 observations of advance coincident with rigid conditions, the average advance was 190 m over 97 days. We recorded 11 instances (~17% of rigid intervals) of retreat >50 m during rigid periods.

There are only a few instances of mixed mélange in our data, with the majority of the data from 2010 (Fig. 4.6). Within this sample, most periods of mixed conditions coincided with retreat. Unlike open (spring/summer) and rigid (winter/early spring) periods, our observations of mixed condition do not occur at the same time each year. Five mixed intervals began in June or July; during these intervals there was 1 instance of advance and 4 instances of retreat. The remaining 7 mixed intervals began during September-December and lasted into February and were also primarily coincident with terminus retreat, with only 1 observation of advance.

### *4.4.4 Extended records*

To gain insight on longer-term change, we chose 4 focus glaciers to examine for 1999-2012, with observations shown in Figure 4.7. We selected G1, SV, HA, and G7 because they have a range of mean ice velocities that represent the full northwest group (Table 4.2). All four glaciers retreated significantly between 1999 and 2012, with substantial simultaneous increases in velocity (Table 4.2, Fig. 4.7). The data indicate open and rigid mélange conditions for each glacier during most years (Fig. 4.7). Though fewer mélange/terminus observation windows met our strict criteria for persistent mélange conditions (Table C1), the onset of retreat generally coincides with the end of the winter rigid-ice period (Fig. 4.7).

The northernmost glacier, G1, maintained a relatively stable terminus position from late summer 1999 until 2010 with a seasonal advance and retreat of several hundred meters, though winter velocity measurements show interannual speedup beginning by 2006 (Fig. 4.7). In 2010, terminus behavior changed significantly: the glacier did not advance in spring and then retreated ~2 km during summer and fall. Seasonal terminus fluctuations diminished markedly after retreat. We observed only 4 intervals of continuous (>2 weeks) open water during 1999-2008, with notable (>50 m) retreat during 2 periods and advance during 1 period (Table C1). Of 8 pre-2009 rigid intervals, 5 coincide with terminus advance and 2 with retreat.

Sverdrup Glacier retreated ~4.3 km from summer 1999 to late 2012, with relatively steady retreat throughout the record (Fig. 4.7). Velocity measurements also show sustained increase, potentially with a somewhat higher rate between 2001 and 2006 than during 2006-2012. Beginning in about 2004, the amplitude of the spring/summer terminus change increased and the late summer terminus position retreated for every year after 2006. The largest seasonal advance occurred in 2010, followed by only small seasonal advances in 2011 and 2012. In addition to the greatest overall retreat, SV also had the largest advance and retreat during periods of rigid and open mélange, respectively, for 1999-2008 (Table C1).

Hayes Glacier retreated steadily from 1999 through 2012, although at a somewhat reduced range from late 2005 to late 2008 (Fig. 4.7). The largest increases in interannual velocity were also after 2008. Unlike the other glaciers with long-term records, HA fluctuated seasonally by several hundred meters throughout the record. There were 6 intervals of persistent open mélange conditions during 1999-2008, with substantial retreat in most cases (5 of 6) (Table C1).

Rigid conditions, observed during 9 intervals, coincided with 4 advances of >50 m and 2 large retreats (180 m and 310 m). Both retreat and advance occurred during mixed mélange conditions.

Of the 4 extended record glaciers, G7 retreated the least (Fig. 4.7). Comparing late summer terminus position from 1999 until 2011, G7 consistently retreated (~50-150 m) during summer with minimal (~0-50 m) spring re-advance, producing ~720 m of total retreat. The location of furthest retreat was relatively consistent during 2011 and 2012, and winter velocities also declined after summer 2010, perhaps indicating a change in terminus setting (e.g., the terminus retreated to a more stable position with a shallower bed). Of the 17 intervals of consistent mélange behavior during 1999-2008, terminus changes of more than 50 m occurred in only 4 cases; 3 instances of retreat during open conditions and 1 instance of retreat during rigid conditions (Table C1).

For an additional perspective on longer-term changes, we also compared 2009-2012 retreat rates to 1993-2010 rates for glaciers examined by Carr et al. [2013a]. We found that AG's retreat rate remained high during 2009-2012, NW3's rate decreased, and retreat rates for HA, NW4, and NW2 increased. For NW4 and NW2, retreat during 2009-2012 was equal to ~50% of the total 1993-2010 retreat. Though these two glaciers had smaller total retreat than many other study glaciers, the change is notable as compared to changes over the previous 2 decades; this pattern may be true of other glaciers with retreat <500 m (Table 4.1).

## 4.5 Discussion

Previous observation and modeling work indicates that multiple mechanisms may induce ice-flow speedup [e.g., *Howat et al.*, 2008; *Joughin et al.*, 2008c; *Nick et al.*, 2009; *Andersen et al.*, 2011]. One mechanism is water input to the glacier bed coincident with onset of the spring melt season [*Zwally et al.*, 2006]. As surface melting begins, some water reaches the ice-bed interface, where initially there is likely a distributed, less-efficient, more highly pressurized subglacial hydrologic network, and the additional water increases ice velocity [*Cuffey and Paterson*, 2010; *Schoof*, 2010; *Sundal et al.*, 2011]. This effect subsequently decreases as the subglacial drainage system becomes more channelized, increasing efficiency, lowering water pressure, and reducing the influence of melt in the latter part of the summer. There is substantial observational evidence of this mechanism for speedup in Greenland [e.g., *Zwally et al.*, 2006; *Joughin et al.*, 2008c; *Howat et al.*, 2010; *Sole et al.*, 2011; *Bevan et al.*, 2012; *Cowton et al.*, 2012] and it is supported by models [e.g., *Schoof*, 2010; *Hewitt*, 2013].

A second mechanism that may induce speedup is reduction in resistive stress and increased terminus thickness as the calving front retreats into deeper water. As advance and retreat modulate the near-terminus resistive stress and thickness-dependent pressure boundary condition at the ice-ocean interface, force balance is maintained by varying ice flow speed to alter nearby resistive stresses. Dynamic changes on Jakobshavn Isbræ, Helheim Glacier, and Kangerdlugssuaq Glacier, among others, provide observational support for velocity changes via this mechanism [*Howat et al.*, 2005; 2008; *Joughin et al.*, 2012a]. Modeling work by Nick et al. [2009] also suggests that interannual changes in outlet glacier speed may be influenced primarily by terminus advance or retreat rather than subglacial hydrology. Links between terminus position and velocity are evident on short (daily to monthly) and long (interannual) timescales [*Nettles et al.*, 2008; *Joughin et al.*, 2008c; *Podrasky et al.*, 2012].

Terminus advance and retreat can be affected by a variety of factors [e.g., *Carr et al.*, 2013b]. Surface melt-induced fractures may increase calving during the spring and summer as observed, for example, in Antarctica [*van der Veen*, 1998; *MacAyeal et al.*, 2003; *Glasser and Scambos*, 2008]. Thinning of the terminus to near floatation may also allow increased calving [*van der Veen*, 1996; *Amundson et al.*, 2010]. Subglacial runoff and/or warm subsurface ocean water can thin or melt back the terminus [*Rignot et al.*, 2010a; *Xu et al.*, 2013]. Finally, observations and theoretical work suggest that substantial ice mélange can suppress calving, and loss of mélange may increase calving [*Joughin et al.*, 2008b; *Amundson et al.*, 2010; *Carr et al.*, 2013b]. Furthermore, glacier dynamics can be highly sensitive to terminus change, and even a small perturbation can produce substantial changes in ice front position and/or ice-flow speed [*Nick et al.*, 2009; *Vieli and Nick*, 2011]. For our study region, we examined the interaction among ice-flow speed, terminus position, and environmental factors to determine the mean behavior and potential causes for the range of patterns we observed.

### *4.5.1 Mélange control on seasonal terminus change*

Examination of mélange conditions during 2009-2012 revealed retreat of more than 50 m during 73% of the open ocean periods and advance of greater than 50 m during 56% of the rigid mélange periods. In contrast, only 7% of open intervals coincided with notable advance and only 17% of rigid intervals corresponded with retreat. The long-term records on 4 glaciers also indicate that the onset of retreat generally coincides with the seasonal decline of the rigid mélange. Our observations linking terminus change to mélange conditions agree well with results from other studies along the western Greenland coast. For example, Carr et al. [2013a] found a strong connection between terminus advance and retreat and the formation and breakup of mélange during much of the last decade at AG. Studies on Jakobshavn Isbræ and in the Uummannaq region also found: 1) that mélange may inhibit calving and support terminus advance and 2) calving may increase as mélange breaks up [*Sohn et al.*, 1998; *Joughin et al.*, 2008b; *Ahn and Box*, 2010; *Amundson et al.*, 2010; *Howat et al.*, 2010]. Carr et al. [2013a] found weaker correspondence between terminus position and mélange conditions for other glaciers in their study. The stronger association in our study may be due to sampling differences; their study focused on monthly measurements whereas we generally have higher resolution data for terminus position and mélange condition. Consistent with earlier work, our results suggest a strong relationship between mélange conditions and terminus advance and retreat.

### *4.5.2 Mechanisms affecting seasonal velocity change*

Observations of mélange formation and breakup and ice sheet meltwater runoff indicate that both are potentially connected to seasonal velocity fluctuations. The 12 northernmost study glaciers had consistent seasonal velocity patterns, with spring-to-summer speedup every year. This speedup coincided with the rapid spring breakup of mélange and the onset of runoff (e.g., Fig. 4.5). For these glaciers, the daily SIF dropped to 0% prior to the summer velocity measurement, and in many cases the full period of near-terminus ice loss (from 100% to 0%) occurred between spring and summer measurements. The onset of spring runoff also happened between the spring and summer measurements, coinciding with spring-to-summer speedup.

Relative to the northern 12 glaciers, spring-to-summer speedup, mélange condition, and runoff do not coincide as clearly for the 4 southernmost glaciers. In the cases when spring-to-summer speedup was observed on these glaciers, it did coincide with both mélange breakup and the beginning of runoff. There were, however, 7 instances of pre-spring speedup (fall/winter to early May) before the onset of meltwater runoff (after early May). In these instances, the glaciers may have reached maximum velocities after the onset of spring runoff, but the sparse temporal resolution of our record limits our ability to determine whether this happens. Pre-spring speedup also preceded mélange breakup (from visual analysis), although daily SIF began to drop prior to the early May measurement in some instances. Despite these 7 cases, the majority of our observations (88%) suggest that the onset of spring runoff and/or breakup of mélange may affect spring speedup.

Spring runoff may be a strong influence on velocity due to affects on subglacial hydrology. The mean per-glacier summer speedup was ~150 m/yr (~11%), which is similar to the magnitude of seasonal forcing observed on land-terminating glaciers due to surface melt reaching the glacier bed [*Joughin et al.*, 2008c; *Bartholomew et al.*, 2010; *Joughin et al.*, 2013; *Sole et al.*, 2013]. Velocity changes on land-terminating glaciers are likely almost entirely a response to changes in subglacial hydrology since the termini of these glaciers play little if any role in seasonal dynamics. The similarity in timing and magnitude of seasonal velocity changes for land-terminating glaciers and our marine-terminating glaciers suggests that the same mechanism – subglacial hydrology – may play a significant role in the observed seasonal velocity changes for our glacier group. The concurrence of speedup and onset of spring runoff in at least 88% of our observations supports this hypothesis.

Mélange breakup may affect velocity by modulating terminus position, though our results point to a complex and less certain connection between spring terminus position and velocity. On average, spring-to-summer speedup overlapped with the period of maximum seasonal retreat (e.g., Figure 4.4). Nevertheless, no consistent pattern between seasonal velocity and terminus position is evident across individual glacier records (Fig. 4.3). Our velocity observations, however, preclude determination of when maximum summer velocity occurred. Measurements of terminus position also do not indicate whether the terminus was advancing into deeper or shallower water, or whether it was floating or grounded. Such factors likely contribute to the lack of a clear pattern. Overall, however, our results suggest that both terminus retreat and changes in subglacial hydrology may play key roles in triggering spring speedup.

### *4.5.3 Mechanisms affecting inter-annual terminus and velocity change*

Many of our 2009-2012 and 1999-2012 records show large multi-year retreat coincident with significant interannual increases in velocity (Fig. 4.3 and 4.7). Terminus retreat is theoretically associated with speedup for cases in which retreat reduces resistive stress and increases ice thickness at the terminus, which is common for glaciers with a reverse-slope bed (bed depth increases up-glacier from terminus). Other factors, however, can affect velocity and may explain anomalous behavior for some study glaciers. Six study glaciers had negative velocity trends but also retreated during 2009-2012 (Table 4.1). All of them, however, retreated less than 0.5 km over 4 years and these modest retreats may reflect bed topography that is not reverse-slope. Terminus thinning may also play a role in the timing of speedup and retreat. For example, the long-term record for G1 indicates steady speedup from at least 2006, well before the onset of the ~2 km of retreat largely concentrated in 2010 (Fig. 4.7). Thinning rates of 3.4 m/yr (sampled several kilometers inland from the terminus) during 2003-2007 [*Pritchard et al.*, 2009] may have reduced bed traction by causing the terminus to reach floatation [*Pfeffer*, 2007], resulting in ice-flow speedup even with no visible retreat. This hypothesis is supported by our observation of likely tabular icebergs from G1 prior to 2010, which suggests that the terminus was at or near floatation before retreat. Overall, however, we observe many instances of interannual speedup coincident with large-scale sustained retreat as expected for grounded termini with reverse-slope glacier beds [e.g., *Howat et al.*, 2008; *Nick et al.*, 2009; *Podrasky et al.*, 2012; *Joughin et al.*, 2012a].

To understand potential causes for interannual change, we examined the role that mélange may play in multi-year retreat and speedup. The longest mélange-free period occurred in 2010 and the subsequent winter mélange then lasted for a shorter time period and with less consistency (Fig. 4.5d). This extended ice-free period coincided with the largest cumulative retreat for the region (Fig. 4.4). In contrast, the cumulative data show no sustained retreat after the shorter mélange-free periods in 2009 and 2011. A longer mélange-free period occurred again in 2012, likely in connection with an anomalously high summer melt season [*Nghiem et al.*, 2012; *Tedesco et al.*, 2013]. For some individual glaciers, a clear link between longer mélange-free periods and retreat is not evident, though factors such as bed topography could be at play. Together, our observations do suggest that longer mélange-free periods may cause relatively large glacier retreat with lasting effects on mean terminus position.

Results from Uummannaq and Jakobshavn support the hypothesis that longer calving seasons may in part cause larger interannual retreat [*Joughin et al.*, 2008b; *Howat et al.*, 2010]. Carr et al. [2013a] also observed particularly large retreat events during 2004 and 2005 on AG, which followed a decline in SIF and more persistent ice-free conditions. While our 2009-2012 record may be too short for identifying SIF trends, others' work finds that the ice-free season throughout Baffin Bay lengthened from 1979 through 2012 (Laidre et al., manuscript in preparation, 2014). This may have had a significant influence on the slow but sustained retreat in this region [*Moon and Joughin*, 2008], leading to the present elevated speeds for many of these glaciers [*Moon et al.*, 2012]. Continuation of the trend may cause further terminus retreat, though predicting retreat is dependent on a wide set of factors that must include bed topography and other changes in ice dynamics.

## 4.6 Conclusions

Combining observations of terminus position and mélange conditions in northwestern Greenland, we find an apparent relationship between terminus advance and retreat and the potential rigidity (or lack thereof) of the near-terminus mélange, consistent with earlier results

[*Sohn et al.*, 1998; *Joughin et al.*, 2008b; *Ahn and Box*, 2010; *Amundson et al.*, 2010; *Howat et al.*, 2010]. Velocity measurements show a seasonal velocity signal, with consistent increases in speed between spring and summer (mean of 151 m/yr). In most cases, the increase in velocity is coincident with the breakup of ice mélange and the onset of glacial runoff and overlaps regional seasonal retreat, suggesting that both terminus change and subglacial hydrology likely influence seasonal speedup. The differences in temporal resolution among our observations, particularly the velocity observations, remain a limiting factor. Improving temporal resolution of velocity observations with broad coverage should be a focus of future research. On interannual timescales, relatively large retreat is accompanied by multi-year speedup. Our observations of sustained slowdown coincident with modest terminus retreat in a few cases provide an important indicator that some glaciers may have retreated into more stable positions due to specific local topography. Thus, a concerted effort to continue to improve our high-resolution knowledge of subglacial topography will be important for predicting future ice sheet mass loss.

Overall our data support the following conclusions:

- The seasonal presence and breakup of a rigid mélange (and sea ice) at the glacier terminus in many instances may be a dominant control on seasonal terminus advance and retreat.
- Seasonal changes in ice-flow velocity are of a magnitude that may be sufficiently explained by a combination of seasonal melt modifying subglacial conditions and seasonal variation in terminus position.
- Longer ice-free periods and/or shorter periods of rigid mélange may allow large-scale terminus retreat past previous annual retreat locations, potentially by creating a small initial perturbation that is enhanced by dynamical feedbacks associated with retreat down a reverse bed slope [e.g., *Howat et al.*, 2008; *Nick et al.*, 2009].

- Large-scale retreat likely induces sustained multi-year velocity increase.

While our observations do include exceptions to these relationships, this set of glacier and environment interactions provides a useful base hypothesis, which should continue to be examined in detail through future research. These relationships also point towards possible climate-driven changes that may affect Greenland outlet glaciers, in some instances with the potential for increased ice sheet mass loss. Longer mélange-free periods and the associated loss of rigid mélange may continue to increase large-scale retreat around Greenland, which is commonly associated with multi-year speedup and greater mass loss [e.g., *Howat et al.*, 2008; *Joughin et al.*, 2010]. Earlier runoff from warming temperatures may create earlier seasonal speedup, though enhanced flow may not be sustained, which could minimize impacts on total annual ice discharge [*Sundal et al.*, 2011; *Shannon and Payne*, 2013; *Sole et al.*, 2013]. Continued observation and modeling of the ice-ocean system and associated climate conditions is critical to further understanding these processes, determining the applicability of our main conclusions to other regions of the ice sheet, and predicting future ice mass loss and associated changes in sea level.

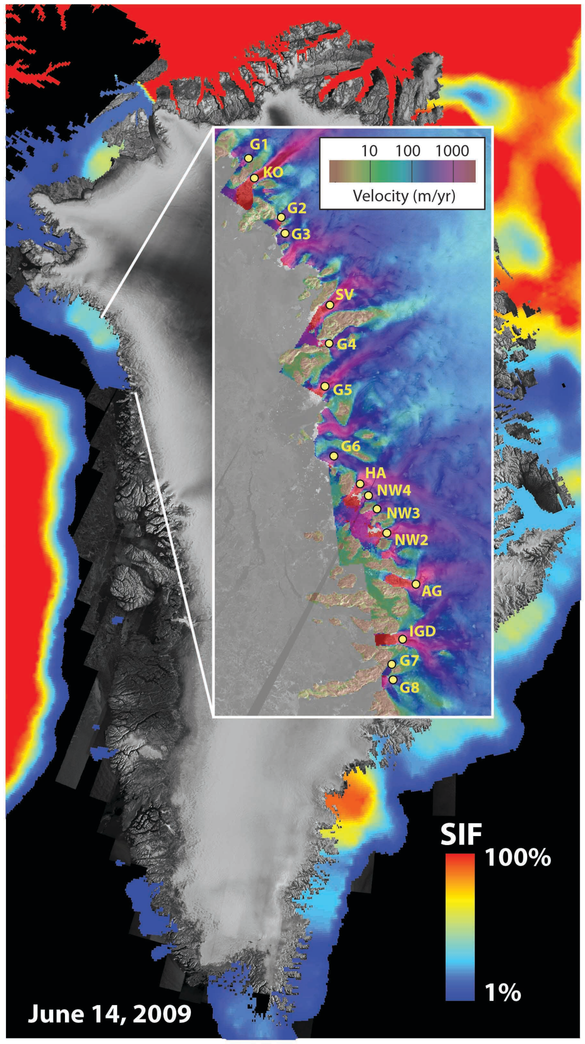


Figure 4.1 – Locations of the 16 northwest glaciers examined in this study. Background image shows a snapshot of late spring sea ice fraction (SIF) around Greenland (black indicates no sea ice), with a RASARSAT mosaic of the ice sheet and land surface. Inset image includes composite winter velocities from 2007-2010. Named glaciers are: Kong Oscar (KO), Sverdrup Glacier (SV), Hayes Glacier (HA), Alison Glacier (AG), and Igdlugdlip Sermia (IGD). Our naming scheme was designed to provide easy comparison with the results in Carr et al. [2013a] for IGD, AG, NW2, NW3, NW4, and HA. The remaining glaciers were assigned labels G1 through G8.

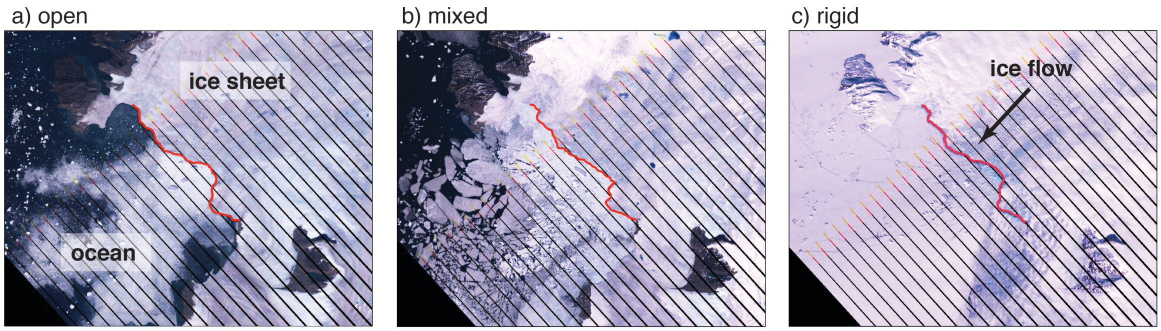


Figure 4.2 – Landsat images (with gaps from SLC failure) showing a) open, b) mixed, and c) rigid mélange conditions at the terminus of G5. Digitized terminus position indicated by red line.

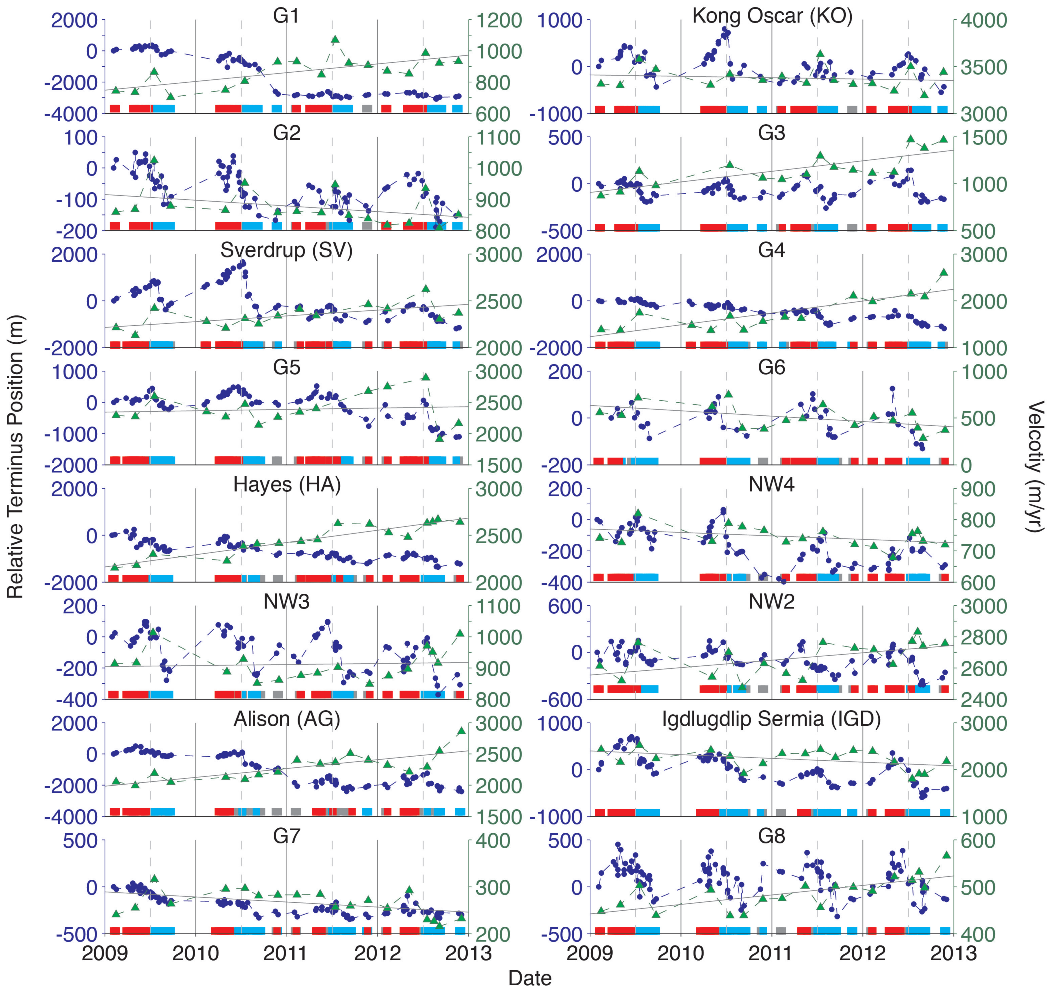


Figure 4.3 – Terminus position (blue circles), velocity (green triangles) with linear trendline (grey), and mélange conditions (red=rigid, grey=mixed, blue=open) for all study glaciers for 2009-2012.

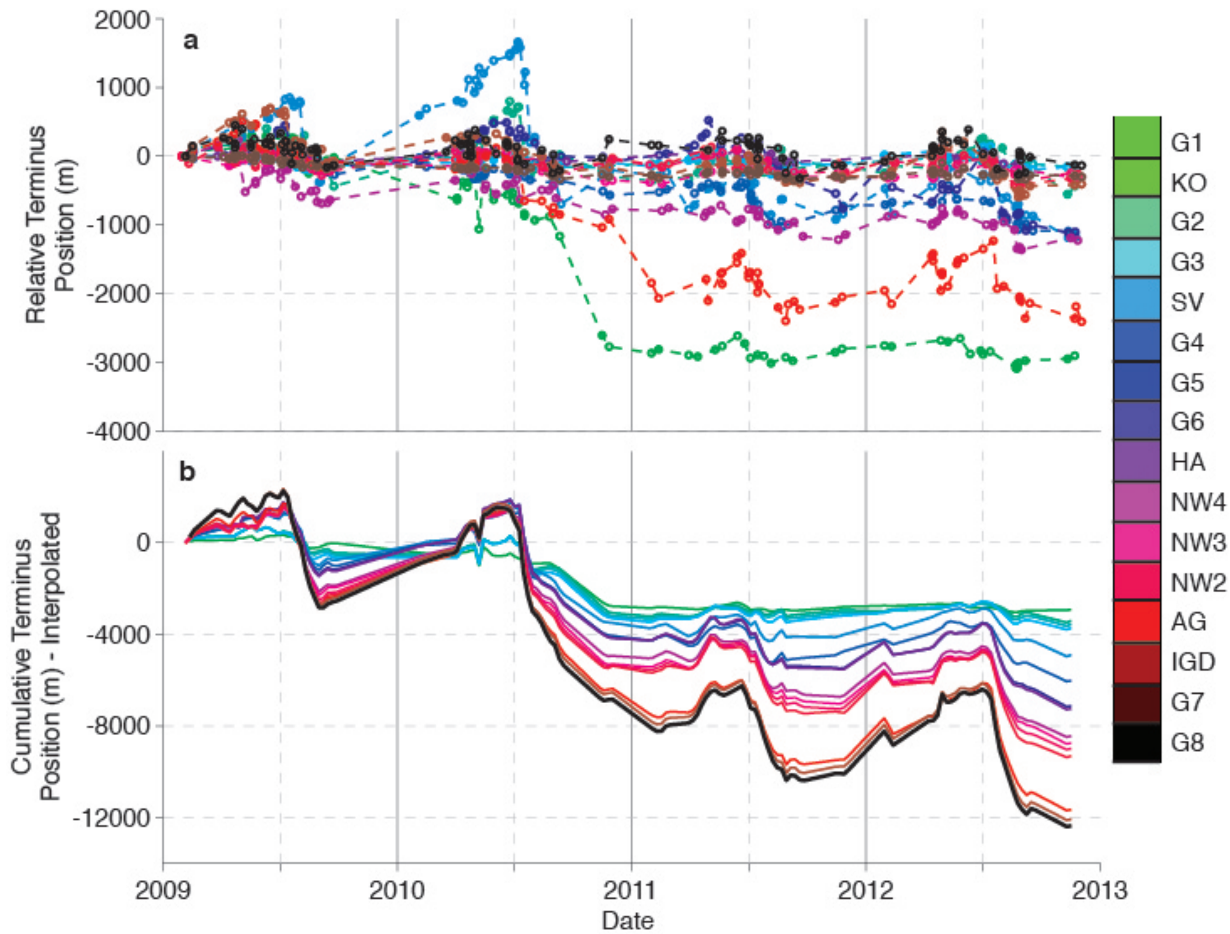


Figure 4.4 – a) Full record of terminus positions for all 16 glaciers. b) Cumulative terminus position, using weekly-interpolated data, with the color indicating the addition of that glacier to the sum (added in north to south order).

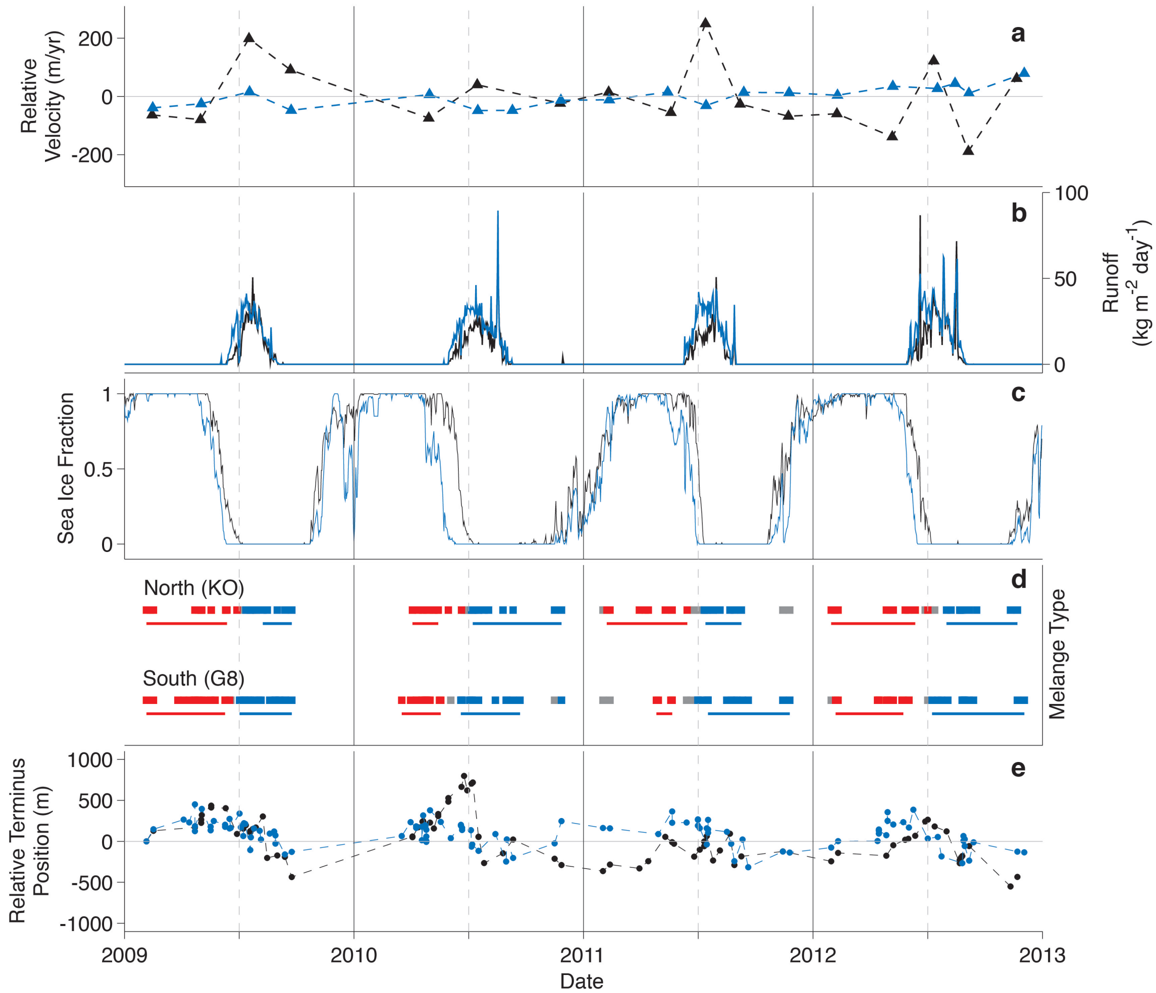


Figure 4.5 – Data for the second most northern (KO, black) and most southern (G8, blue) study glaciers during 2009-2012 for: a) relative ice-flow velocity (normalized by subtracting 4-year mean velocity), b) runoff from RACMO2, c) sea ice fraction from OSTIA, d) mélange type from our analysis (red=rigid, grey=mixed, blue=open) with raw data on top for each glacier and mélange/terminus observation intervals indicated by solid lines, and e) relative terminus position.

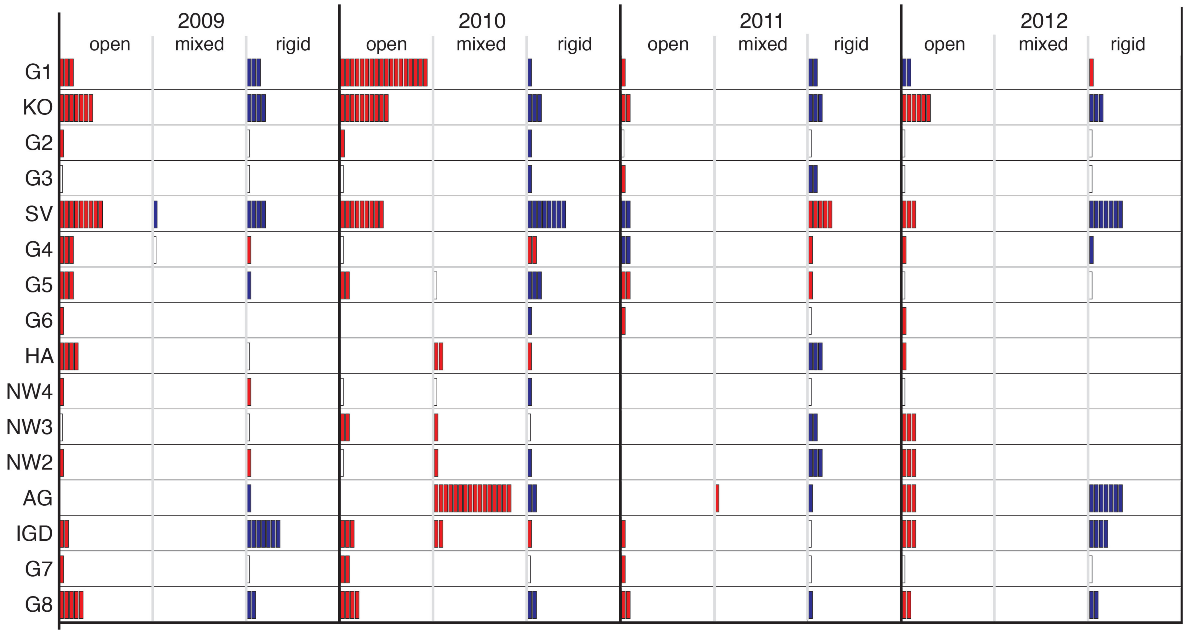


Figure 4.6 – Observed terminus change (rounded to nearest 100 m) during open, mixed, and rigid mélange conditions. Each bar indicates 100 m of change, and red indicates retreat, blue indicates advance. Consistent mélange conditions must be observed for at least 2 weeks and have >2 terminus position observations during the period; boxes with no bars indicate that no observations met these requirements during that year for the associated glacier. On average, mélange/terminus observation windows cover ~50% of each year, and terminus changes during the remainder of each year are not shown. A single white bar indicates terminus change was <50 m.

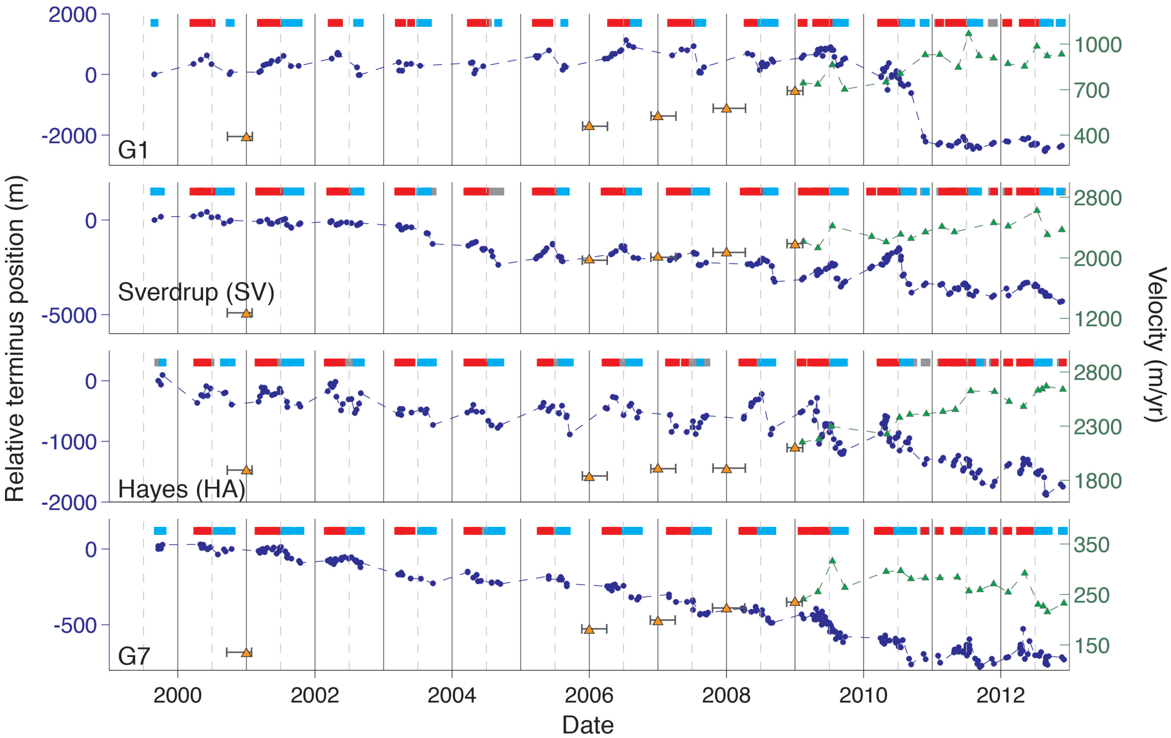


Figure 4.7 – Terminus position (blue circles), annual winter velocities for 2000/01 and 2005/06-2008/09 (orange triangles with bars indicating sample period), TerraSAR-X seasonal velocities for 2009-2012 (green triangles), and mélange conditions (red=rigid, grey=mixed, blue=open) for late 1999 through 2012.

Table 4.1 – Velocity and terminus position data for 2009-2012, including regional mean values[1]

| Glacier | 4-yr mean velocity (m/yr) | Linear velocity trend (m/yr$^2$) | Total measured speedup (% of 2009 velocity) | Total measured terminus position change (m) |
|---|---|---|---|---|
| G1 | 869 | 56 | 26% | -2900 |
| KO | 3378 | -15 | 4% | -440 |
| G2 | 876 | -18 | -1% | -150 |
| G3 | 1154 | 112 | 68% | -170 |
| SV | 2340 | 61 | 7% | -1150 |
| G4 | 1744 | 253 | 87% | -1180 |
| G5 | 2387 | 21 | -6% | -1100 |
| G6 | 504 | -57 | -34% | -130 |
| HA | 2458 | 130 | 23% | -1220 |
| NW4 | 745 | -11 | -3% | -290 |
| NW3 | 912 | 3 | 10% | -310 |
| NW2 | 2663 | 47 | 6% | -260 |
| AG | 2286 | 142 | 39% | -2410 |
| IGD | 2221 | -80 | -10% | -410 |
| G7 | 265 | -11 | -3% | -300 |
| G8 | 487 | 20 | 26% | -130 |
| *Mean* | *1580* | *41* | *15% (grand mean)*<br>*19% (total mean)* | *-780* |

[1] Total measured speedup and terminus position change compare the last 2012 measurement (roughly November 2012 for velocity) to the first 2009 measurement (roughly February 2009 for velocity). The total measured speed grand mean is the mean of means and the total mean is the sum of all velocity changes divided by the sum of 2009 velocities.

Table 4.2 – Velocity and retreat data for extended-record glaciers

| **Glacier** | **2000/01 winter velocity (m/yr)** | **Last-measured 2012 velocity (m/yr)** | **Velocity increase (% of 2000/01 velocity)** | **1999-2012 total retreat (m)** | **Mean retreat rate (m/yr)** |
|---|---|---|---|---|---|
| G1 | 382 | 934 | 145% | 2350 | 178 |
| SV | 1255 | 2371 | 89% | 4290 | 324 |
| HA | 1887 | 2640 | 40% | 1750 | 133 |
| G7 | 133 | 232 | 74% | 730 | 55 |

# Chapter 5: Insights from More Than a Decade of Greenland Outlet Glacier Observations

Interferometric synthetic aperture radar (InSAR) velocity measurements of seasonal to interannual outlet glacier behavior across the Greenland Ice Sheet reveal complex patterns both spatially and over time. Interannual velocity observations show local and regional variability within the context of widespread ice-flow speedup. Seasonal velocity patterns also vary regionally and may correspond both to differing local hydrologic regimes and differing sensitivity of glacier speeds to terminus change. Combining velocity with other datasets in northwest Greenland, including terminus advance and retreat and pro-glacial ice mélange conditions, indicates that seasonal terminus fluctuations may be closely tied to ice mélange conditions, while seasonal velocities may be strongly controlled by runoff. Interannual speedup, however, corresponds to persistent terminus retreat and may be linked to lengthening ice-free periods. Together, these data provide a detailed examination of ice-flow behavior that explores the processes controlling ice dynamics and can contribute to modeling efforts to predict future mass loss and associated sea-level rise.

## 5.1 Ice-sheet-wide patterns of interannual surface velocity

Ice flow measurements on most Greenland outlet glaciers during 2000-2010 revealed notable regional and local variability underlying mean speedup across much of the ice sheet. Examining winter ice sheet velocities for 2000 and annually from 2005-2010, we found little change in speeds on ice-shelf-terminating glaciers, which are concentrated in the north. Eastern and southwestern Greenland are dominated by land-terminating and slow-moving (< 200 m/yr) glaciers, limiting the potential for significant ice discharge from these regions and, thus, also their contribution to sea-level rise. The areas with the highest current mass loss via discharge, the northwest and southeast regions, however, experienced a mean regional speedup of ~30% over the decade. Along with notable regional differences in velocity behavior, the decade-long velocity record also reveals significant velocity variations on individual glaciers from year to year and from glacier to glacier. As a result, predicting individual glacier behavior may not be possible without specific knowledge of local characteristics. By sampling all large Greenland glaciers over many years, however, our data can help in efforts to improve ice sheet modeling and prediction.

## 5.2 Seasonal velocity patterns and variability

Considering only fast-flowing, marine-terminating glaciers, seasonal velocity patterns do vary across the ice sheet, with some regional division. A handful of glaciers, both on the west and southeast coasts, are quite sensitive to seasonal terminus behavior. Most of the 55 glaciers studied during 2009-2013, however, are relatively insensitive to seasonal terminus advance or retreat and velocity patterns on these glaciers appear to be largely driven by hydrological changes. Northwest glaciers and a cluster of southeast glaciers exhibit a distinct summer spike in speeds suggesting that ice velocity closely follows runoff patterns and there may be little evolution of the subglacial hydrologic network. In contrast, sharp reductions in summer speed for many glaciers further south on the west and southeast coasts suggest that high water availability in these regions may induce seasonal subglacial evolution from distributed to channelized drainage. These differences in seasonal velocity behavior and likely also hydrologic regime highlight the ice-sheet-wide variability that we first uncovered examining interannual velocity patterns.

## 5.3 Interaction among multiple elements of the glacier-ocean system

Focusing on 16 glaciers in northwestern Greenland, we examined seasonal to interannual patterns during 2009-2012, with extended records for 4 glaciers for 1999-2012. Using terminus position, sea ice and ice mélange data, and modeled ice sheet surface runoff, we investigated how each of these may influence velocity on seasonal to interannual scales. The observations point towards several important conclusions that address velocity change on both time scales. Seasonally, we found: 1) there is a strong seasonal signal of spring-to-summer speedup followed by slowing that may continue into winter, 2) the magnitude and timing of seasonal speedup suggests that it is linked to subglacial hydrologic modification and terminus retreat, and 3) pro-glacial mélange conditions may be a primary control on seasonal retreat and advance. In regards to interannual patterns, we found: 1) sustained multi-year retreat may be linked to unusually long sea-ice-free periods and 2) multi-year retreat is usually accompanied by interannual speedup.

## 5.4 Future studies of ice sheet velocity

Our understanding of Greenland outlet glacier velocity and variability across both space and time will continue to improve as the satellite records lengthens, sampling increases, and as new technology and techniques are developed to measure velocity. The wide applicability of velocity data could lead to future projects from improving understanding of mechanisms controlling glacier response to ocean forcing via observation to full ice sheet modeling that applies velocity data to understanding and predicting limits of ice sheet mass loss. Sparse sampling of velocity data in regards to seasonal behavior remains a challenge for understanding the mechanisms responsible for seasonal velocity changes on marine-terminating glaciers and how these are linked to sustained interannual speedup or slowing. High-temporal-resolution velocity measurements from many or all Greenland outlet glaciers are needed to better understand the dominant mechanisms controlling velocity and how they vary both spatially and temporally. I plan to continue to work on creating higher temporal resolution observations of Greenland Ice Sheet velocities and improving our understanding of ice dynamics across space and time.

Understanding variability of Greenland outlet glacier speeds remains a complex challenge, likely involving the interplay of all elements of the glacier-ocean system. As a result, velocity data alone is insufficient for scientific progress in understanding ice sheet behavior. For example, broad regional patterns may be well aligned with large-scale climate behavior, while individual glaciers may show widely varying behavior due to localized conditions. Focused data collection in several categories is critical to advancing knowledge of ice sheet behavior and how it links to climatic and environmental changes. Needed observations include high-temporal-resolution velocity observations on an ice-sheet-wide scale, high-resolution bed elevation and bathymetric data, and subsurface oceanographic measurements. Progress on all fronts will be crucial in the continued effort to understand ice sheet dynamics and the current and future impacts of climate change, including sea-level rise.

## 5.5 Summary

While understanding and predicting variability in Greenland Ice Sheet motion remains a challenge, substantial progress has been made. Understanding velocity patterns on multiple timescales and from both local and ice-sheet-wide perspectives allows us to better design studies for examining the mechanisms driving ice sheet change and provides necessary information for modeling and prediction efforts on the future evolution of the ice sheet and its role in global sea-level rise. Based on the measurements and data sets presented here we found that:

1. Overall, mean velocities increased by ~30% from 2000 to 2010 in northwestern and southeastern Greenland, areas with the greatest ice discharge.
2. There is notable variability in interannual glacier velocity, including regionally, locally, and from year-to-year.
3. Seasonal velocity patterns also vary regionally, with northwest and Ikertivaq area glaciers in particular showing different behavior than for other areas.
4. Seasonal velocity patterns indicate high sensitivity to seasonal terminus behavior for some glaciers, but velocity patterns on more glaciers appear to respond primarily to changes in the hydrologic system.
5. Seasonal velocities on northwest and Ikertivaq-region glaciers appear to track with the seasonal runoff signal and the subglacial hydrologic system for these glaciers may change little. Velocity behavior for glaciers in other areas seems to indicate a more responsive subglacial system that does evolve between less and more efficient drainage structures during the year.
6. For northwest Greenland glaciers, seasonal changes in ice mélange correspond to changes in terminus position and longer sea-ice-free periods may induce sustained retreat.
7. Sustained retreat is associated with multi-year speedup for northwest glaciers.

These findings provide an expansive yet detailed view of ice sheet flow patterns for the Greenland Ice Sheet, indicating a variety of potentially important connections between ice sheet speed and other environmental factors. Continued work based on these observations will further improve our understanding of the ice-sheet-ocean-climate system and the changes we can expect with future warming.

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# Appendix A

## A.1 Methods

We sampled glacier velocity measurements at the center of the flow field (roughly coincident with maximum cross-glacier velocity) approximately one half-width upstream of the point of greatest retreat between 1992-2008 [*Moon and Joughin*, 2008]. The point was adjusted if the ice front subsequently retreated past the measurement point (observed using MODIS or RADARSAT data) or to maximize data return. Below the 2000 m contour, where we sample glacier velocity, bedrock control points create control-related errors <10 m/yr.

Beginning with 206 outlet glaciers, we first use a linear interpolation to add data for missing data points ($x$) with measurements in the year before and after ($x+1$ and $x-1$) (thus, only for $x$ = 2006 through 2009) (interpolated points indicated in Fig. A2-A3). Data are then separated into the following categories (also indicated in Fig. 1.1):

1. Land-terminating glaciers
2. Ice-shelf terminating glaciers (ice shelf >10 km long)
3. Marine-terminating outlet glaciers with average velocity <200 m/yr
4. Glaciers with insufficient data: Glaciers that lack one or two measurements for 2000-2005 have insufficient data (28 glaciers total), as are glaciers that have fewer than 2 measurements for 2005-2010 (11 glaciers).

The remaining marine-terminating glaciers are each fit with a linear regression for 2000-2010 and evaluated for misfit to a linear trend (*mf*), which allows a comparison between the measured speeds (*s*) and the linear regression ( $m\bar{t} + b$ ):

$$mf(\%) = \frac{\left\| s - (m\bar{t} + b) \right\|}{\sqrt{\left\| s \right\| \cdot \left\| m\bar{t} + b \right\|}} \cdot 100$$

We separate all glaciers with *mf* >15% to avoid representing erratic or highly variable behavior with a consistent trend. The remaining fast-flow marine-terminating glaciers are fit with linear regressions through all available data for 2000-2005 and 2005-2010. These trends are used to fill any remaining data gaps, so that data presented in, for example, Fig. 1.2 are complete for all glaciers (interpolated points indicated in Fig. A2-A3).

Using the completed dataset of fast-flow marine-terminating glaciers, we also review the results by 1) width-weighting the glaciers:

$$\left( \frac{v}{w} \cdot \overline{w} \right)$$

where $v$ = measured velocity, $w$ = glacier width, and $\overline{w}$ = mean regional width and 2) removing the 5 fastest 2010 glaciers: Jakobshavn and Upernavik North in the northwest and Helheim, Kangerdlugssuaq, and Ikeq Fjord glaciers in the southeast. When width-weighted, the general pattern of northwest and southeast regional annual mean remains the same, though the decadal regional mean is increased in both cases. Removing the top-5 fastest glaciers also has a negligible affect on the regional patterns, but does decrease the decadal mean velocity.

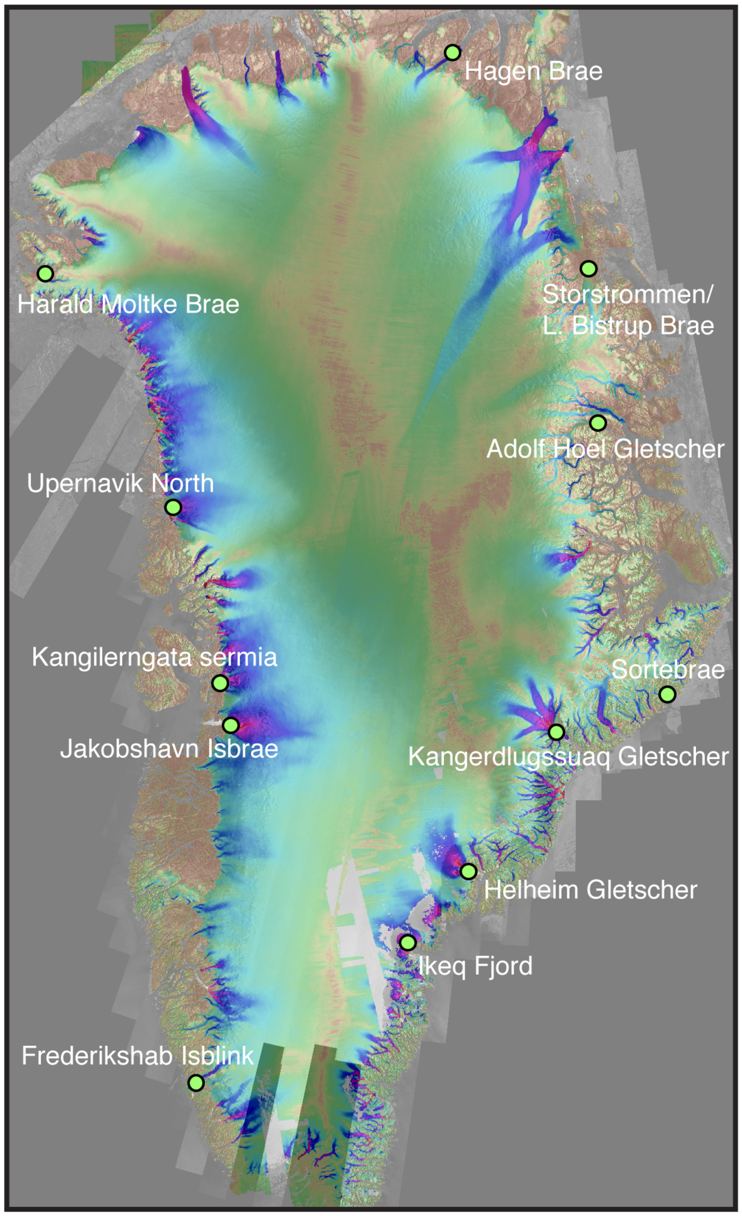



Figure A.1 – Names and locations of glaciers referenced in the text. The background map is a 2007-2010 composite velocity map.

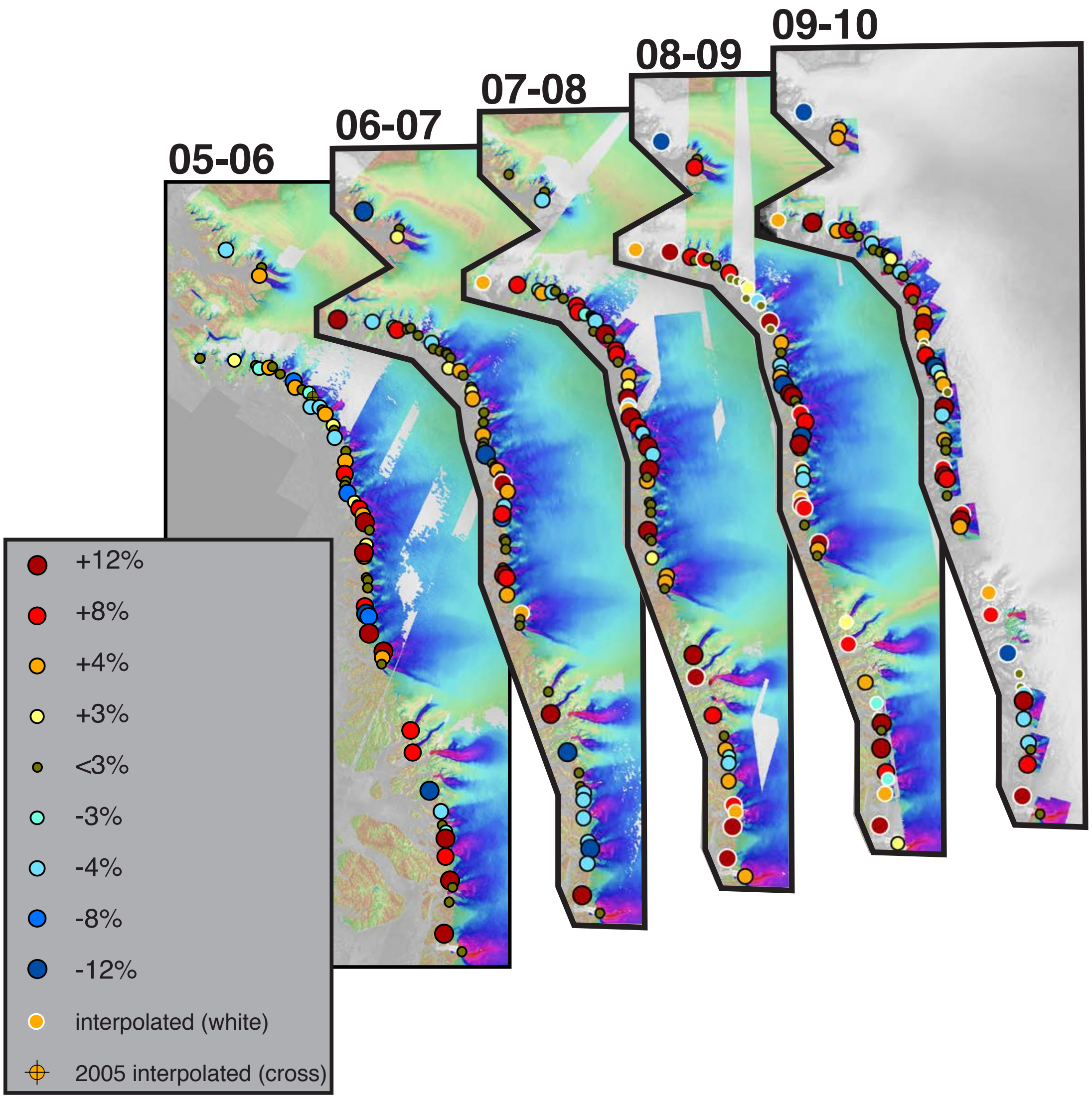



Figure A.2 – Annual velocity change (% change from previous year) for northwest marine-terminating glaciers with sufficient data and mean velocity >200 m/yr. Interpolated data for the most recent year (e.g., 2010 for 09-10 change) is indicated with a white circle. An additional cross on the marker indicates interpolated data for 2005. The background velocity map in each case is for the most recent year of data (e.g., winter 2010 map for 09-10 change).

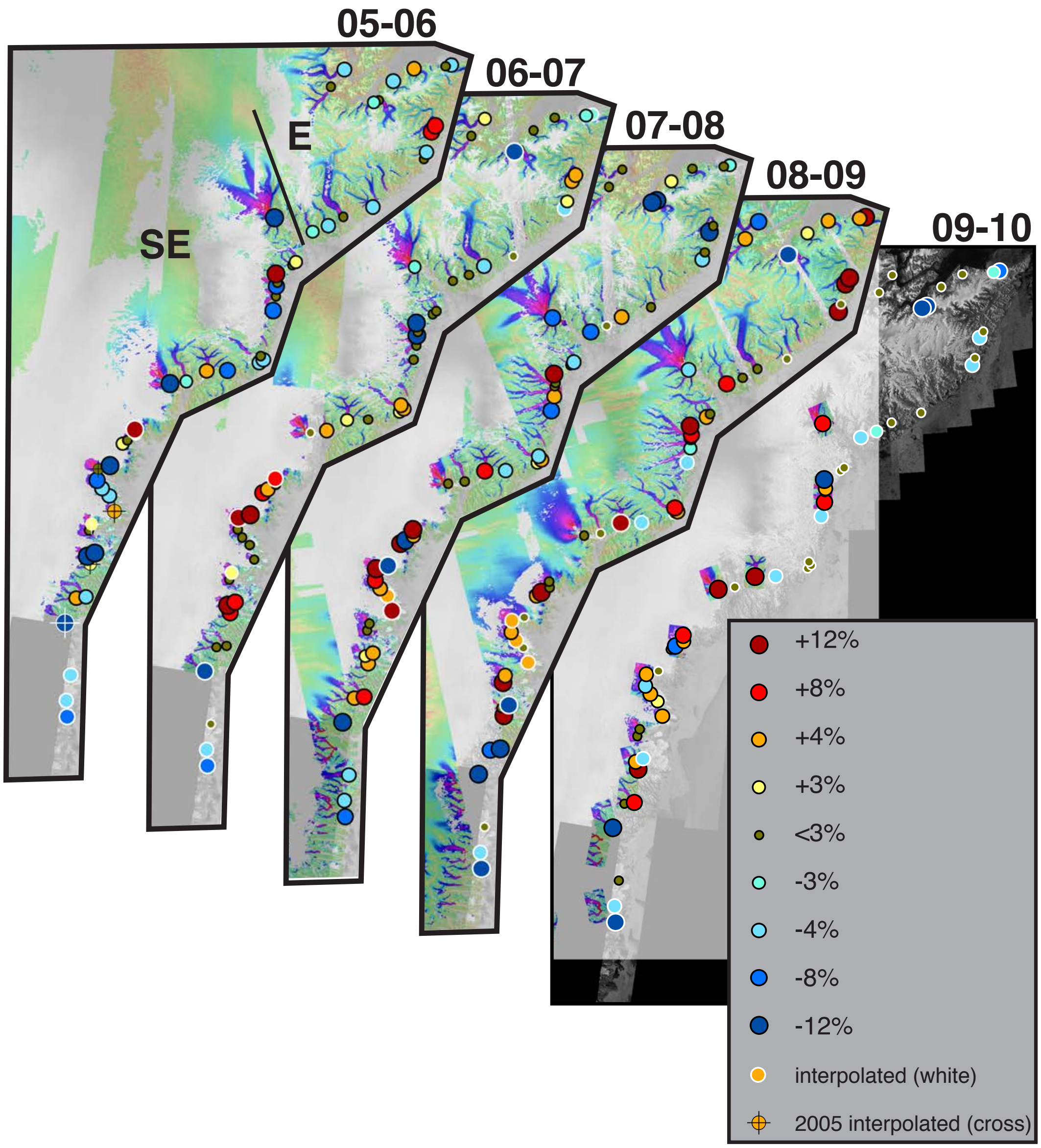



Figure A.3 – Annual velocity change (% change from previous year) for southeast (and some east) marine-terminating glaciers with sufficient data and mean velocity >200 m/yr. Interpolated data for the most recent year (e.g., 2010 for 09-10 change) is indicated with a white circle. An additional cross on the marker indicates interpolated data for 2005. The background velocity map in each case is for the most recent year of data (e.g., winter 2010 map for 09-10 change).

Table A.1 – Summary of data source used and acquisition date range for each winter velocity map.

| Map year | Data type | Acquisition date range |
|---|---|---|
| **2000**/01 | RADARSAT | Sept 2000-Jan 2001 |
| **2005**/06 | RADARSAT | Dec 2005-Apr 2006 |
| **2006**/07 | RADARSAT | Dec 2006-Apr 2007 |
| **2007**/08 | RADARSAT | Nov 2007-Apr 2008 |
| **2008**/09 | RADARSAT | Dec 2008-Feb 2009 |
| **2009**/10 | TerraSAR-X, ALOS | Oct 2009-Feb 2010 |
| **2010**/11 | TerraSAR-X | Oct 2010–Feb 2011 |

# Appendix B

Figures B1 – B55. Measured velocity (black triangles) and a trend line showing either best linear fit (green) or best quadratic fit (purple) (top panel), detrended velocity data (removing either linear or quadratic trend as indicated in top panel) (upper middle panel), smoothed daily RACMO2 runoff data (lower middle panel), and measured terminus position (black dots) relative to first measurement position (bottom panel) for each study glacier. The date that runoff exceeded 3 kg m$^{-2}$ d$^{-1}$ is indicated for every year (blue dotted line). Information on glacier names and other notes pertinent to individual glaciers are included with the associated figure number.

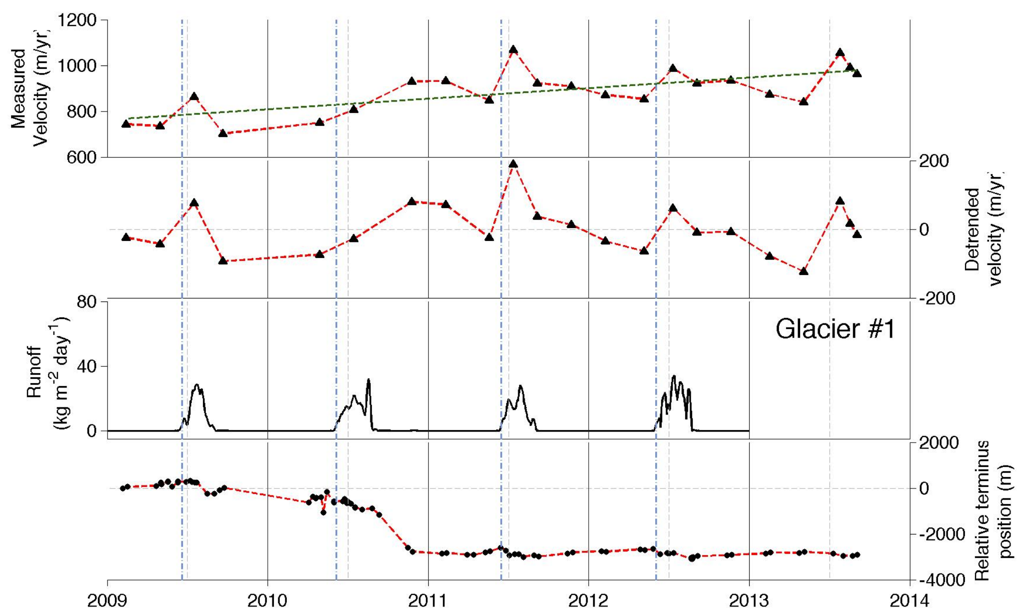



Figure B1.

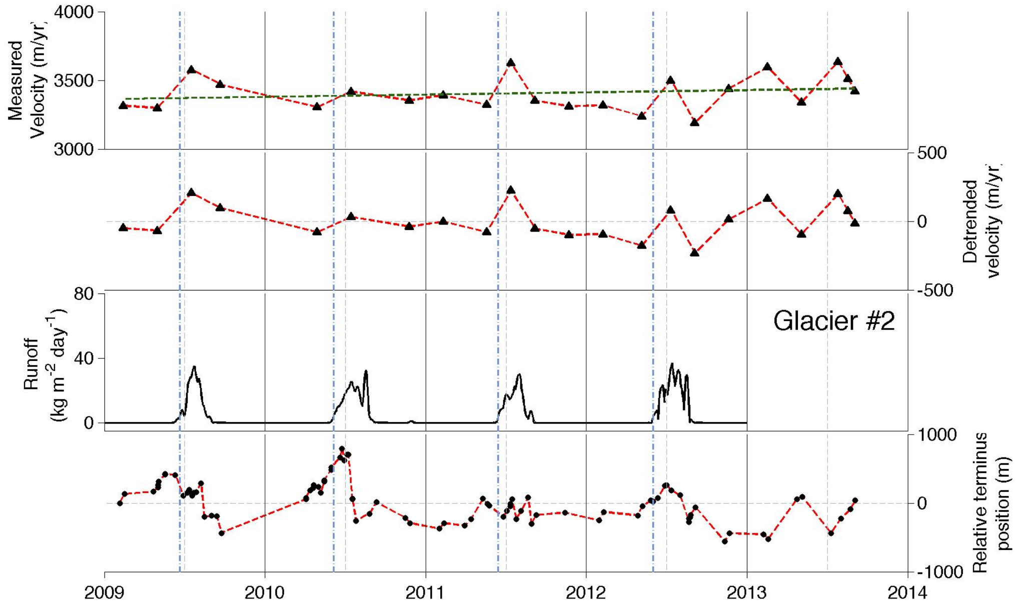



Figure B2. Kong Oscar Glacier

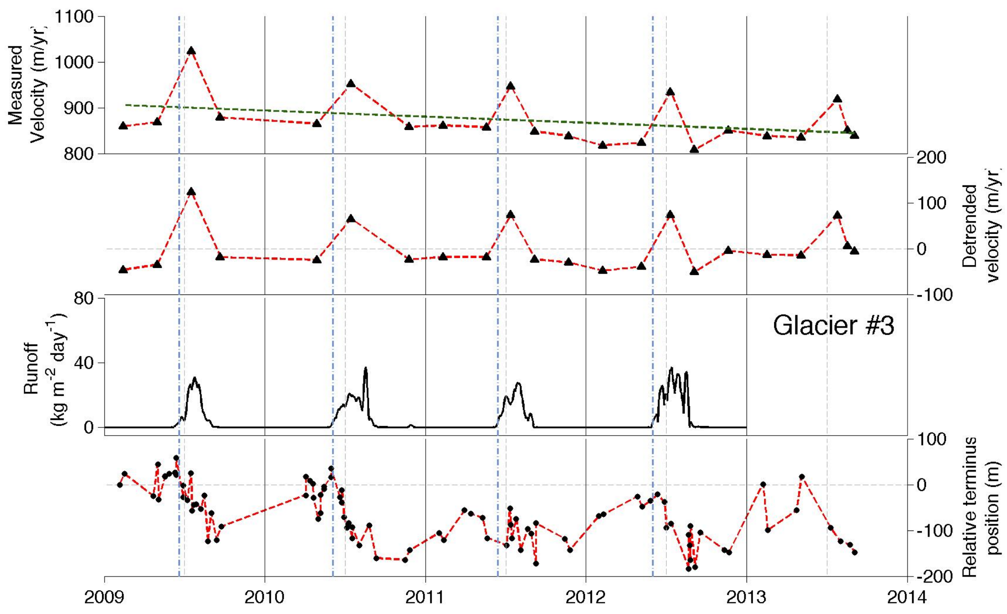



Figure B3.

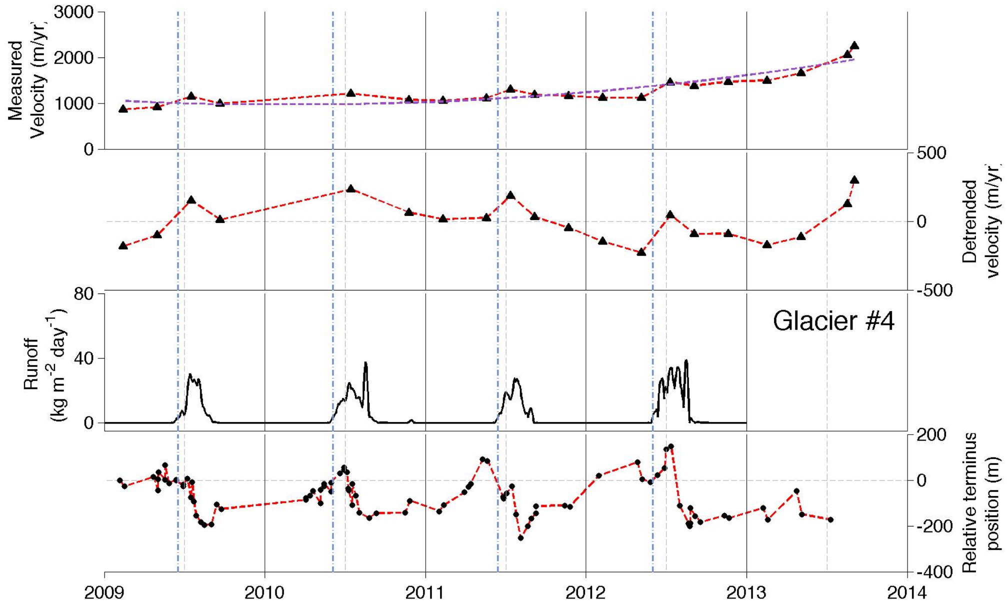



Figure B4.

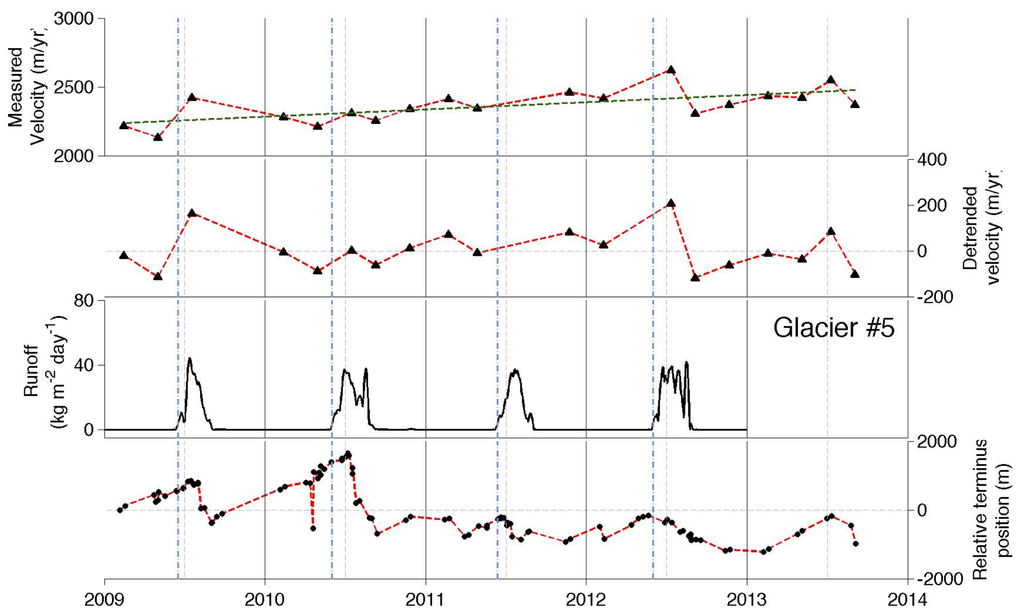



Figure B5. Sverdrup Bræ

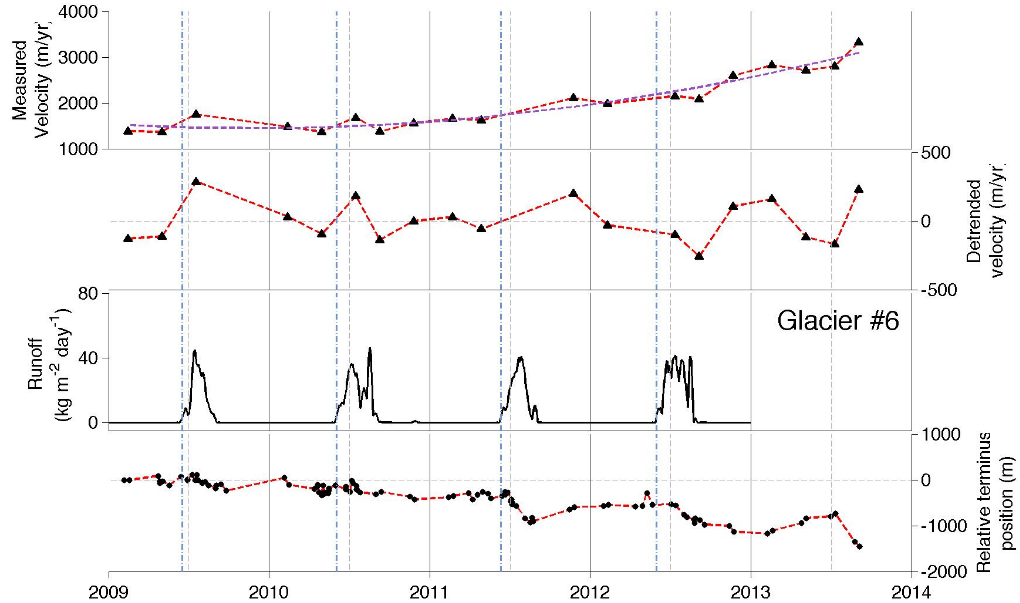



Figure B6. Dietrichson

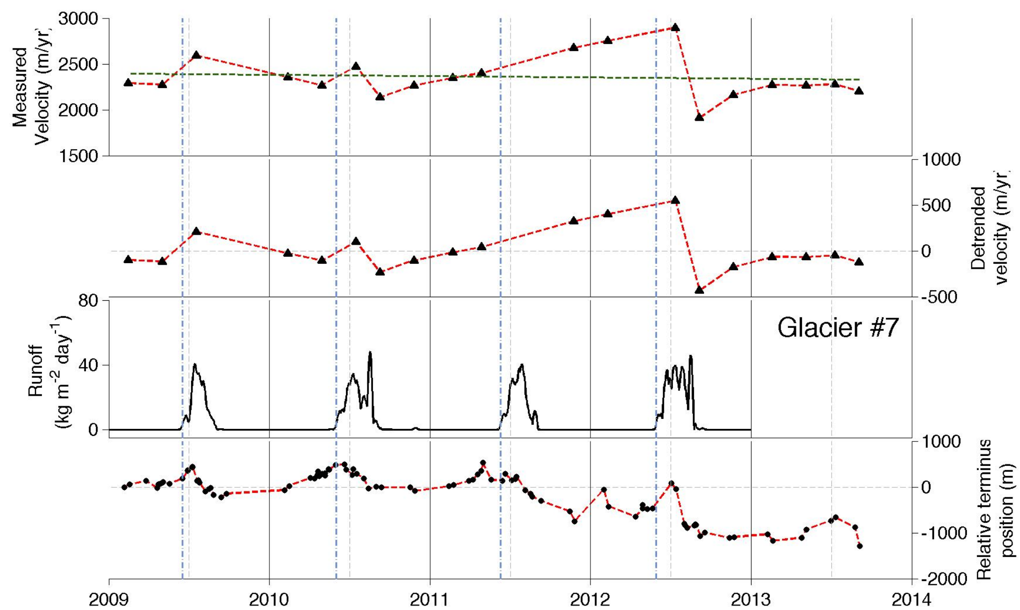



Figure B7. Steenstrup Glacier

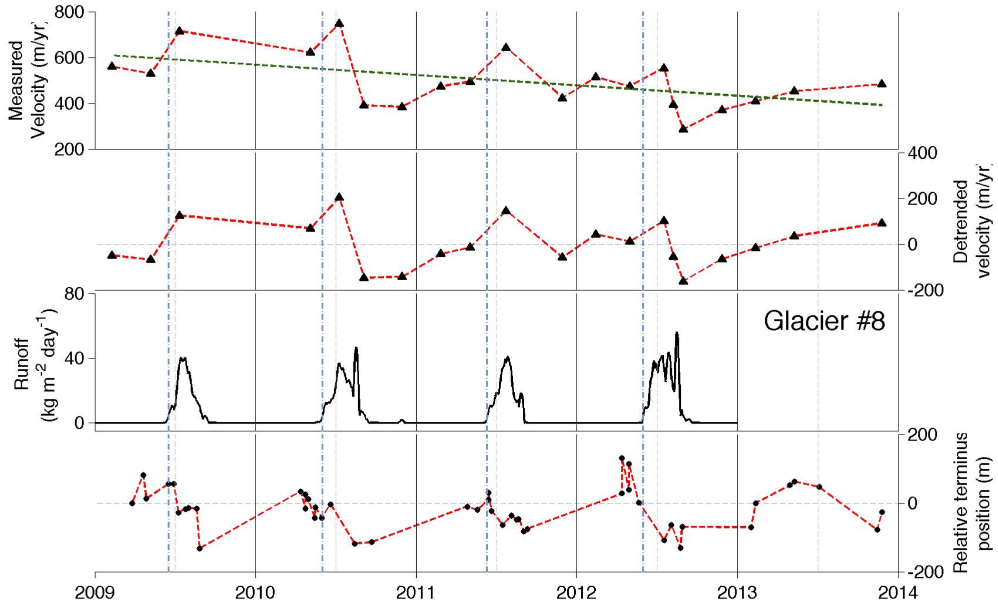



Figure B8.

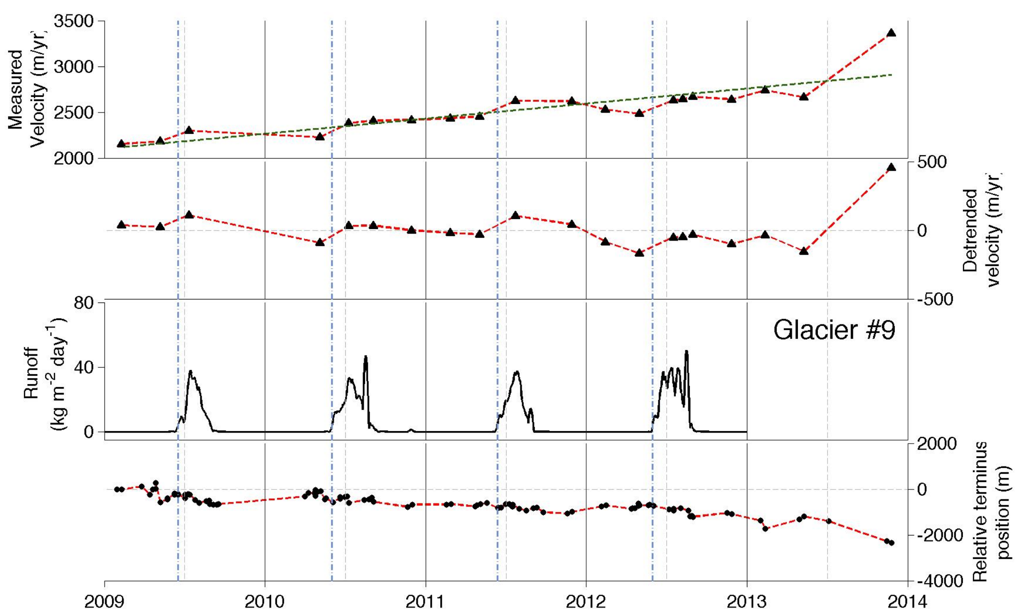



Figure B9. Hayes Glacier

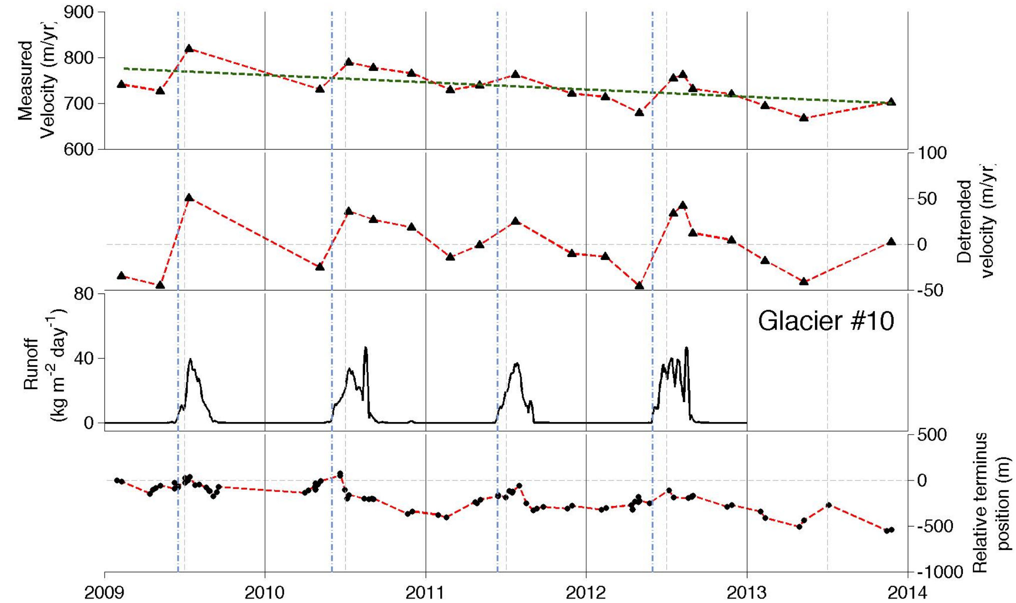



Figure B10.

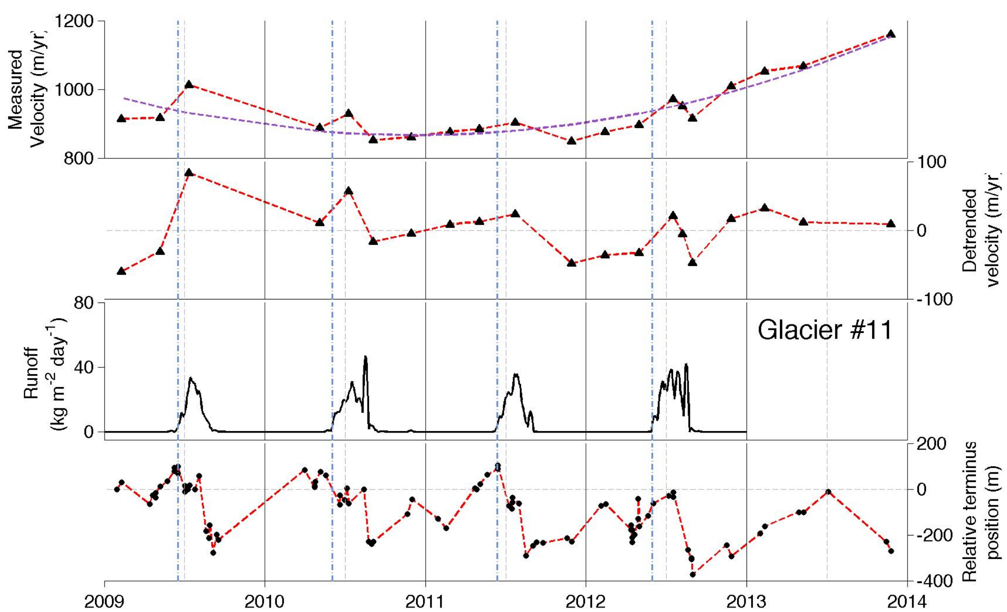



Figure B11.

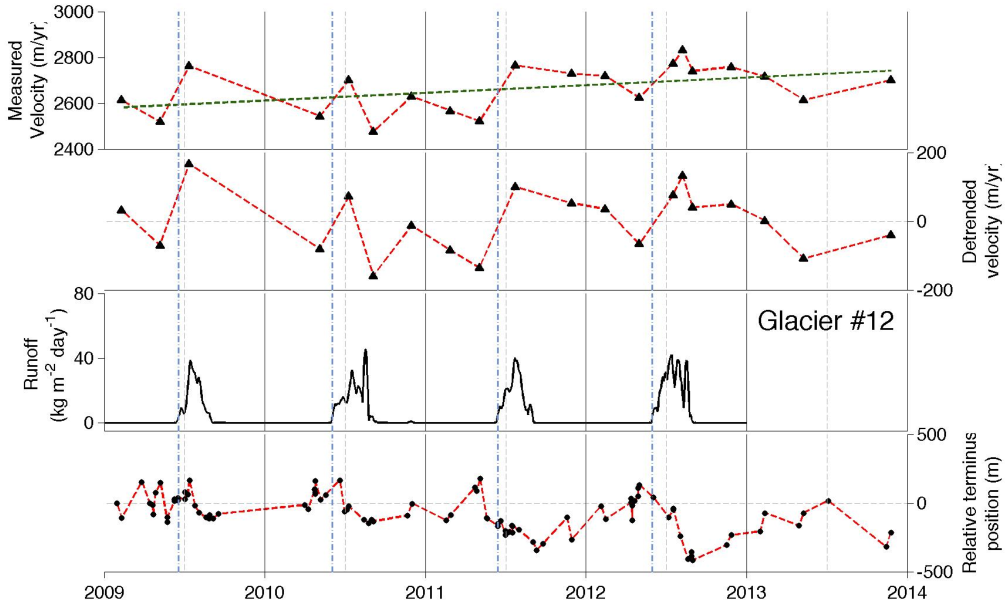



Figure B12.

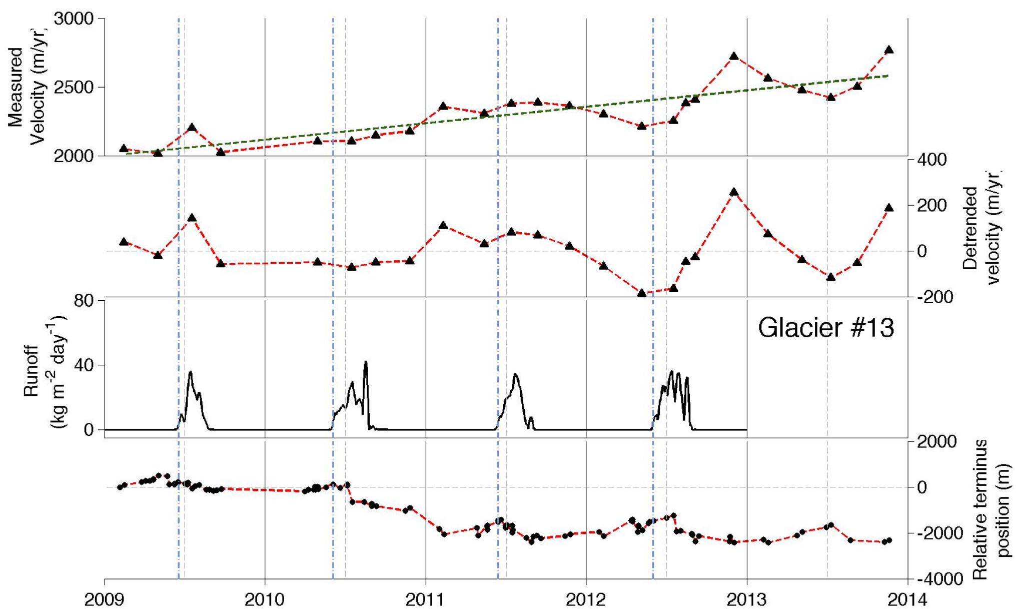



Figure B13. Alison Glacier

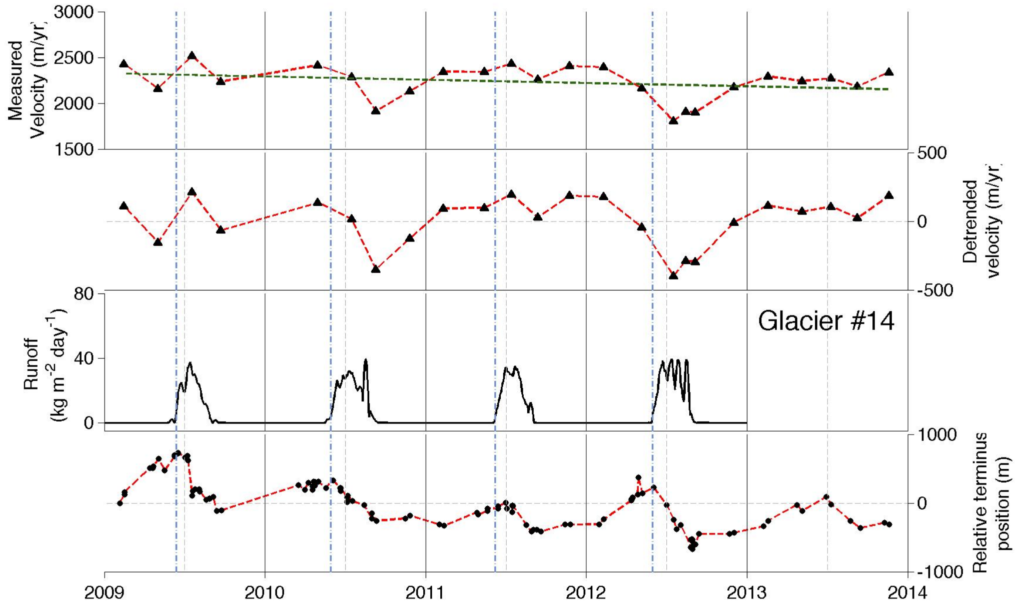



Figure B14. Igdlugdlip Sermia

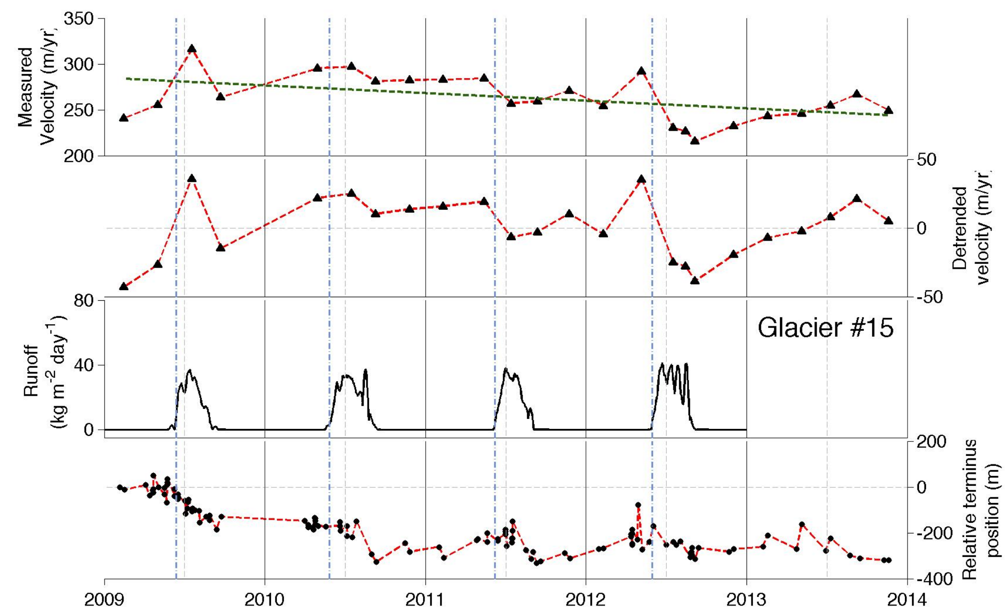



Figure B15.

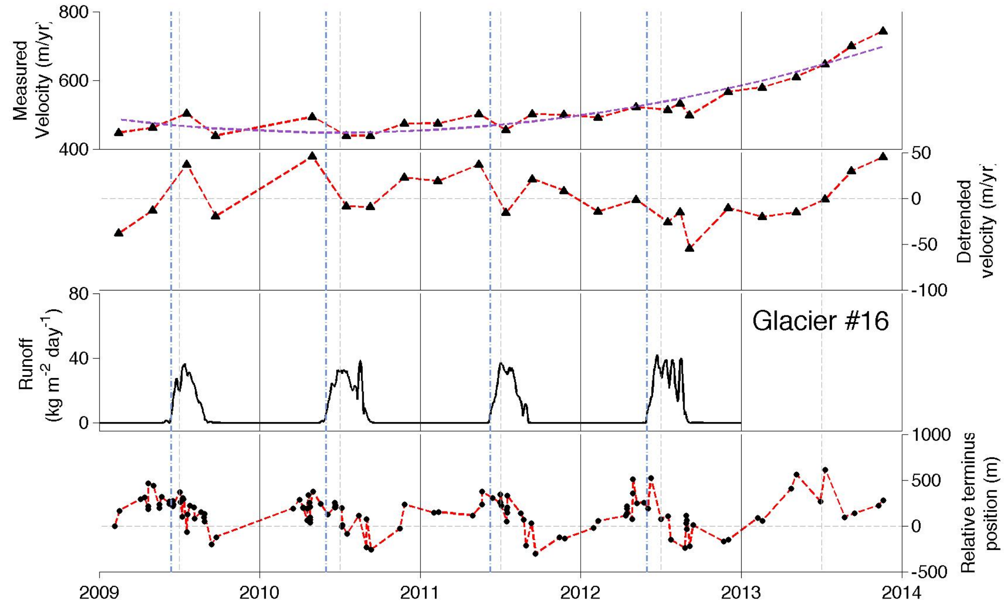



Figure B16. Cornell Glacier

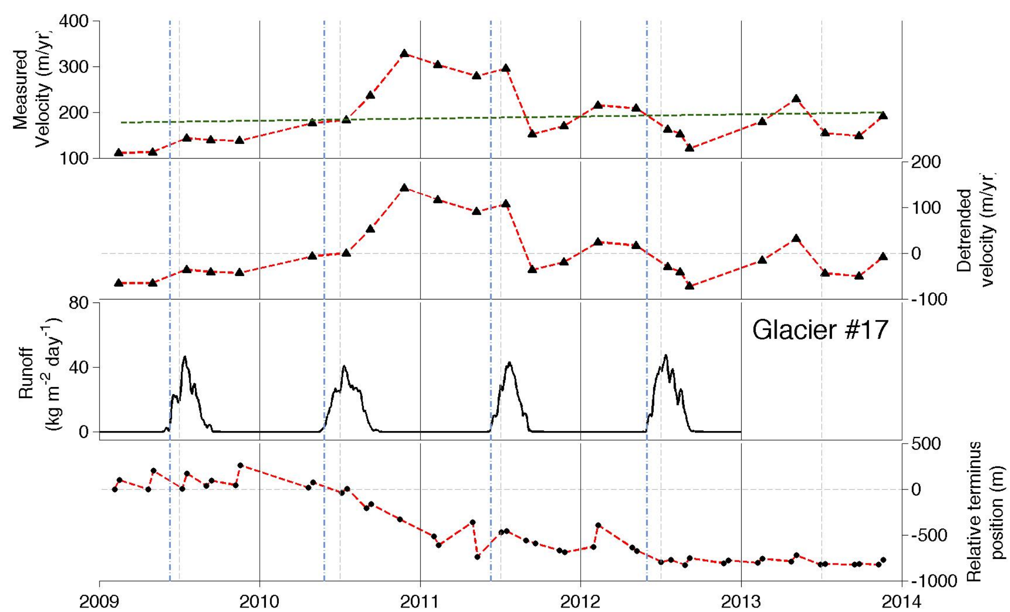



Figure B17.

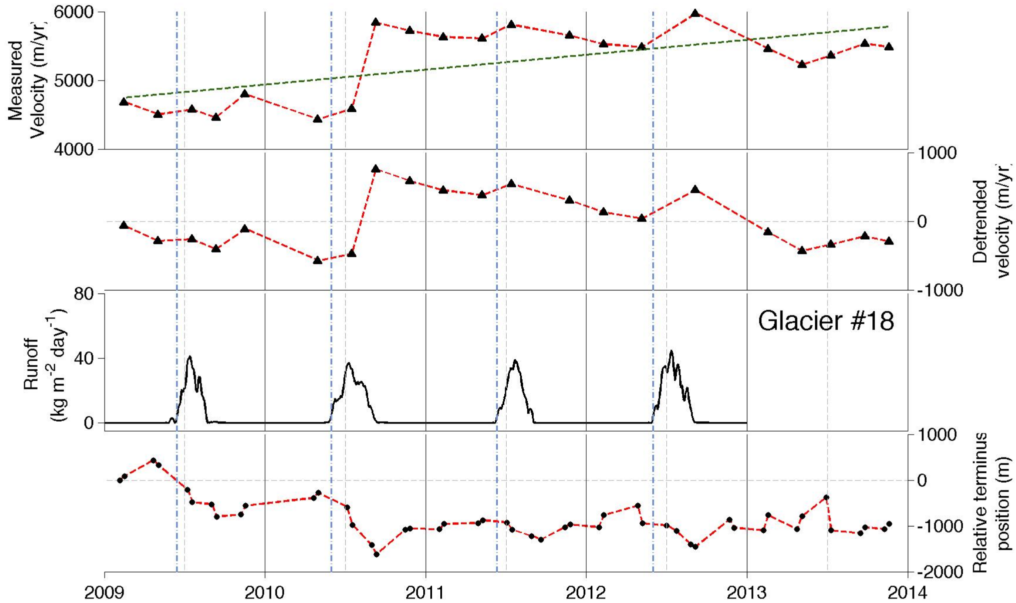



Figure B18.

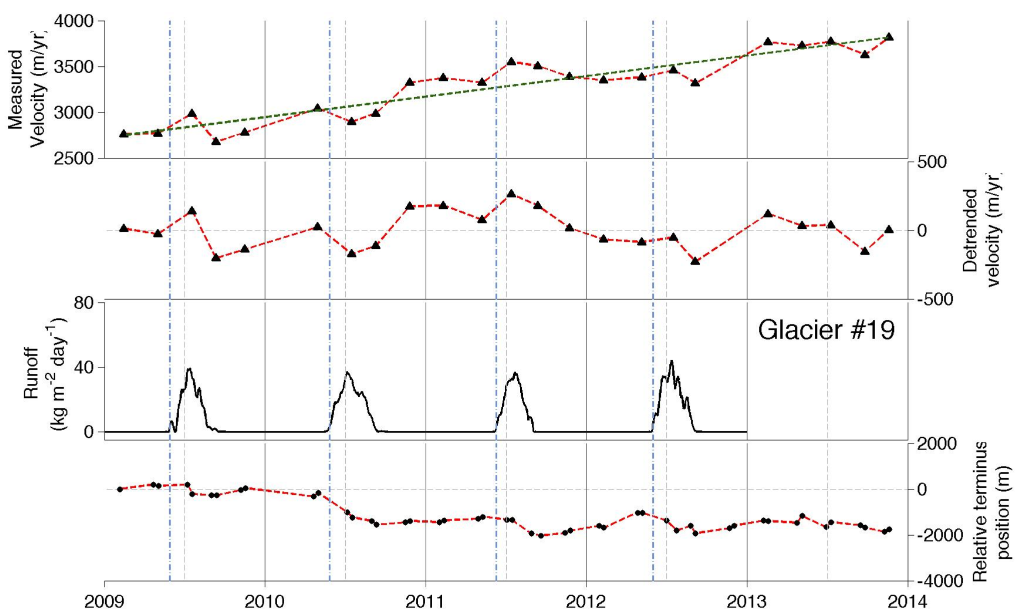



Figure B19. Upernavik Isstrom

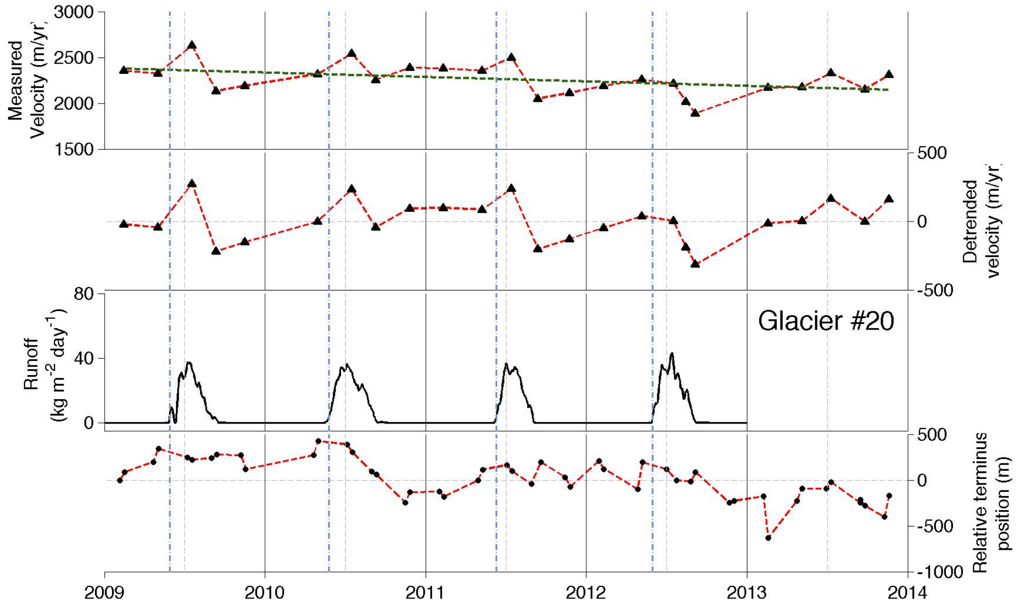



Figure B20.

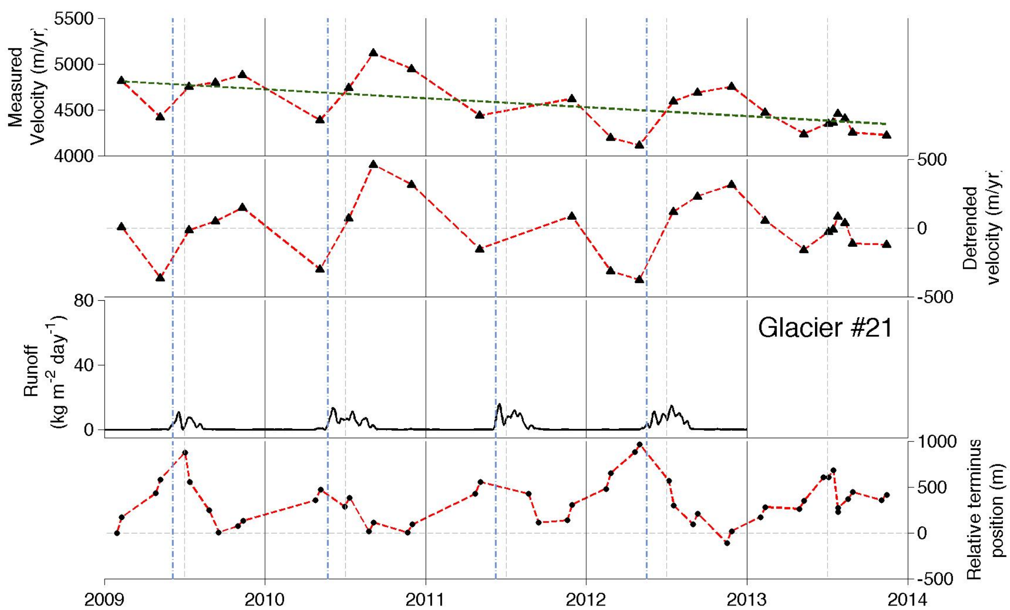



Figure B21. Rink Glacier

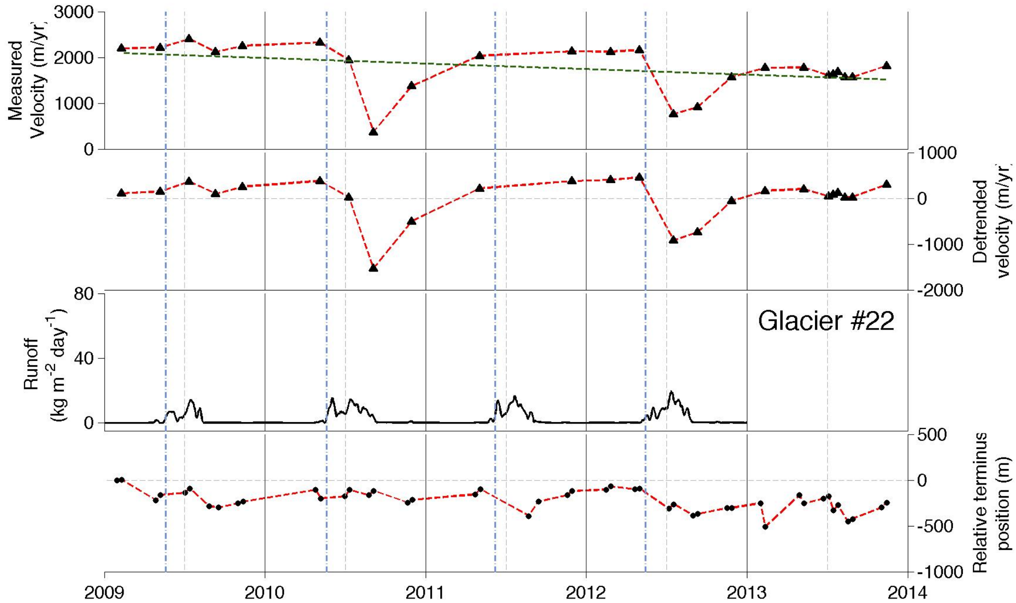



Figure B22. Kangerdlugssup Sermerssua

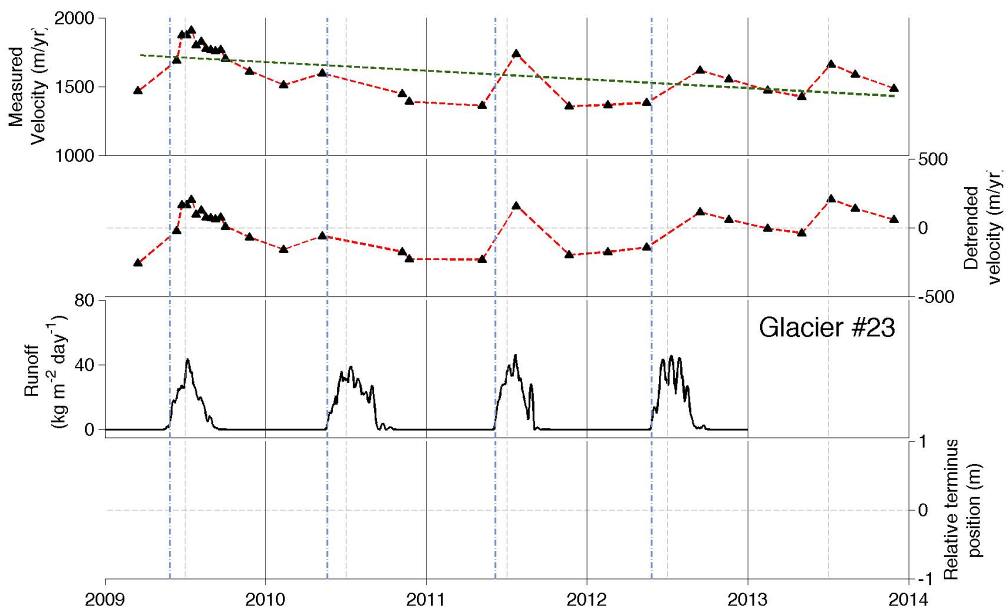



Figure B23. Kangilleq Isbræ. Terminus data is not available for this glacier because of the spatial limits of the TerraSAR-X footprints.

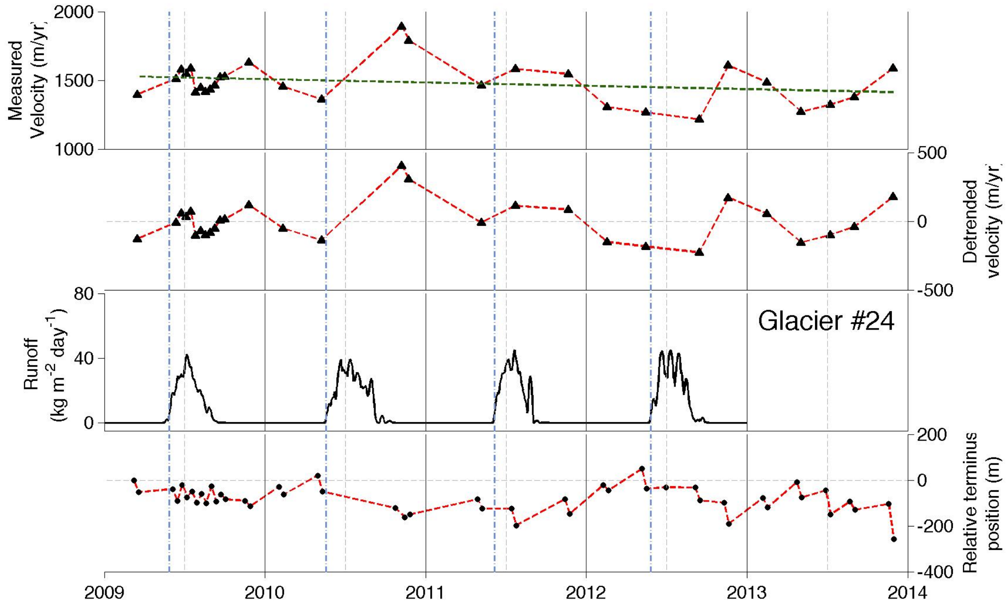



Figure B24. Sermilik

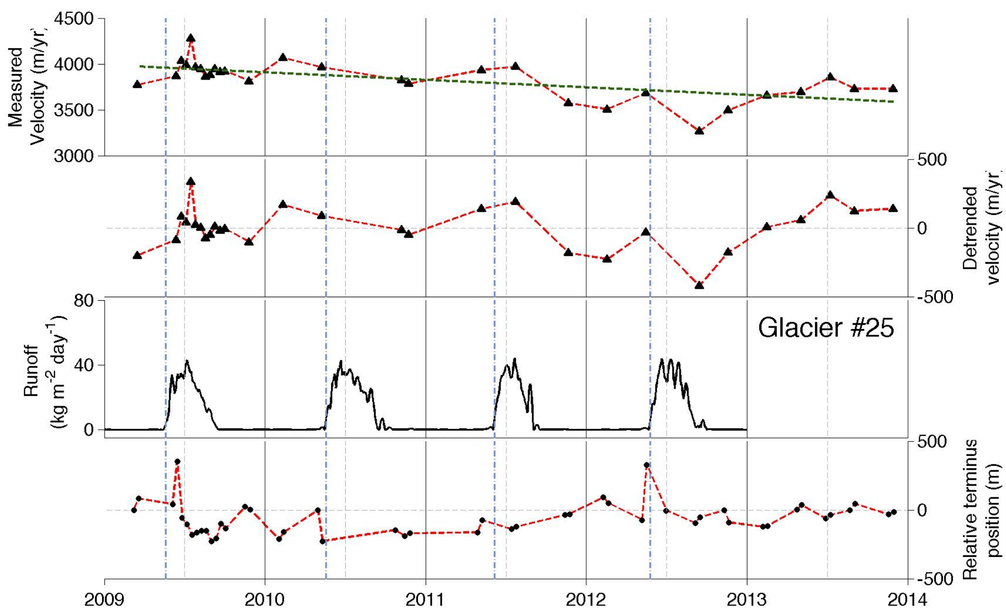



Figure B25. Store Glacier

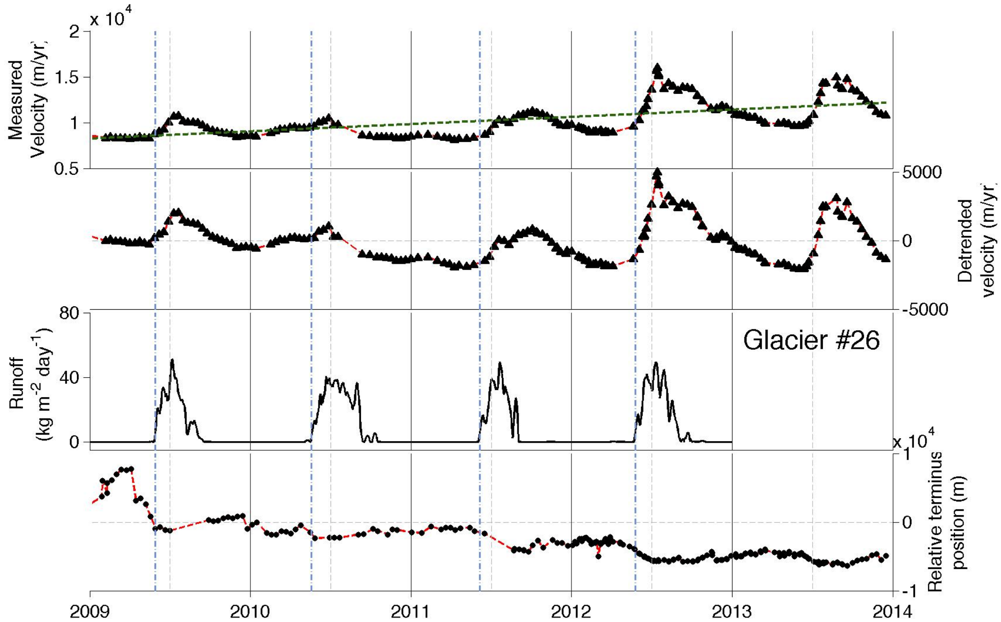



Figure B26. Jakobshavn Isbræ

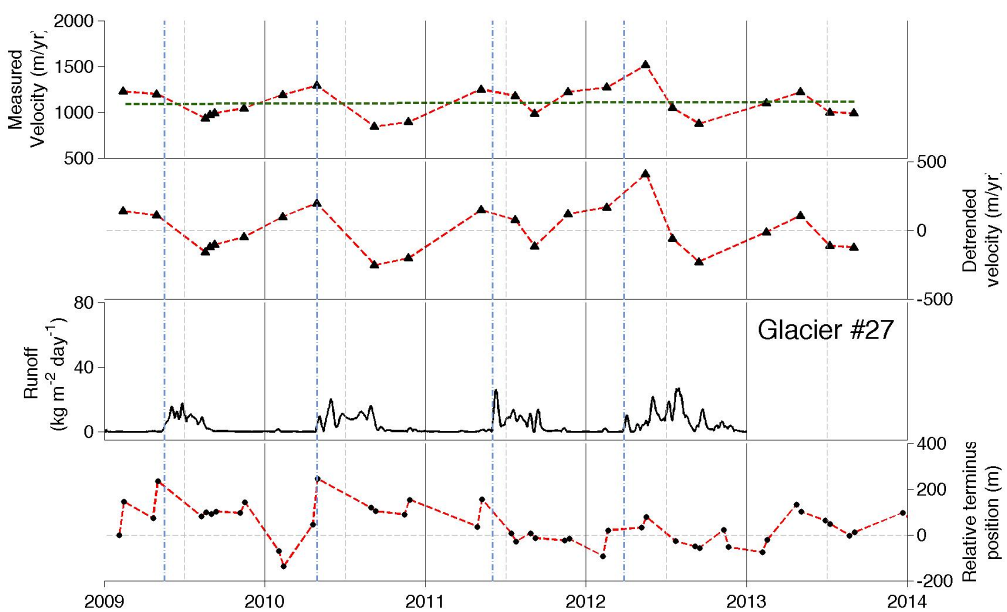



Figure B27. Akugdlerssup Sermia

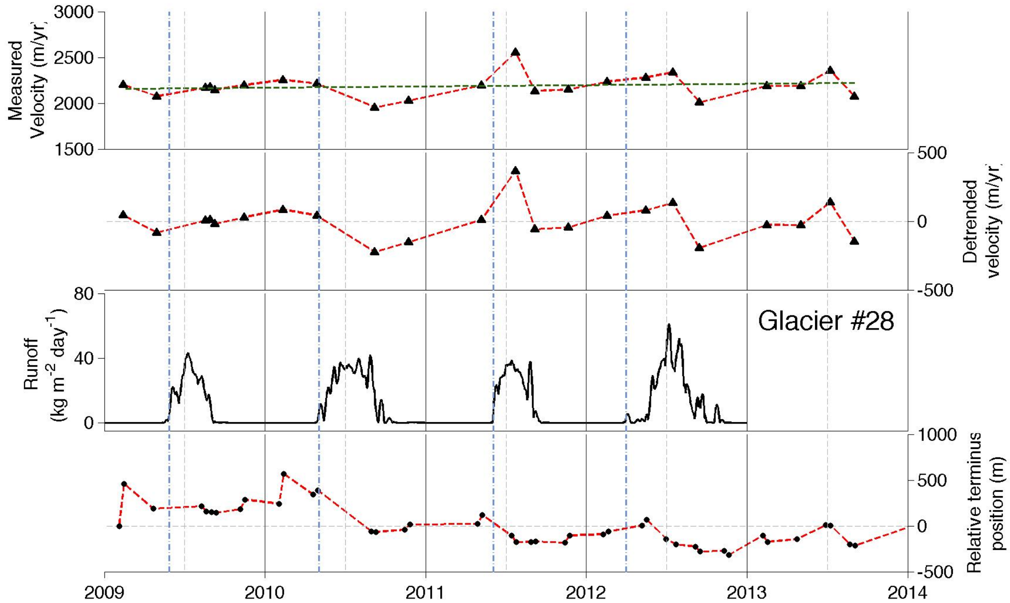



Figure B28. Kangiata Nunata Sermia

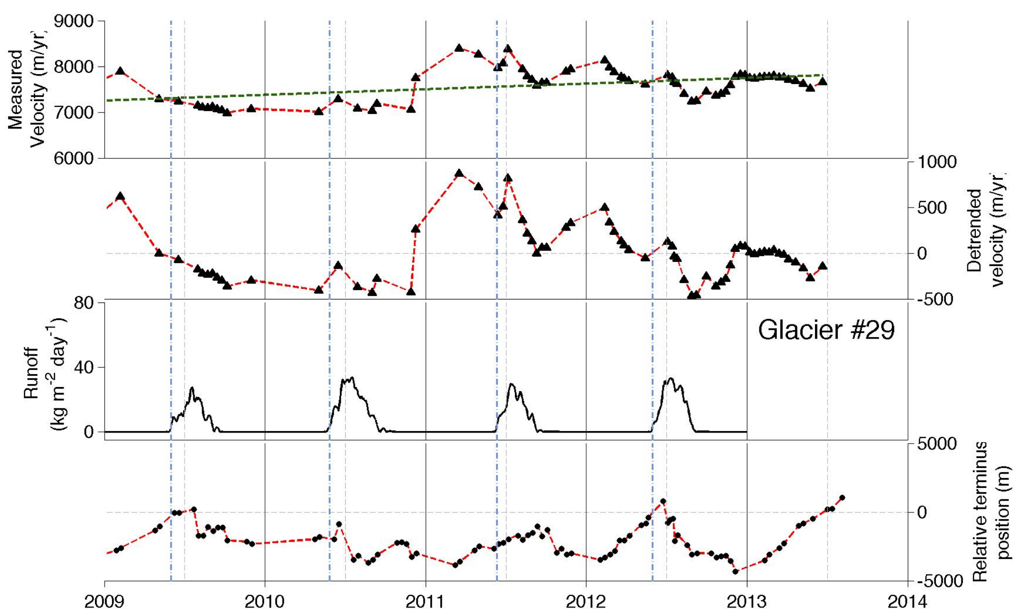



Figure B29. Kangerdlugssuaq Glacier

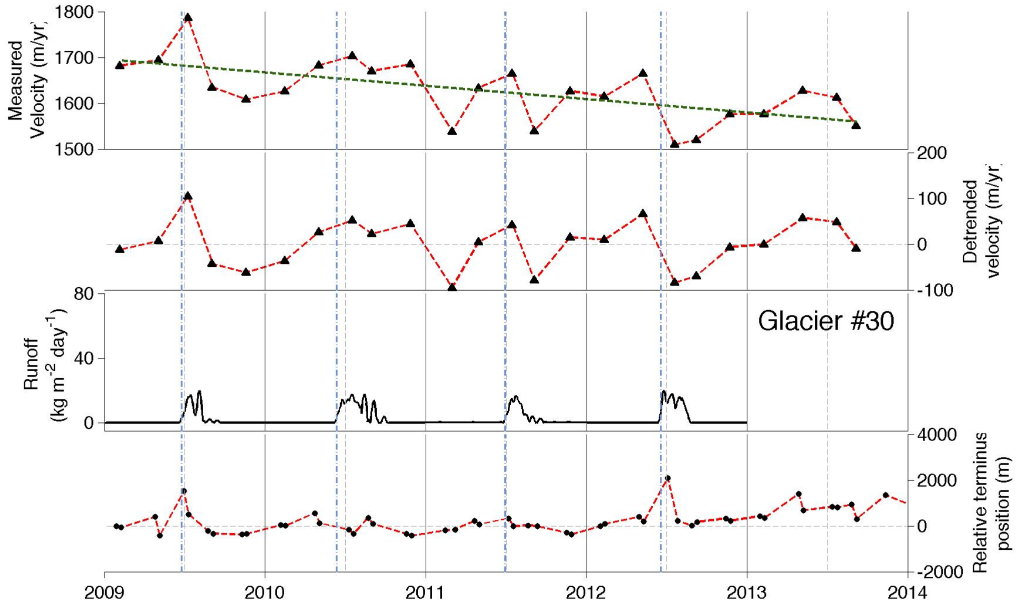



Figure B30.

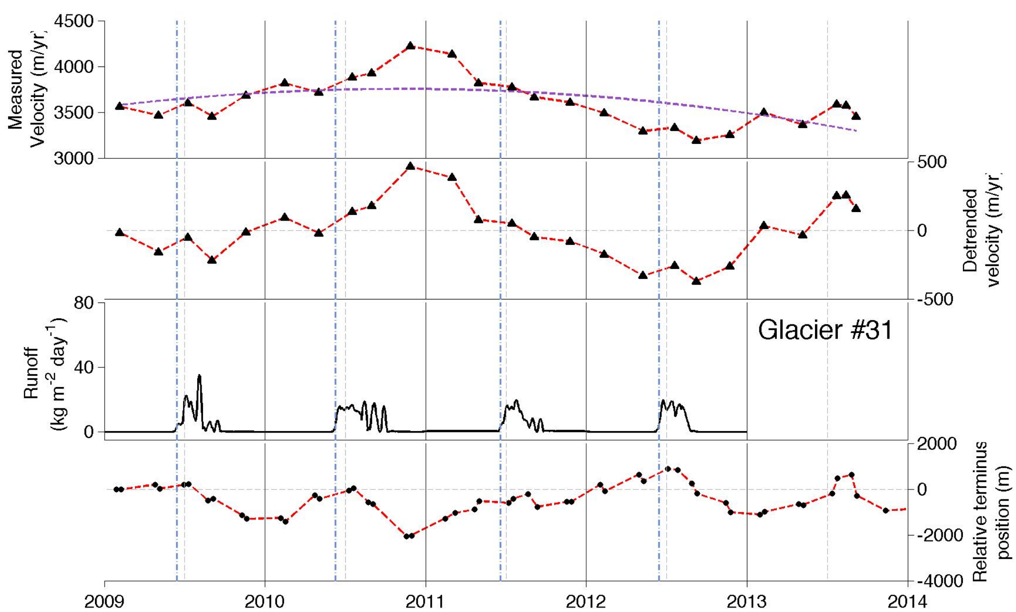
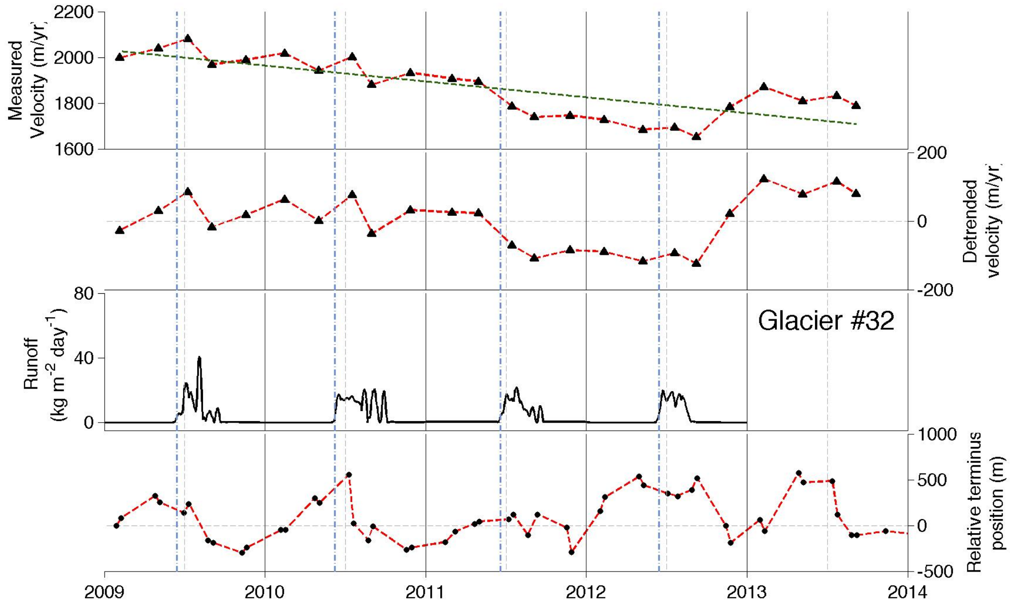



Figure B31.

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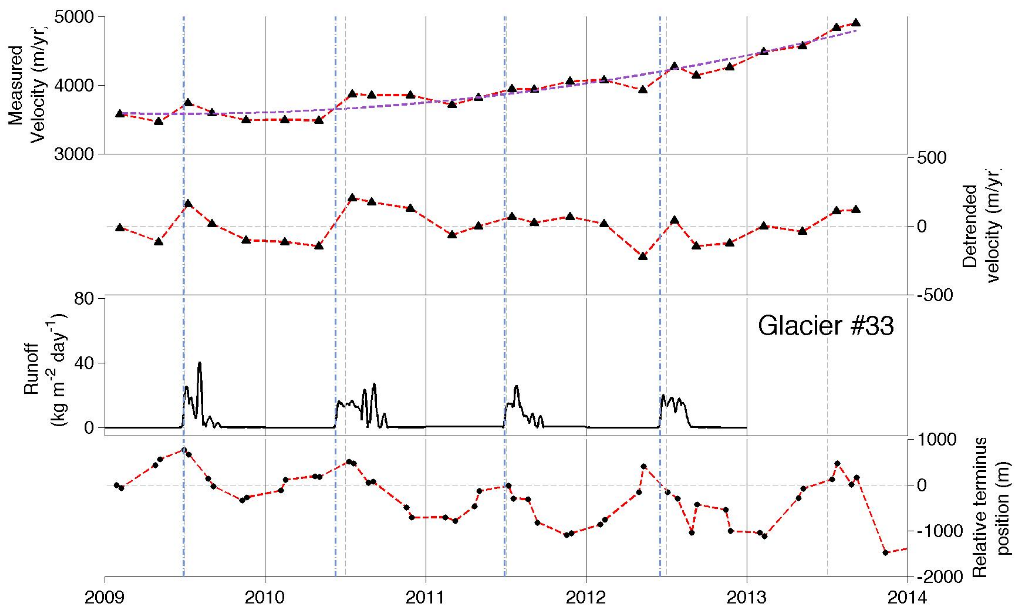



Figure B33. Unartit

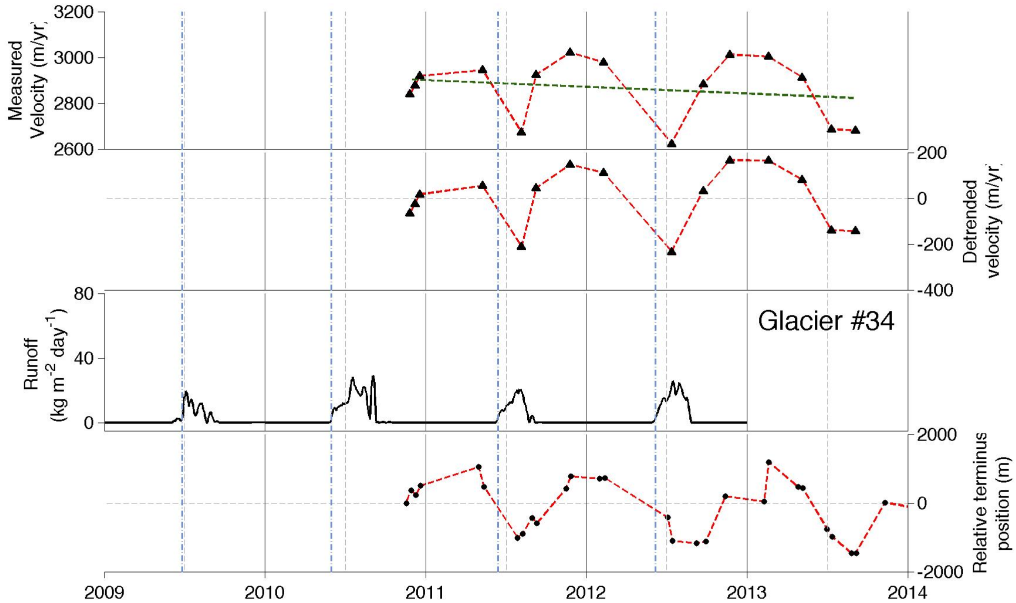



Figure B34. Midgaard

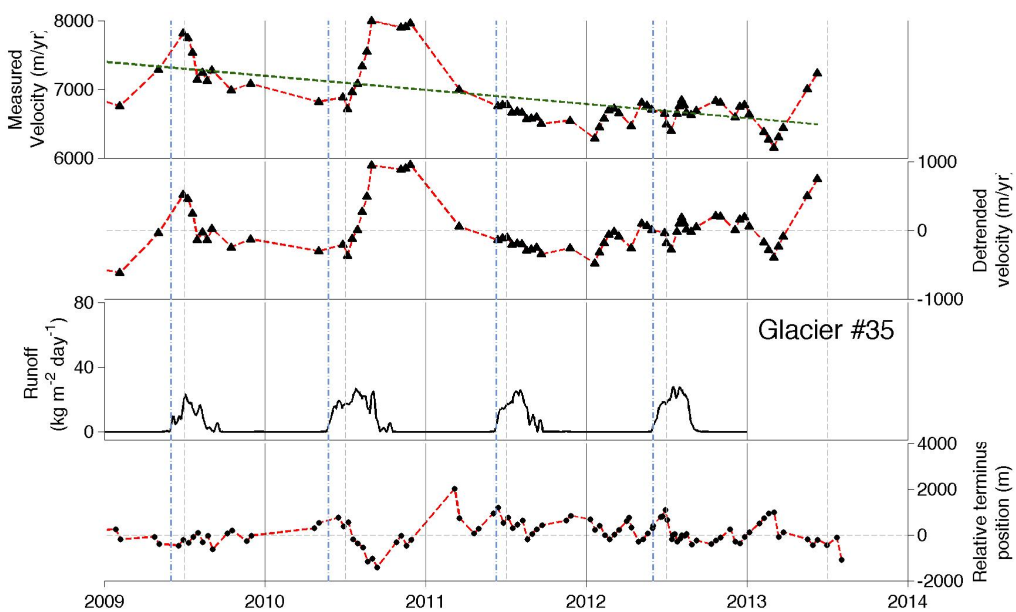



Figure B35. Helheim Glacier

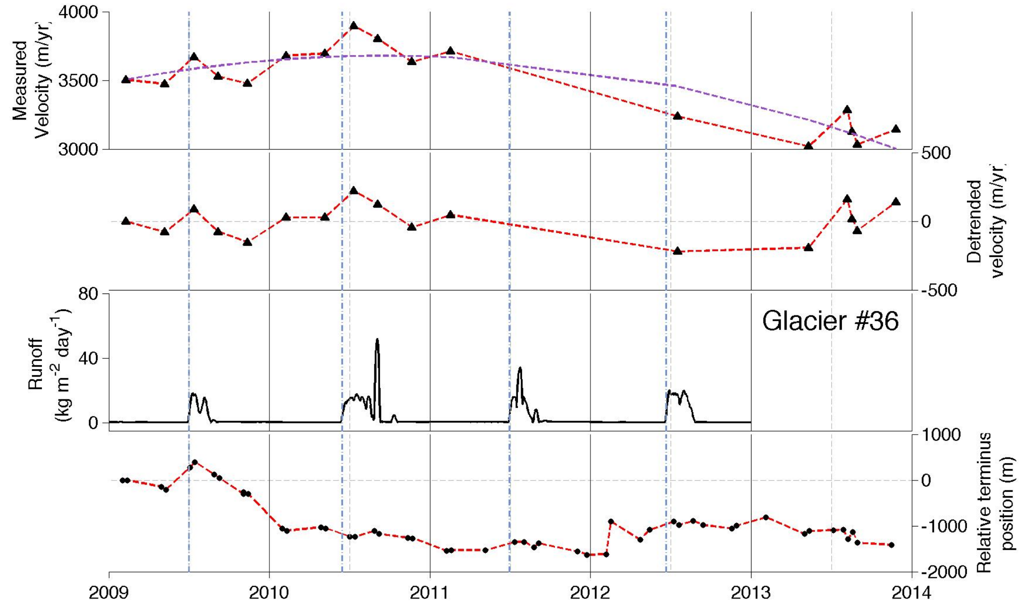



Figure B36.

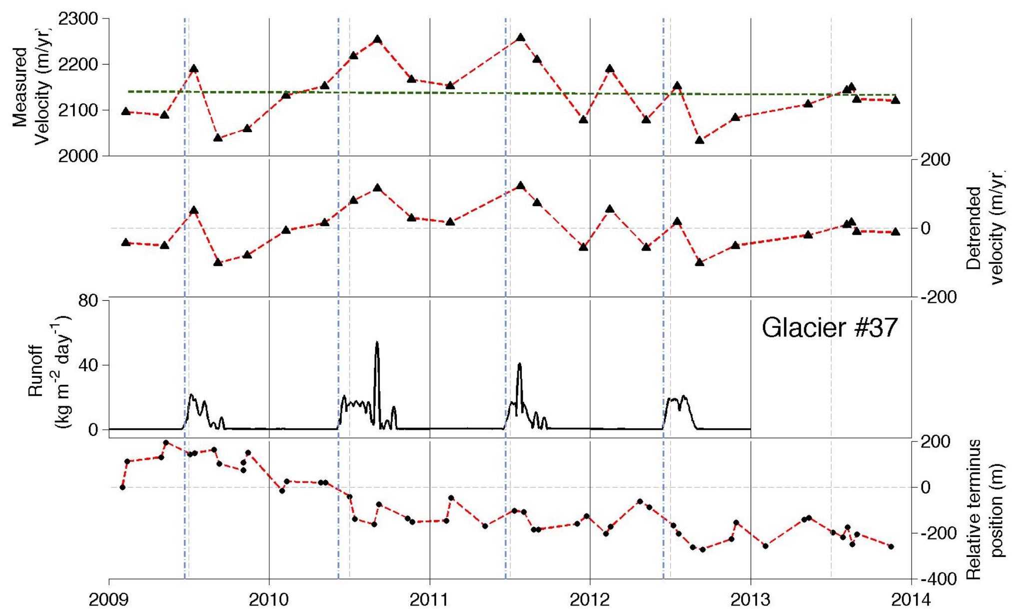
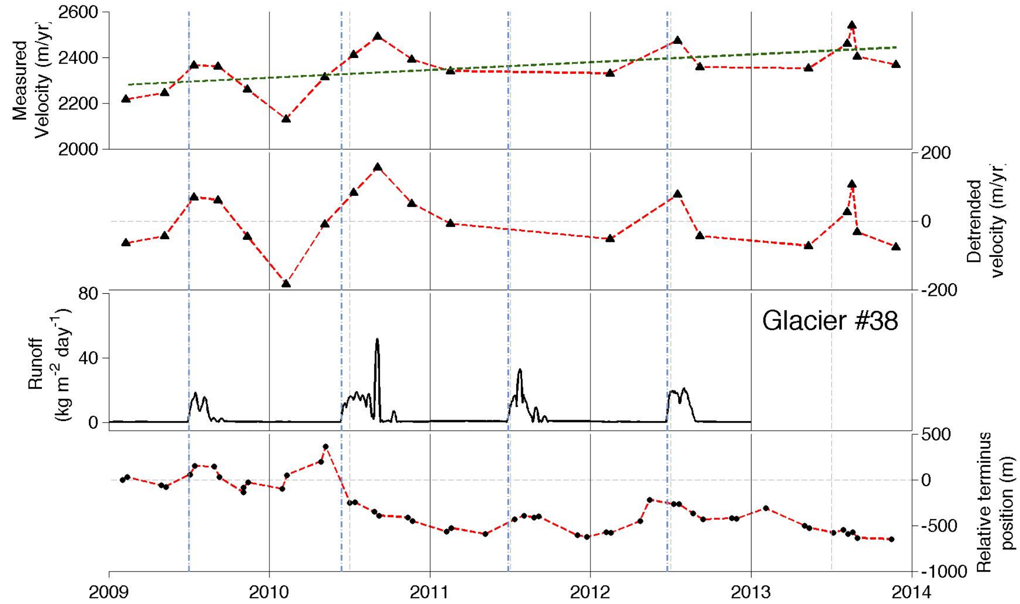



Figure B37.




Figures B38.

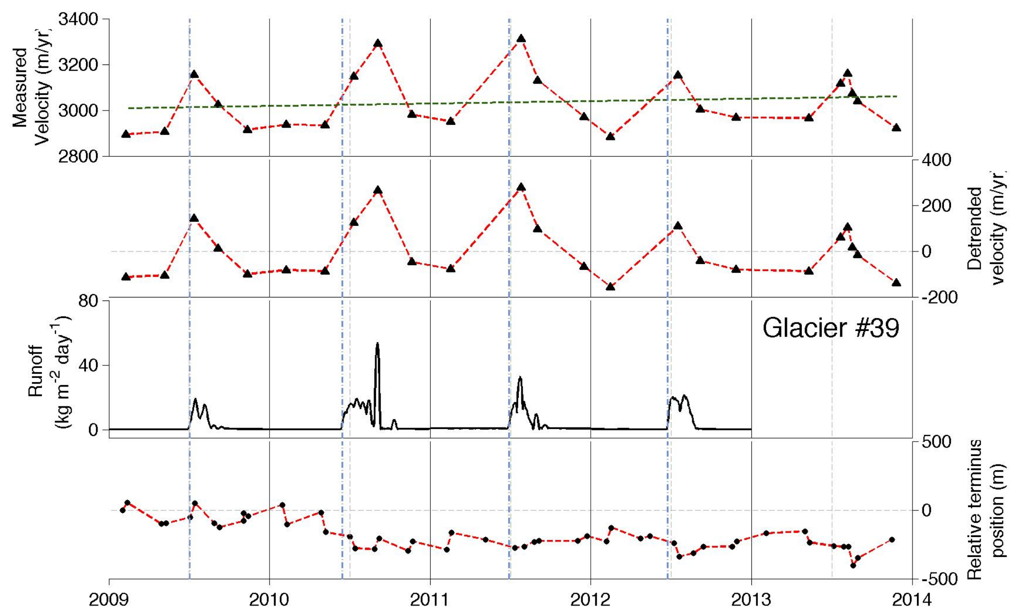



Figure B39.

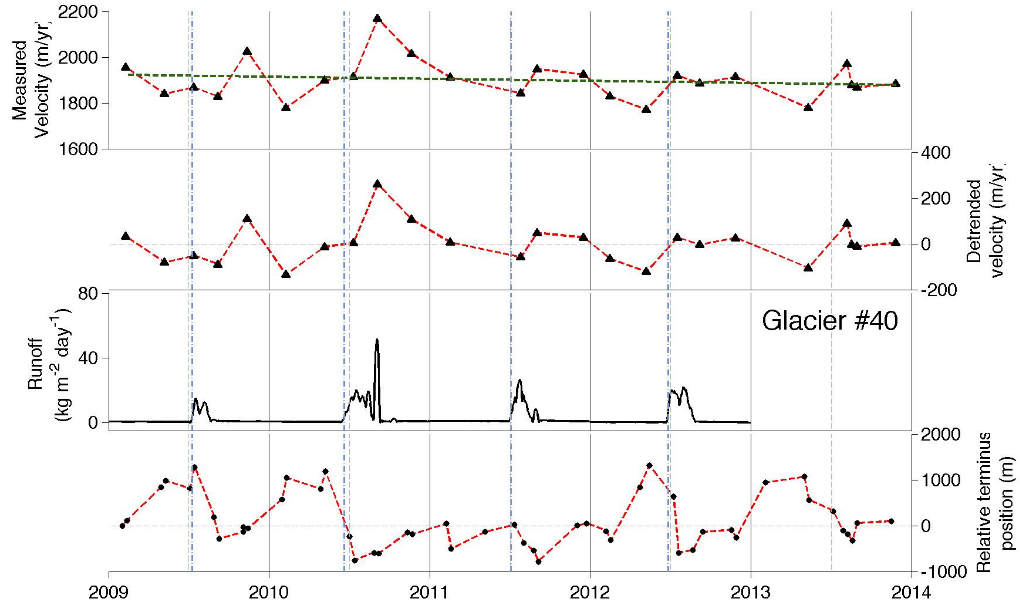



Figure B40. Ikertivaq

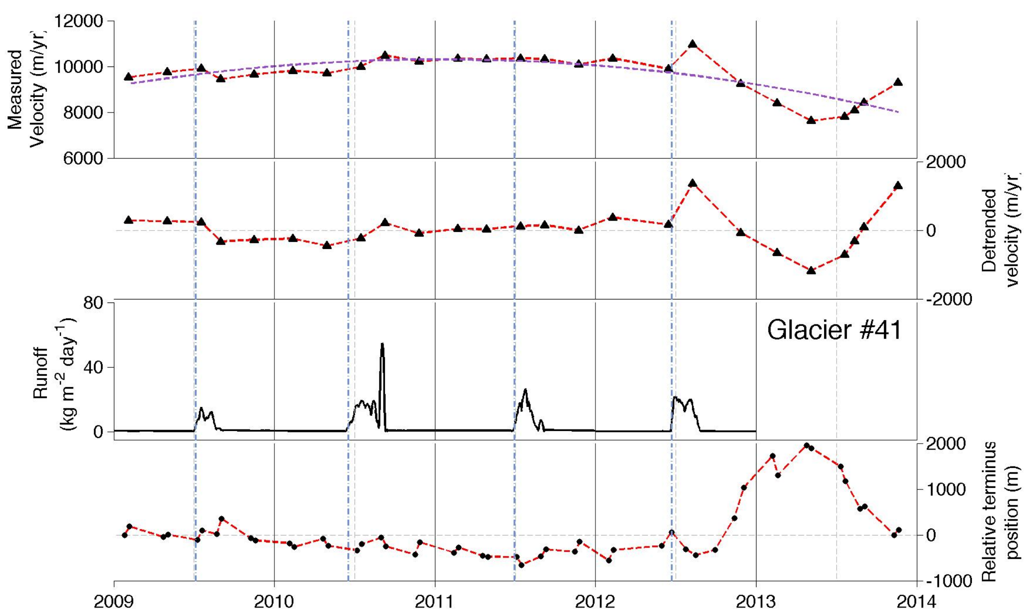



Figure B41.

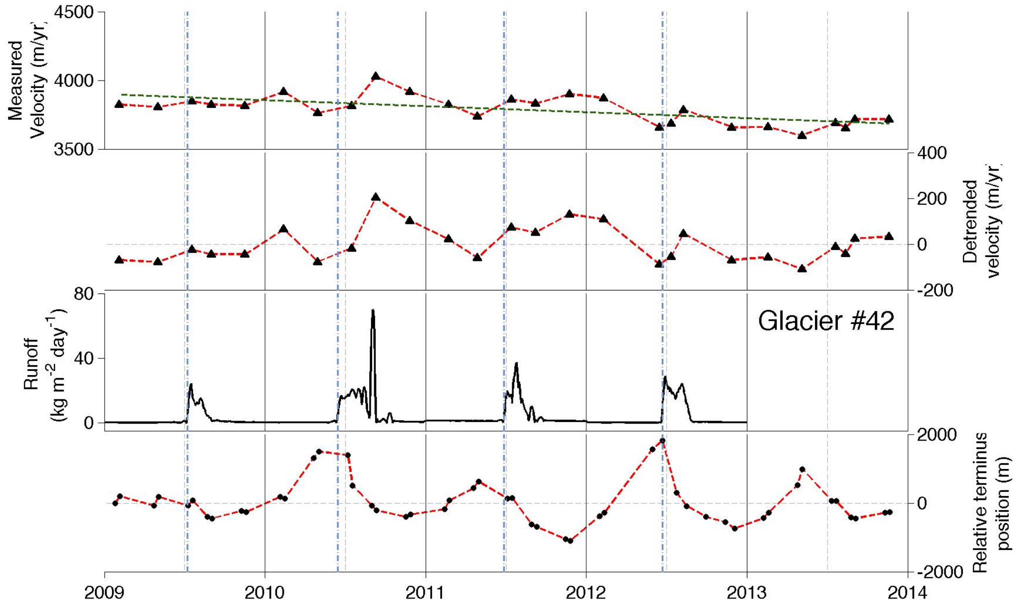



Figure B42.

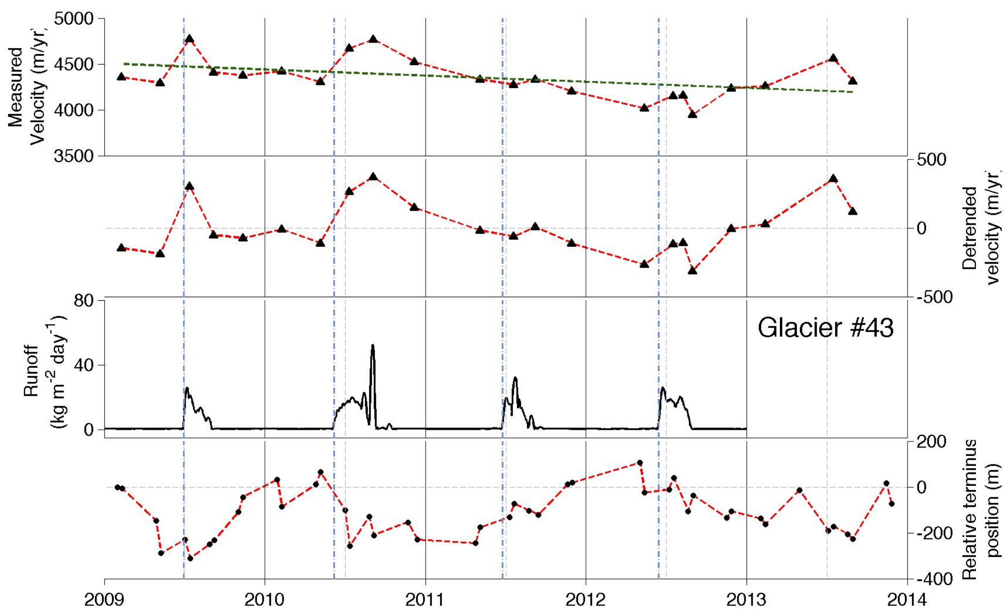



Figure B43.

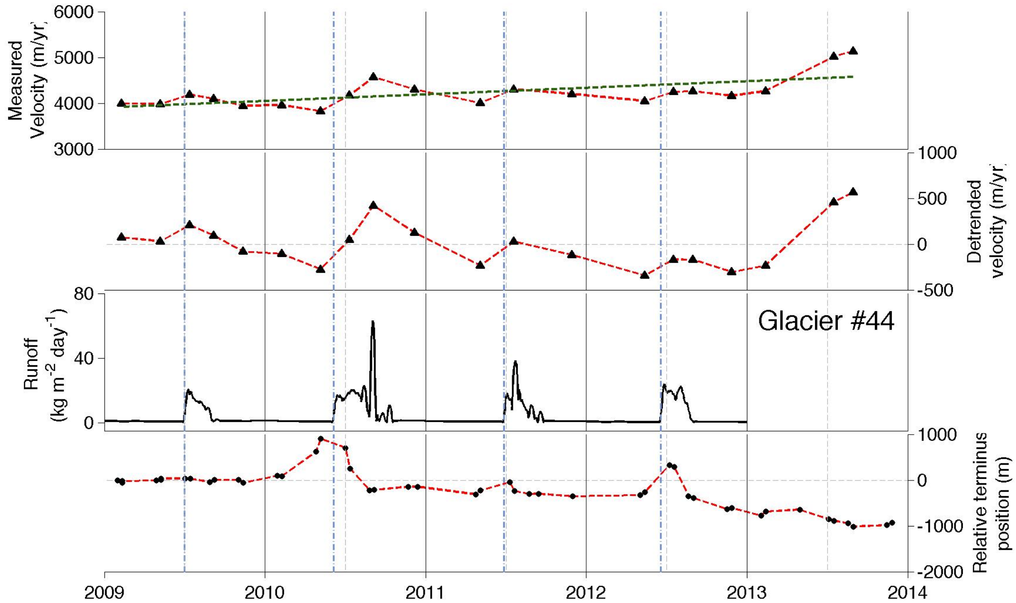



Figure B44.

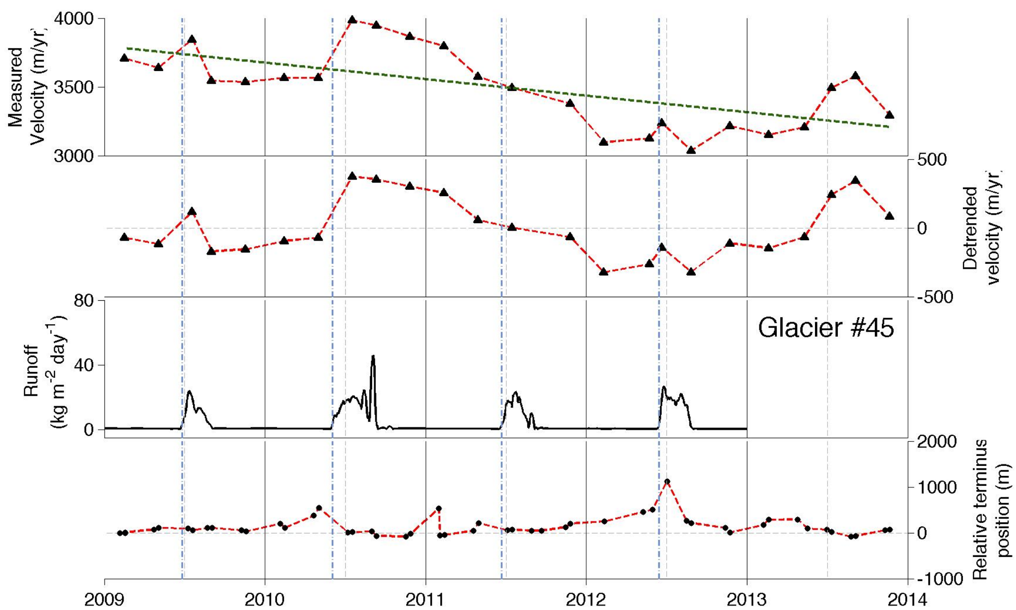



Figure B45. A. P. Bernstorff

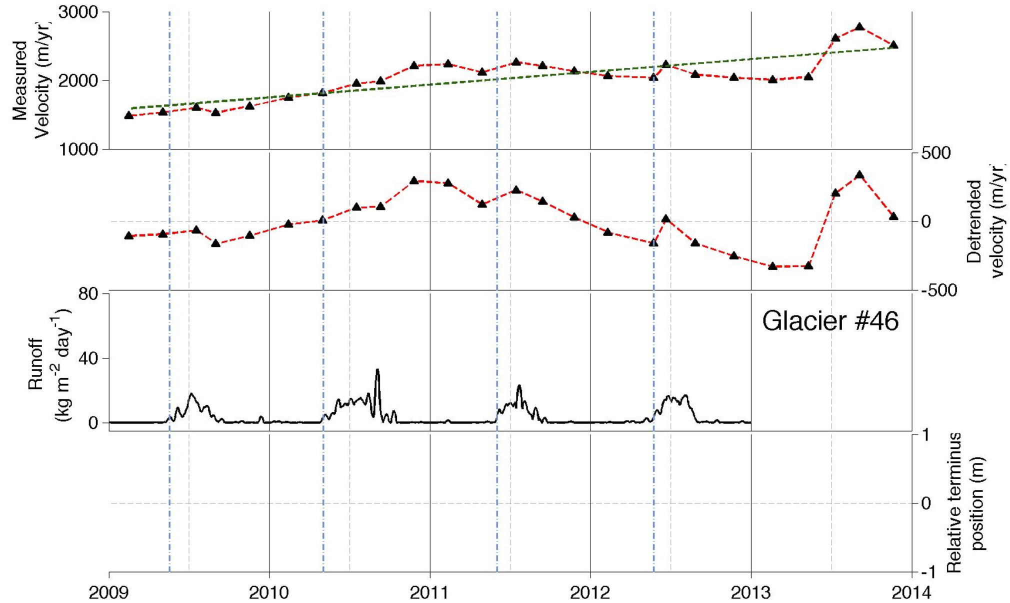



Figure B46. Maelkevejen. Terminus data is not available for this glacier because of the spatial limits of the TerraSAR-X footprints.

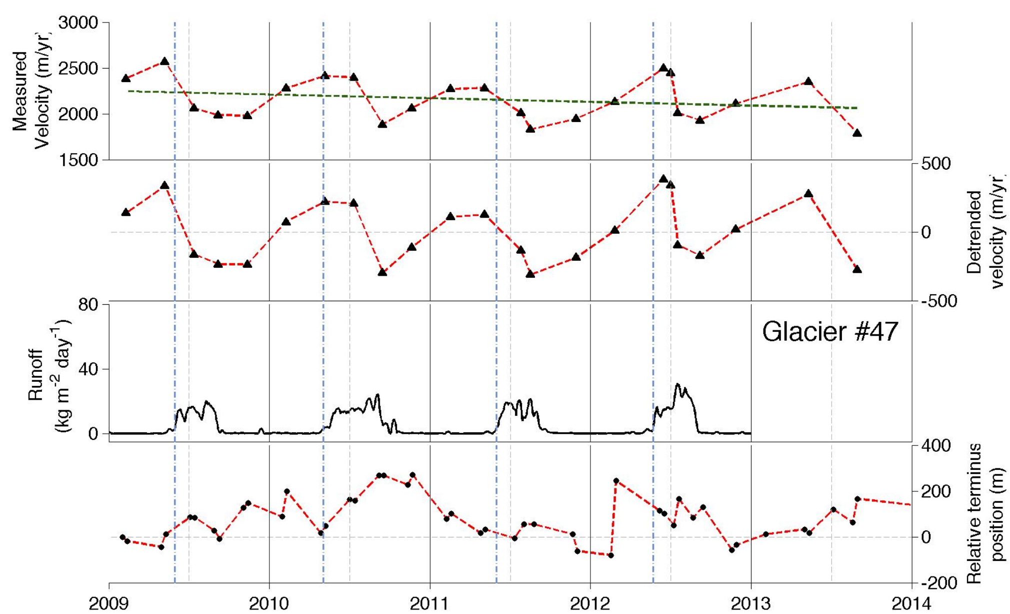



Figure B47. Skinefaxe

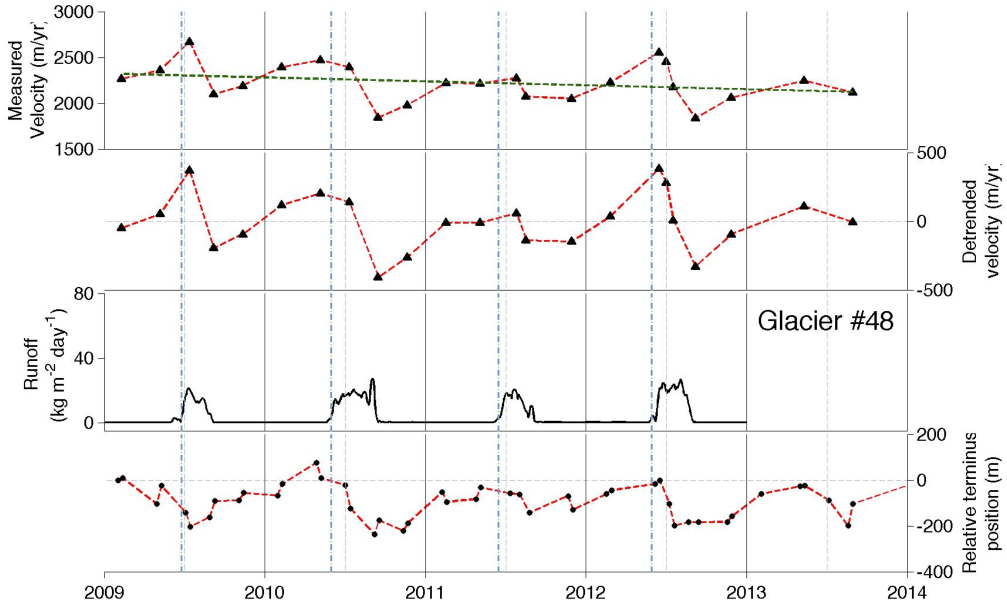



Figure B48. Rimfaxe

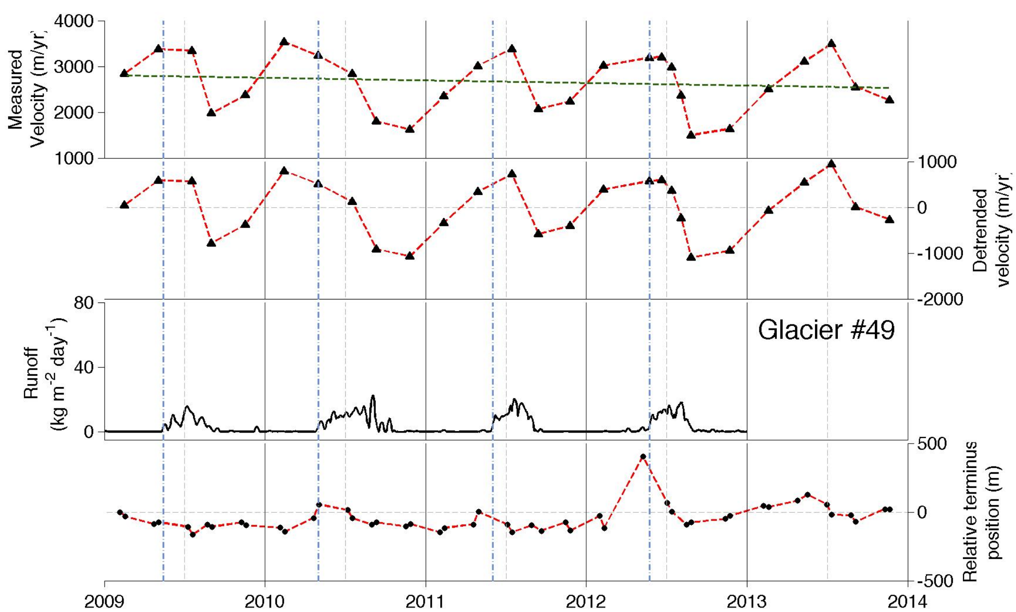



Figure B49. Heimdal

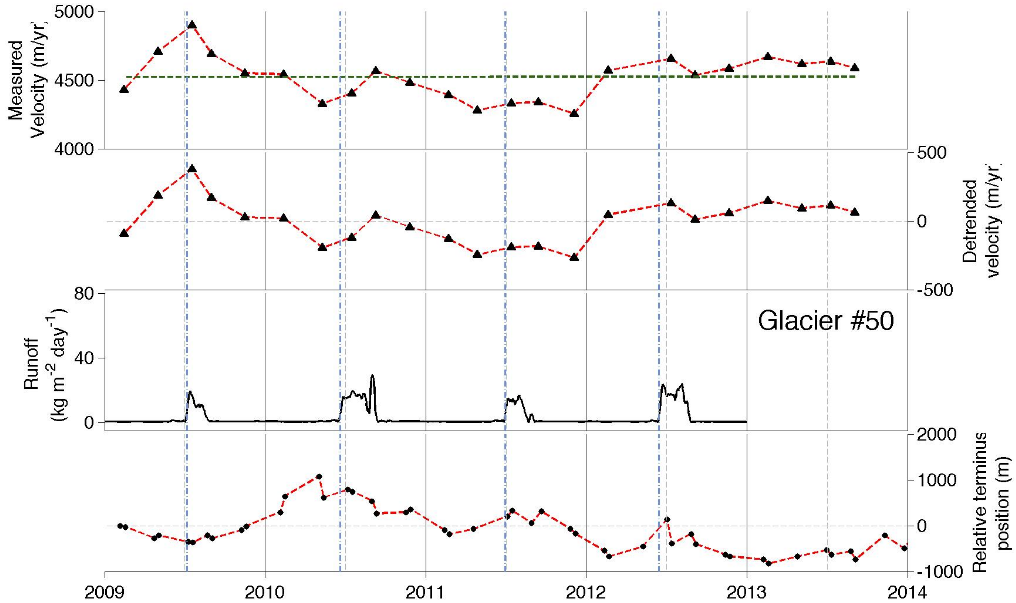



Figure B50.

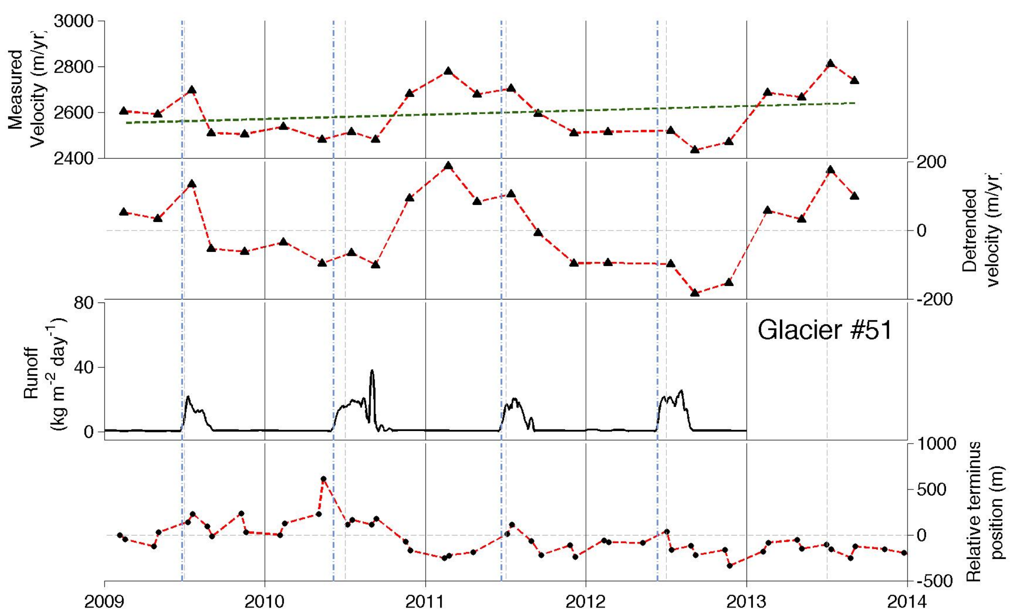



Figure B51.

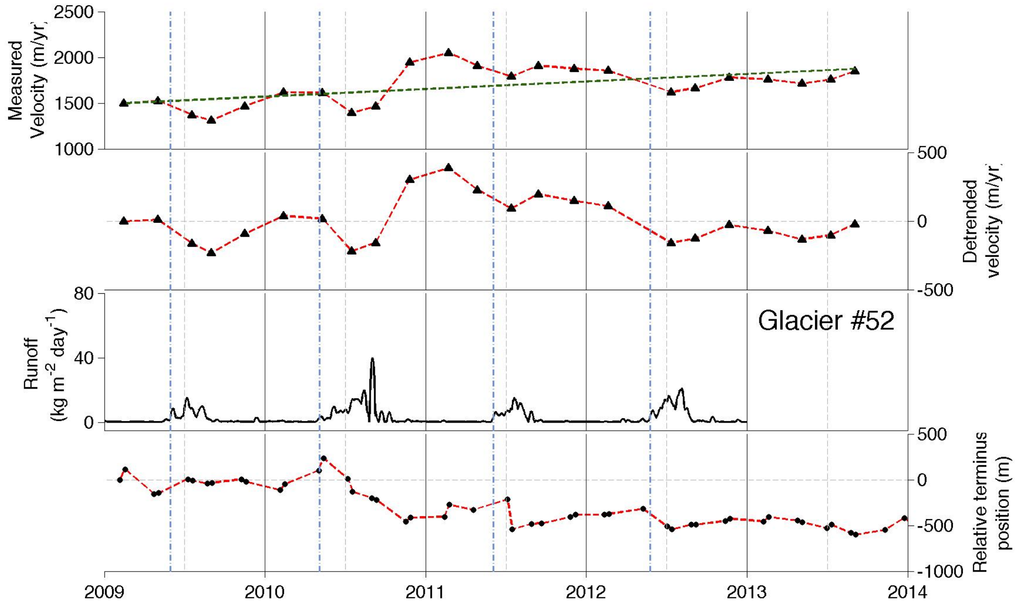



Figure B52.

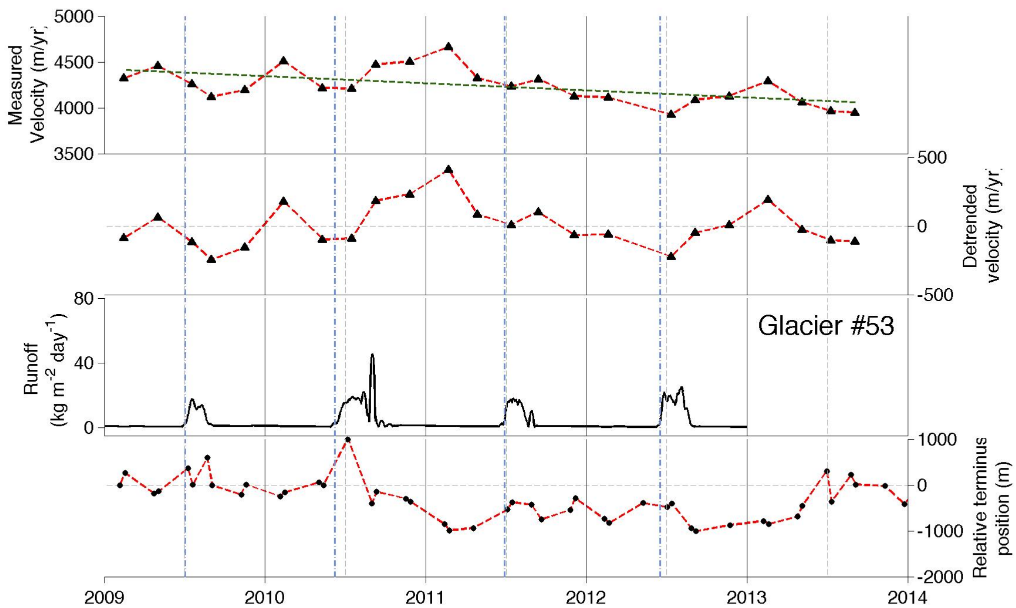



Figure B53.

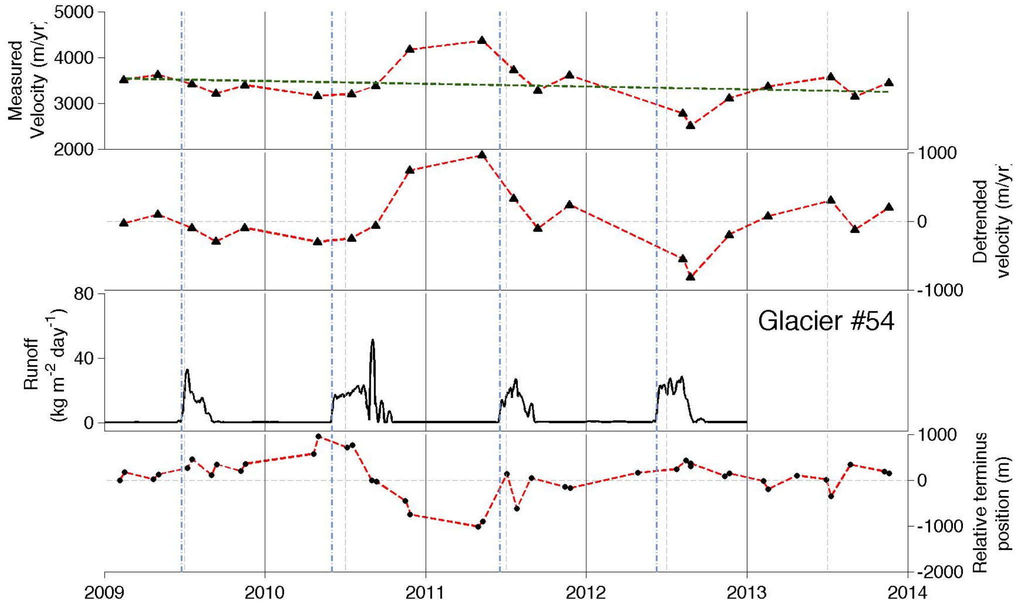



Figure B54.

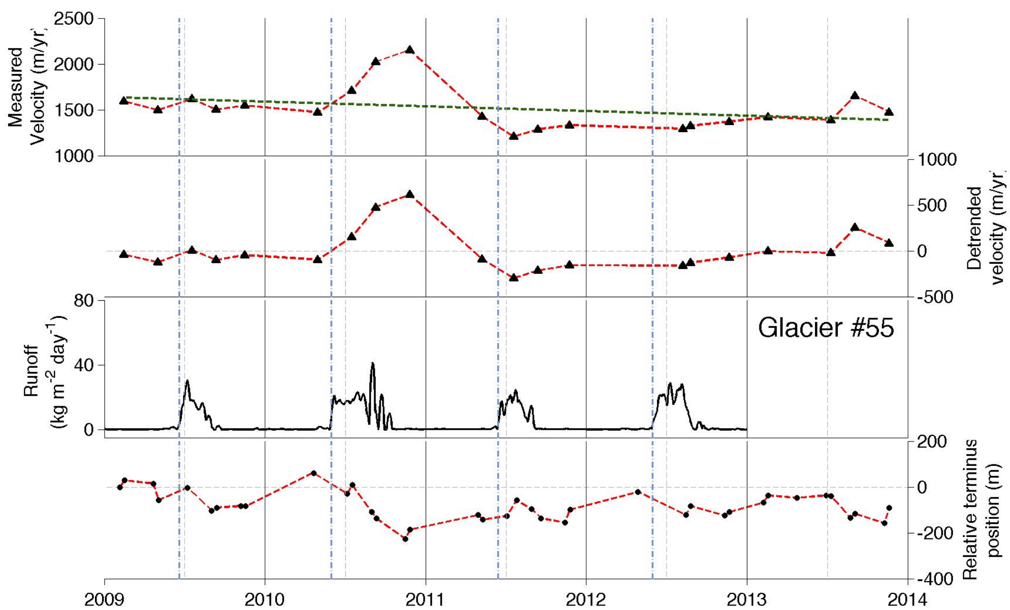



Figure B55.

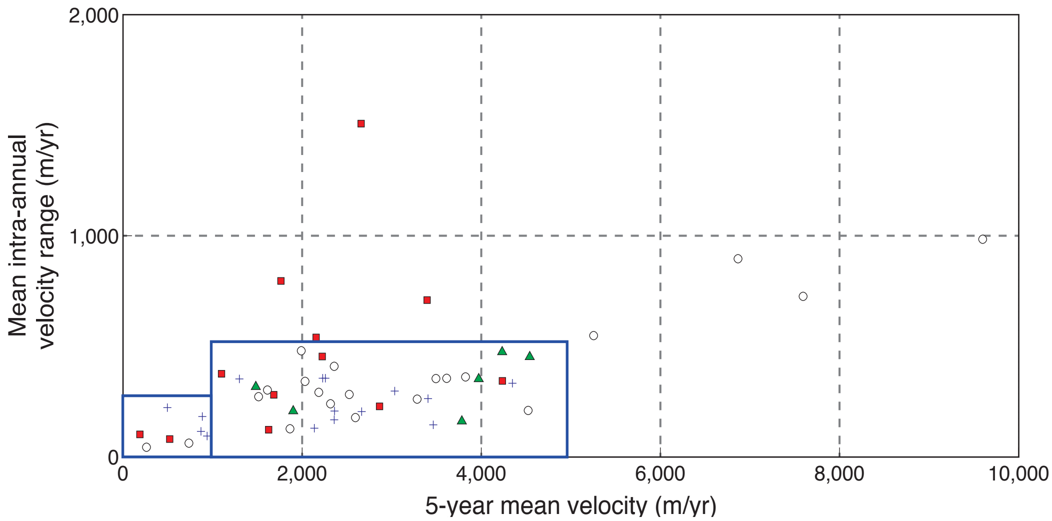



Figure B56. Mean intra-annual velocity range versus 5-year mean velocity for all glaciers. Symbols match those used in Fig. 3.1 to show seasonal velocity pattern and boxes indicate groups discussed in the main text (velocity < 1 km/yr and velocity from 1-5 km/yr). Jakobshavn not included in plot.

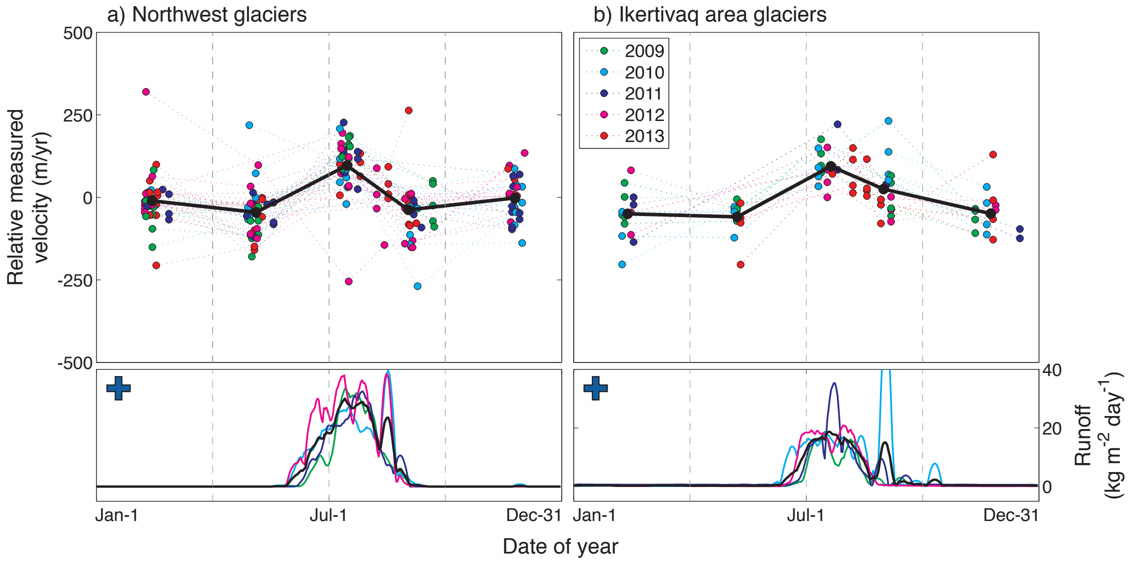



Figure B57. Mean seasonal velocity pattern and runoff for a) northwest glaciers and b) Ikertivaq area glaciers. Top row: Plots include all glaciers with dominant seasonal velocity modes for type 1 in a) the northwest region and b) the Ikertivaq region. Measured velocity (m/yr) is detrended (removing either linear or quadratic trend), divided by year with mean annual velocity subtracted for that year, and plotted on a 1-Jan to 31-Dec scale. Mean velocity pattern is indicated (thick black line). Bottom row: Smoothed daily runoff (kg/m$^2$d) from RACMO2 for 2009-2012 for glaciers in top row plots. Mean runoff is included for each year (colored lines) as well as the 4-year mean runoff (black line).

Table S1. Data for glacier mean velocity and intra-annual velocity range.

| Glacier ID | Glacier name | Mean 5-yr velocity | Mean intra-annual velocity range | (Intra-annual velocity range)/(Mean 5-yr velocity) (%) | R | R-squared |
|---|---|---|---|---|---|---|
| 1 | | 886 | 183 | 21 | -0.36 | 0.13 |
| 2 | | 3406 | 264 | 8 | -0.11 | 0.01 |
| 3 | | 871 | 116 | 13 | 0.00 | 0.00 |
| 4 | | 1300 | 353 | 27 | -0.22 | 0.05 |
| 5 | Sverdrup Brae | 2362 | 207 | 9 | -0.01 | 0.00 |
| 6 | Dietrichson | 1991 | 480 | 24 | 0.08 | 0.01 |
| 7 | Steenstrup | 2359 | 409 | 17 | 0.15 | 0.02 |
| 8 | | 496 | 222 | 45 | 0.21 | 0.04 |
| 9 | Hayes | 2527 | 282 | 11 | -0.32 | 0.10 |
| 10 | | 736 | 62 | 8 | 0.32 | 0.10 |
| 11 | | 939 | 94 | 10 | 0.16 | 0.03 |
| 12 | | 2665 | 204 | 8 | -0.30 | 0.09 |
| 13 | Alison | 2318 | 240 | 10 | -0.27 | 0.07 |
| 14 | Igdlugdlip Sermia | 2230 | 356 | 16 | 0.12 | 0.01 |
| 15 | | 262 | 44 | 17 | -0.18 | 0.03 |
| 16 | Cornell | 522 | 81 | 15 | 0.45 | 0.20 |
| 17 | | 189 | 102 | 54 | -0.11 | 0.01 |
| 18 | | 5255 | 548 | 10 | -0.62 | 0.38 |
| 19 | Upernavik Isstrom | 3285 | 261 | 8 | -0.18 | 0.03 |
| 20 | | 2260 | 355 | 16 | 0.01 | 0.00 |
| 21 | Rink | 4542 | 452 | 10 | -0.78 | 0.61 |
| 22 | Kangerdlugssup Sermerssua | 1763 | 796 | 45 | 0.18 | 0.03 |
| 23 | Kangilleq Isbrae | 1613 | 302 | 19 | no data | no data |
| 24 | Sermilik | 1483 | 317 | 21 | -0.74 | 0.54 |
| 25 | Store | 3824 | 361 | 9 | -0.33 | 0.11 |
| 26 | Jakobshavn | 10421 | 4042 | 39 | -0.21 | 0.04 |
| 27 | Akugdlerssup Sermia | 1101 | 376 | 34 | -0.05 | 0.00 |
| 28 | Kangiata Nunaata Sermia | 2187 | 292 | 13 | 0.21 | 0.05 |
| 29 | Kangerdlugssuaq | 7594 | 726 | 10 | -0.26 | 0.07 |
| 30 | | 1626 | 123 | 8 | 0.33 | 0.11 |
| 31 | | 3614 | 355 | 10 | -0.64 | 0.41 |
| 32 | | 1865 | 127 | 7 | -0.12 | 0.02 |
| 33 | Unartit | 3972 | 353 | 9 | 0.39 | 0.15 |
| 34 | Midgaard | 2865 | 228 | 8 | 0.68 | 0.46 |
| 35 | Helheim | 6867 | 896 | 13 | -0.38 | 0.15 |
| 36 | | 3465 | 145 | 4 | -0.60 | 0.36 |
| 37 | | 2136 | 130 | 6 | -0.17 | 0.03 |
| 38 | | 2358 | 168 | 7 | -0.01 | 0.00 |
| 39 | | 3035 | 298 | 10 | -0.36 | 0.13 |
| 40 | Ikertivaq | 1900 | 207 | 11 | -0.66 | 0.43 |
| 41 | | 9599 | 984 | 10 | -0.75 | 0.57 |
| 42 | | 3784 | 161 | 4 | -0.45 | 0.20 |
| 43 | | 4348 | 333 | 8 | -0.59 | 0.35 |
| 44 | | 4234 | 474 | 11 | -0.19 | 0.04 |
| 45 | A. P. Bernstorff | 3495 | 354 | 10 | -0.51 | 0.26 |
| 46 | Maelkevejen | 2032 | 342 | 17 | no data | no data |
| 47 | Skinefaxe | 2157 | 540 | 25 | -0.15 | 0.02 |
| 48 | Rimfaxe | 2225 | 454 | 20 | 0.65 | 0.42 |
| 49 | Heimdal | 2659 | 1507 | 57 | 0.35 | 0.12 |
| 50 | | 4524 | 210 | 5 | -0.54 | 0.29 |
| 51 | | 2595 | 178 | 7 | -0.18 | 0.03 |
| 52 | | 1684 | 281 | 17 | -0.24 | 0.06 |
| 53 | | 4236 | 344 | 8 | -0.40 | 0.16 |
| 54 | | 3396 | 709 | 21 | -0.86 | 0.74 |
| 55 | | 1514 | 272 | 18 | -0.47 | 0.22 |

# Appendix C

Table S1. Extended data records for mélange condition and terminus change for 1999-2008. For mélange condition: 1=rigid, 0.5=mixed, 0=open.

| Glacier | Mélange condition | Start of mélange condition (decimal date) | End of mélange condition (decimal date) | Linear trend in terminus change (m/yr) | Total terminus change over period (m) | Number of terminus data points during period |
|---|---|---|---|---|---|---|
| G1 | 1 | 2000.2295 | 2000.4918 | 235 | -9 | 4 |
| G1 | 1 | 2001.211 | 2001.4548 | 1239 | 334 | 6 |
| G1 | 0 | 2001.5425 | 2001.7616 | -1480 | -327 | 3 |
| G1 | 1 | 2002.2438 | 2002.3507 | 1511 | 127 | 4 |
| G1 | 0 | 2002.6137 | 2002.6521 | -6982 | -250 | 3 |
| G1 | 1 | 2003.2219 | 2003.4027 | 638 | -50 | 5 |
| G1 | 1 | 2004.2732 | 2004.3661 | -4767 | -232 | 4 |
| G1 | 1 | 2005.2219 | 2005.4164 | 1161 | 184 | 4 |
| G1 | 1 | 2006.3178 | 2006.4685 | 1154 | 203 | 5 |
| G1 | 1 | 2007.1945 | 2007.4767 | 854 | 172 | 3 |
| G1 | 0 | 2007.5644 | 2007.6466 | -760 | -3 | 3 |
| G1 | 0 | 2008.5082 | 2008.7022 | 731 | 67 | 7 |
| G7 | 0 | 1999.7096 | 1999.7781 | 214 | 29 | 4 |
| G7 | 1 | 2000.2842 | 2000.4344 | -267 | -32 | 7 |
| G7 | 0 | 2000.5847 | 2000.7842 | 169 | 36 | 4 |
| G7 | 1 | 2001.1781 | 2001.4411 | 9 | -18 | 11 |
| G7 | 0 | 2001.5041 | 2001.7863 | -314 | -105 | 8 |
| G7 | 1 | 2002.1863 | 2002.3863 | 74 | 18 | 11 |
| G7 | 0 | 2002.4932 | 2002.6685 | -280 | -27 | 8 |
| G7 | 1 | 2003.2137 | 2003.4082 | -171 | -27 | 5 |
| G7 | 1 | 2004.2213 | 2004.377 | -309 | -59 | 5 |
| G7 | 0 | 2004.5273 | 2004.7213 | -40 | -10 | 4 |
| G7 | 0 | 2005.5589 | 2005.6712 | -418 | -27 | 6 |
| G7 | 1 | 2006.2356 | 2006.4164 | 16 | -13 | 9 |
| G7 | 0 | 2006.5178 | 2006.7233 | -18 | -2 | 4 |
| G7 | 0 | 2007.5068 | 2007.7315 | -331 | -83 | 8 |
| G7 | 1 | 2008.2322 | 2008.388 | -157 | -23 | 4 |
| G7 | 0.5 | 2008.4262 | 2008.4699 | -3944 | -16 | 3 |
| G7 | 0 | 2008.4891 | 2008.6694 | -493 | -54 | 6 |
| HA | 1 | 2000.2842 | 2000.4344 | 1157 | 121 | 6 |
| HA | 0 | 2000.6721 | 2000.7842 | -1828 | -187 | 3 |

| | | | | | | |
|---|---|---|---|---|---|---|
| HA | 1 | 2001.1781 | 2001.3973 | 133 | 118 | 8 |
| HA | 0.5 | 2001.4164 | 2001.5041 | 576 | 31 | 4 |
| HA | 0 | 2001.5671 | 2001.7863 | -103 | -78 | 4 |
| HA | 1 | 2002.1863 | 2002.3863 | -1745 | -314 | 8 |
| HA | 0.5 | 2002.4055 | 2002.5808 | -612 | -150 | 4 |
| HA | 0 | 2002.6055 | 2002.6685 | 4154 | 271 | 3 |
| HA | 1 | 2003.2137 | 2003.4082 | 3 | 26 | 5 |
| HA | 0 | 2003.5452 | 2003.7205 | -1458 | -252 | 4 |
| HA | 1 | 2004.2213 | 2004.3525 | 313 | 16 | 4 |
| HA | 1 | 2005.2904 | 2005.4219 | -502 | -22 | 5 |
| HA | 0.5 | 2005.4658 | 2005.5589 | -1290 | -119 | 3 |
| HA | 0 | 2005.6027 | 2005.7151 | -4042 | -474 | 4 |
| HA | 1 | 2006.2356 | 2006.3863 | 1392 | 169 | 4 |
| HA | 0 | 2006.5863 | 2006.7233 | -1246 | -95 | 4 |
| HA | 1 | 2007.1616 | 2007.3945 | -1931 | -181 | 4 |
| HA | 0.5 | 2007.4192 | 2007.6137 | 192 | 77 | 5 |
| HA | 1 | 2008.2322 | 2008.388 | 1941 | 257 | 5 |
| HA | 0.5 | 2008.4262 | 2008.5137 | 1085 | 95 | 3 |
| SV | 1 | 2000.2295 | 2000.4918 | 13 | -62 | 5 |
| SV | 0 | 2000.5738 | 2000.7732 | -904 | -190 | 4 |
| SV | 1 | 2001.1863 | 2001.474 | -215 | 13 | 9 |
| SV | 0 | 2001.5425 | 2001.7863 | -559 | -183 | 8 |
| SV | 1 | 2002.2247 | 2002.463 | -276 | -39 | 10 |
| SV | 0 | 2002.5315 | 2002.663 | -112 | -2 | 6 |
| SV | 1 | 2003.2137 | 2003.4082 | -185 | -76 | 9 |
| SV | 0 | 2003.5342 | 2003.6466 | -1305 | -31 | 3 |
| SV | 1 | 2004.2213 | 2004.347 | 1776 | 203 | 5 |
| SV | 1 | 2004.4399 | 2004.4781 | 394 | 5 | 3 |
| SV | 0.5 | 2004.5273 | 2004.7022 | -6642 | -722 | 3 |
| SV | 1 | 2005.2219 | 2005.4219 | 3237 | 545 | 8 |
| SV | 0.5 | 2005.5534 | 2005.5918 | -718 | -30 | 3 |
| SV | 1 | 2007.1753 | 2007.4192 | 1535 | 236 | 5 |
| SV | 0 | 2007.5507 | 2007.7014 | -2212 | -469 | 5 |
| SV | 1 | 2008.2514 | 2008.4699 | 67 | 19 | 4 |
| SV | 0.5 | 2008.4836 | 2008.5273 | 3811 | 166 | 5 |
| SV | 0 | 2008.571 | 2008.7022 | -8096 | -1128 | 6 |