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Special Section:
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Key Points:
- Strong correspondence between melange conditions and terminus change
- Extended melange-free periods correspond with interannual retreat and speedup
- Seasonal and interannual speedup primarily linked to different mechanisms

Supporting Information:
- Text S1
- Table S1

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Seasonal to multiyear variability of glacier surface velocity, terminus position, and sea ice/ice mélange in northwest Greenland

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Abstract Glacier ice discharge, which depends on ice velocity and terminus fluctuations, is a primary component of Greenland Ice Sheet mass loss. Some research suggests that ice mélange influences terminus calving, in turn affecting glacier velocity. The details and broad spatiotemporal consistency of these relationships, however, is undetermined. Focusing on 16 northwestern Greenland glaciers during 2009 through summer 2014, we examined seasonal surface velocity changes, glacier terminus position, and sea ice and ice mélange conditions. For a longer-term analysis, we also produced extended records of four glaciers from 1999 to 2014. There is a strong correspondence between seasonal near-terminus sea ice/mélange conditions and terminus change, with rigid ice mélange conditions associated with advance and open water associated with retreat. Extended sea ice-free periods and reduced rigid mélange are also linked with anomalously large terminus retreat. In all but one case, sustained multiyear retreat of greater than 1 km during both the 15 year and 6 year records was accompanied by interannual velocity increases. Seasonal velocity patterns, however, correspond more strongly with runoff changes than terminus behavior. 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 multiyear speedup. Longer melt seasons and earlier breakup of mélange may also alter the timing of seasonal ice flow variability.

1. Introduction

Ice loss from the Greenland Ice Sheet is an important component of global sea level rise, with current ice mass losses of 260–380 Gt/yr (contributing ~0.7–1.1 mm/yr to sea level) [*Shepherd et al.*, 2012; *Enderlin et al.*, 2014]. 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]. Projecting future ice discharge is critical for understanding the magnitude and timing of sea level rise. Such projection, however, 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 topography [*Joughin et al.*, 2012b; *Straneo et al.*, 2013]. Exacerbating the challenge are the complexity of outlet glacier systems and the likelihood that the influence of different contributing factors (e.g., bed profile, fjord circulation, and surface melt) varies from glacier to glacier and from year to year.

Previous research has identified several mechanisms that may control changes in outlet glacier behavior, particularly near the terminus:

1. 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.*, 2008a; *Amundson et al.*, 2010; *Howat et al.*, 2010].
2. Terminus advance, retreat, and/or thinning influence 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].
3. 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.*, 2010; *Motyka et al.*, 2011; *Sciascia et al.*, 2013].
4. The position of the terminus relative to basal topography (e.g., overdeepening or sills) influences rates of retreat for a given forcing [e.g., *Oerlemans and Nick*, 2005; *Joughin et al.*, 2012a; *Enderlin et al.*, 2013a, 2013b].

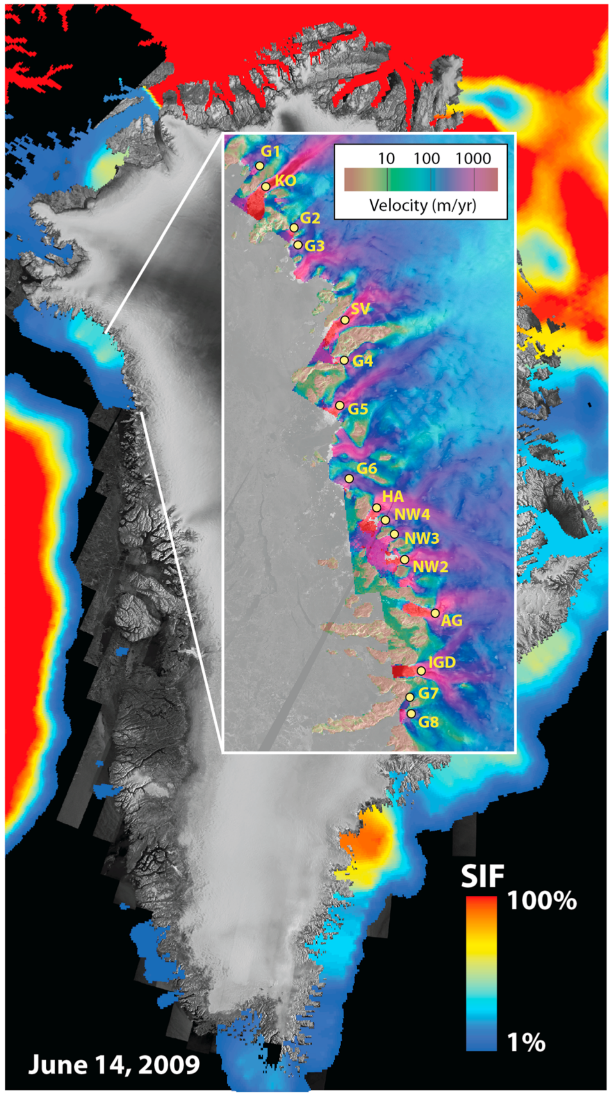

Figure 1. Locations of the 16 northwest glaciers examined in this study. Background image shows a snapshot of late spring sea ice fraction (SIF) around Greenland (black indicates no sea ice), with a RASARSAT mosaic of the ice sheet and land surface. Inset image includes composite winter velocities from 2007 to 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.

However, integrative studies that look at the influence of multiple mechanisms across varying time scales are lacking. To address this need, we focus primarily on the first two mechanisms, examining seasonal to interannual ice flow speed, terminus position, and sea ice and ice mélange conditions. Summer melt runoff is considered in a more limited context.

For this study, we focused on 16 marine-terminating glaciers in northwest Greenland (Figure 1). We chose this region because it includes glaciers with varying characteristics, including mean annual velocity, bed depth [*Allen*, 2013], and fjord setting, but which experience similar climate variability. The study region also spans a transition zone at Melville Bay, within 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 Figure 1). This contrast allows for a better evaluation of how sea ice and mélange may influence outlet glacier behavior. To observe multiple time scales, this study includes two parts: (1) a primary focus on seasonal and short multiyear changes for all 16 glaciers from 2009 to late 2014 and (2) a longer-term record for 4 glaciers beginning in late 1999. Finally, 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.

In this paper, we concentrate on glacier velocity and terminus behavior and the link among dynamics, timing of surface meltwater availability, and the condition (i.e., potential for rigidity) of the ice mélange in contact with the glacier termini. Six of the glaciers in our study were previously examined by *Carr et al.* [2013a], who looked primarily at terminus behavior and its connection with topography and, to some extent, ocean and air temperatures. By leveraging the geographic overlap of some study glaciers, we expand on the analysis of *Carr et al.* [2013a] while also providing new insights into the seasonal to multiyear mechanisms controlling glacier velocity.

2. Methods

We used a variety of data sets to create seasonal-scale records of ice flow velocities, terminus positions, and near-terminus mélange conditions for 16 northwest outlet glaciers from 2009 to 2014. Our analysis also

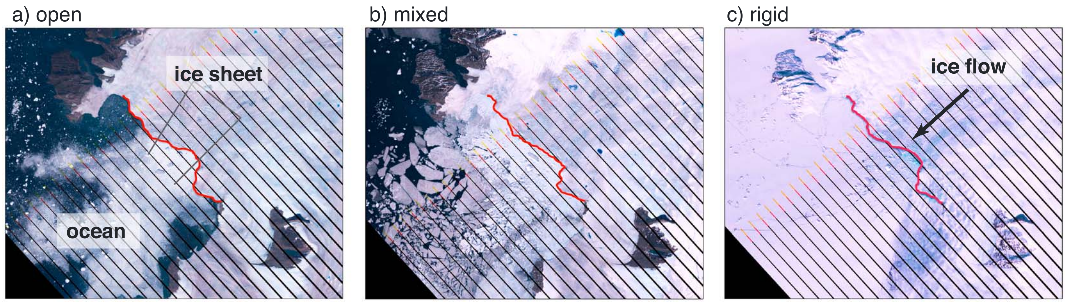

Figure 2. Landsat images (with gaps from SLC failure) showing (a) open, (b) mixed, and (c) rigid mélange conditions at the terminus of G5. Digitized terminus position indicated by red line and glacier bounding box (grey) shown in Figure 2a.

incorporated modeled estimates of surface runoff. Finally, for four glaciers, we extended our records back to 1999 using additional satellite imagery and annual velocity measurements for 2000 and 2005–2008.

2.1. Seasonal Velocity

Using a combination of speckle tracking and interferometric algorithms applied to synthetic aperture radar (SAR) data from the German Space Agency's (Deutsches Zentrum für Luft- und Raumfahrt (DLR)) TerraSAR-X satellite [*Joughin*, 2002; *Joughin et al.*, 2010], we measured ice flow velocity with approximately once-per-season sampling for each glacier during 2009–2014. The availability of appropriate SAR data determined the study period for this research, and we used all available data to construct the velocity time series. There are three to five velocity measurements per year for each glacier during 2009–2013, with higher sampling during 2014 (except for G3, which was only measured twice during 2010 and 2014). We define winter as January–March, spring as April–June, summer as July–September, and fall as October–December, and the timing for velocity measurements is roughly mid-February, early May, mid-July, early September, and late November. 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 TerraSAR-X data are strip-map mode data, with resolution of ~2 m/pixel. Velocities are estimated by cross correlating patches from the images in a pair every 24 pixels [*Joughin*, 2002]. The square patch sizes vary from 48 to 98 pixels, depending on the match quality (i.e., larger patches are used for regions of poor correlation). These offset data are smoothed with a moving average filter to a resolution of ~300 m. The velocity estimates, however, are oversampled to a 100 m grid. Errors for fast-flowing ice are ~3%, although relative accuracy (precision) is substantially better because errors are geometry dependent and the map for each glacier was created using a consistent viewing geometry [*Joughin*, 2002; *Joughin et al.*, 2010]. We may not sample each glacier's annual minimum and maximum velocity because observations do not capture speed variations between measurement periods. We do, however, capture broad seasonal velocity patterns and provide the highest resolution velocity record available for these glaciers.

2.2. 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 based on topography and velocity structure (e.g., Figure 2). 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) [*Moon and Joughin*, 2008].

Using the TerraSAR-X (20 m resolution) image pairs, we measured two terminus positions that are nearly coincident with each velocity measurement. We also used visible band images (30 m resolution) from the Landsat 7 Enhanced Thematic Mapper Plus and Landsat 8 Operational Land Imager to produce a more complete record. 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 in 26 March 2009).

Errors in manual terminus digitization were assessed by repeated digitization of single TerraSAR-X and Landsat 7 images. We digitized the termini of 4 glaciers 10 times each in a TerrSAR-X image and a Landsat

7 image, yielding root-mean-square digitization errors of 24 m and 25 m, respectively. For both TerraSAR-X and Landsat 7 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., $>2\sigma$). 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., Figure 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 (not linear) 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). If these criteria were met, we linearly interpolated between visible terminus locations on either side of the SLC gap.

2.3. Mélange Condition

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 do not distinguish between them. Also, rigid mélange most commonly occurs when sea ice forms, binding together icebergs and bergy bits to create a (semi)rigid material [*Amundson et al*., 2010]. We also assessed sea ice and mélange together, and so, to simplify terminology, we will refer to all ice seaward of the terminus as "mélange," although in some instances, it may be entirely sea ice.

In this study, we used multiple methods for assessing the sea ice concentration and potential rigidity of the near-terminus mélange at each glacier. Our primary data set 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 speckle tracking measured velocity in front of the terminus, it indicated rigid or nearly rigid mélange behavior [*Joughin et al*., 2008a]. However, because of the limited number of TerraSAR-X velocity measurements, this method provided limited data points (2 to 8 per glacier). Thus, the vast 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 (roughly 10 km) 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) (Figure 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. An "open" classification required open water or extensive mélange motion as compared to other near-time images. 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, for example, in misidentification of ocean-surface characteristics. We evaluated the consistency of visual analysis by comparing the TerraSAR-X velocity observations of rigid mélange with the visual analysis results during 2009–2012. Visual analysis creates two near coincident observations for each TerraSAR-X velocity measurement. Visual analysis agreed fully with velocity-assessed rigidity 72% of the time, with partial agreement (one rigid observation, one 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 2009–2014 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 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 individual glacier termini. We also evaluated the agreement between the daily SIF product and our record of mélange condition.

2.4. Ice Sheet Meltwater Runoff

We used modeled runoff results for qualitative comparison of glacier behavior and meltwater availability. Daily runoff data for 2009–2013 are from the Royal Netherlands Meteorological Institute Regional Atmospheric Climate Model v2.3 (RACMO2.3) [*van Meijgaard et al*., 2008; *Lenaerts et al*., 2013; *van Angelen et al*., 2013;

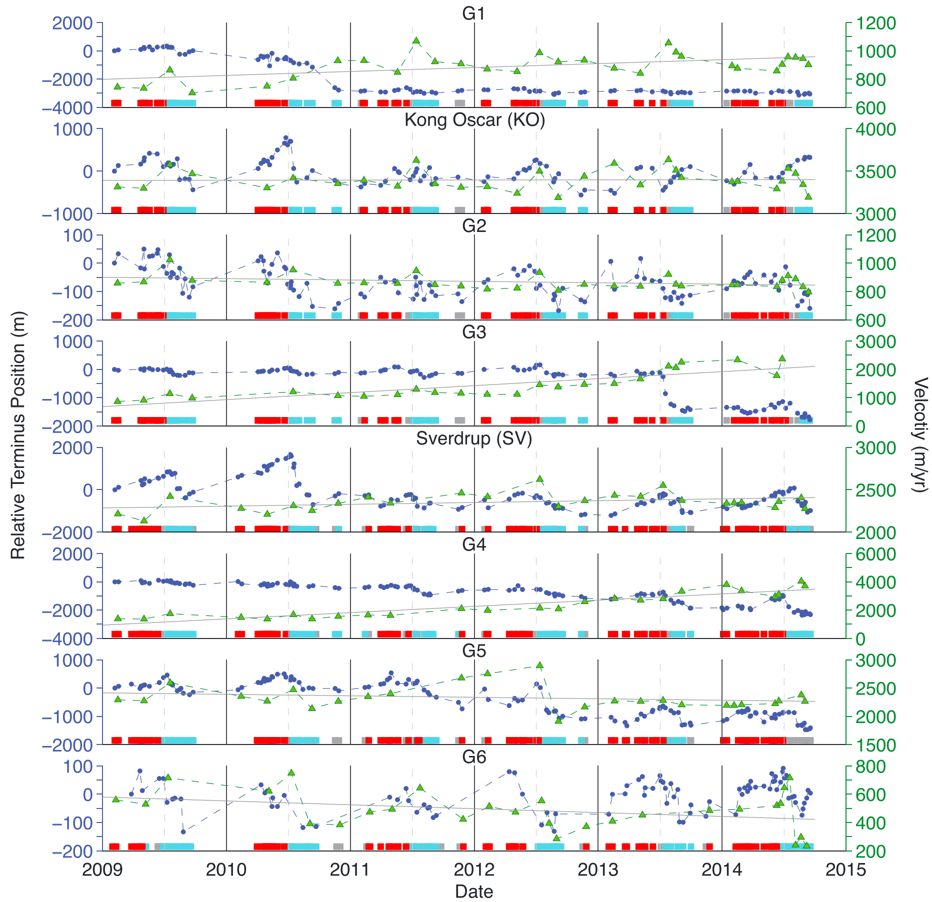

Figure 3. Terminus position (blue circles), velocity (green triangles) with linear trendline (grey), and mélange conditions (red = rigid, grey = mixed, and blue = open) for the eight northernmost glaciers for 2009–2014. Note different scales used for each glacier.

van As et al., 2014], the most recent model version available. Model results for 2014 are not available. RACMO2.3 data were sampled at locations ~10 km up glacier from the velocity measurements to stay within the model's ice mask edge.

2.5. Extended Glacier Records

We chose four glaciers to examine for 1999–2014 to gain insight on longer-term change. We selected G1, SV, HA, and G7 because they have a range of mean ice velocities that represent the full northwest study group (Table 2). We used the visual analysis methods described above with Landsat images from late 1999 to 2008 to extend the terminus and mélange records for each of these glaciers to 15 years. Winter velocity measurements for 2000/20001 and 2005/2006–2008/2009 extend the velocity data set and are derived using SAR data from TerraSAR-X, the Japanese Advanced Land Observation Satellite, and the Canadian Space Agency's RADARSAT-1 [*Joughin et al*., 2010; *Moon et al*., 2012]. The ability to extrapolate results from these four glaciers to the broader northwest region is limited by the diversity of glaciers within the study. Nonetheless, analysis of this subset is an important step in understanding decade-scale glacier and environment interactions.

3. 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. Figures 3 and 4 show the 2009–2014 velocities, terminus positions, and mélange conditions for all

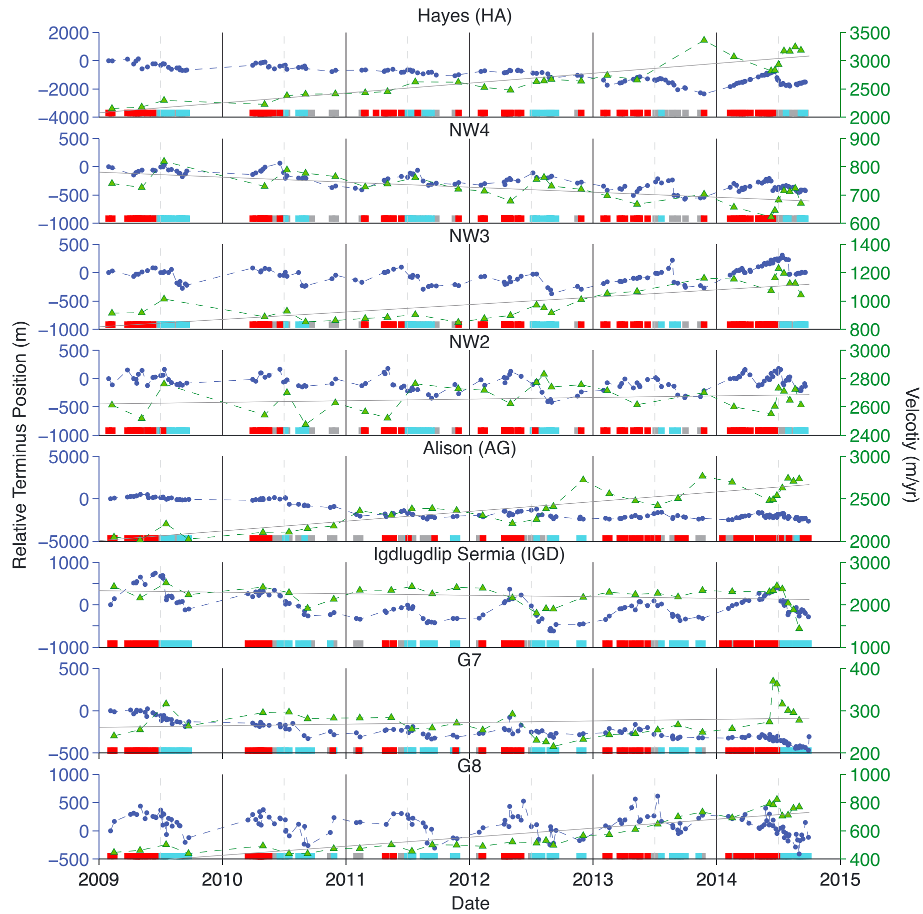

Figure 4. Terminus position (blue circles), velocity (green triangles) with linear trendline (grey), and mélange conditions (red = rigid, grey = mixed, and blue = open) for the eight southernmost glaciers for 2009–2014. Note different scales used for each glacier.

glaciers, providing seasonal to interannual detail. Table 1 lists key parameters for each glacier. Together, our results reveal strong seasonal patterns, connections between glacial and sea surface changes, and likely differences in the strength of environmental mechanisms in influencing seasonal versus multiyear velocity behavior.

3.1. Velocity Patterns

Our study group includes glaciers with 2009–2014 mean velocities ranging from 268 m/yr (G7) to 3392 m/yr (KO), with both increasing and decreasing velocity trends over the 4 year record (Table 1). The largest increasing velocity trends are for G4, HA, AG, and G3 (115–441 m/yr^2). Four other glaciers also have increasing velocity trends greater than 20 m/yr^2. Decreasing velocity trends are generally smaller magnitude; only G5, G6, and IGD slow at rates exceeding 20 m/yr^2, with the greatest slowing at 36 m/yr^2. Interannual trends on the remaining five glaciers are comparable to measurement error. Figure 5c shows the mean velocity (using monthly interpolated data) for all 16 glaciers, reflecting an overall speedup.

A valuable result of our study is the seasonal-scale record of velocity patterns. We also provide data through middle to late 2014, extending the records presented in *Moon et al.* [2014]. Measurements in approximately early May and mid-July allowed for comparison of spring and summer velocities throughout the record for most glaciers (Figures 3 and 4). For SV, G4, and G5, we compared end of April to late November in 2011 and mid-February to mid-July during 2012. We also compared early May to late November for G6, HA, and NW2-NW4 in 2013. Our measurements indicate a strong pattern of spring to summer speedup; glaciers sped up from spring to summer 87% (76 of 87) of the time. On average, those glaciers that sped up

Table 1. Velocity and Terminus Position Data for 2009–2014[a]

Glacier	Latitude	Longitude	6 year Mean Velocity (m/yr)	Linear Velocity Trend (m/yr^2) Linear Velocity Trend (m/yr^2)	Total Measured Terminus Position Change (m)	Annual Range in Terminus Position (m)						
						2009	2010	2011	2012	2013	2014	6 year mean
G1	76.08	−59.90	871	28	−3050	580	2600	390	420	260	290	760
KO	76.01	−59.73	3392	2	320	860	1080	460	830	630	640	750
G2	75.89	−59.16	868	−10	−160	170	200	90	160	160	150	150
G3	75.83	−59.05	1391	247	−1780	250	230	370	390	1410	640	550
SV	75.60	−58.10	2368	21	−990	1230	2360	690	1030	1030	1140	1250
G4	75.46	−57.97	2206	441	−2320	360	480	690	900	1120	1410	830
G5	75.29	−57.89	2378	−26	−1410	690	600	1270	1250	700	740	880
G6	75.04	−57.53	512	−27	0	210	150	100	210	160	170	170
HA[b]	74.96	−57.06	2597	175	−1520	830	680	460	550	1210	1080	800
NW4[b]	74.92	−56.90	727	−18	−430	210	430	350	220	360	240	300
NW3[b]	74.87	−56.74	974	52	0	360	320	390	350	490	350	380
NW2[b]	74.79	−56.53	2654	11	−130	290	310	520	550	350	390	400
AG[b]	74.62	−55.95	2343	115	−2650	670	1160	990	1180	820	1000	970
IGD[b]	74.40	−56.00	2249	−36	−280	870	610	420	990	460	700	670
G7	74.30	−56.08	268	4	−310	210	190	150	240	170	190	190
G8	74.24	−56.03	546	64	−120	640	640	610	770	660	810	690
Mean			*1647*	*65*	*−920*	*530*	*750*	*500*	*630*	*620*	*620*	*610*

[a]Total measured terminus position change compares the last 2014 measurement to the first 2009 measurement. The 6 year mean velocity is calculated using monthly interpolated velocity data to avoid sampling bias.
[b]Glaciers included in *Carr et al.* [2013a].

increased their speed by 145 m/yr. In most cases, the spring to summer speedup was the largest velocity increase during the year.

In many cases, the subsequent summer to fall slowing was the largest slowdown during the year, but with some exceptions. For example, HA had notable speedup every spring during the record, but little

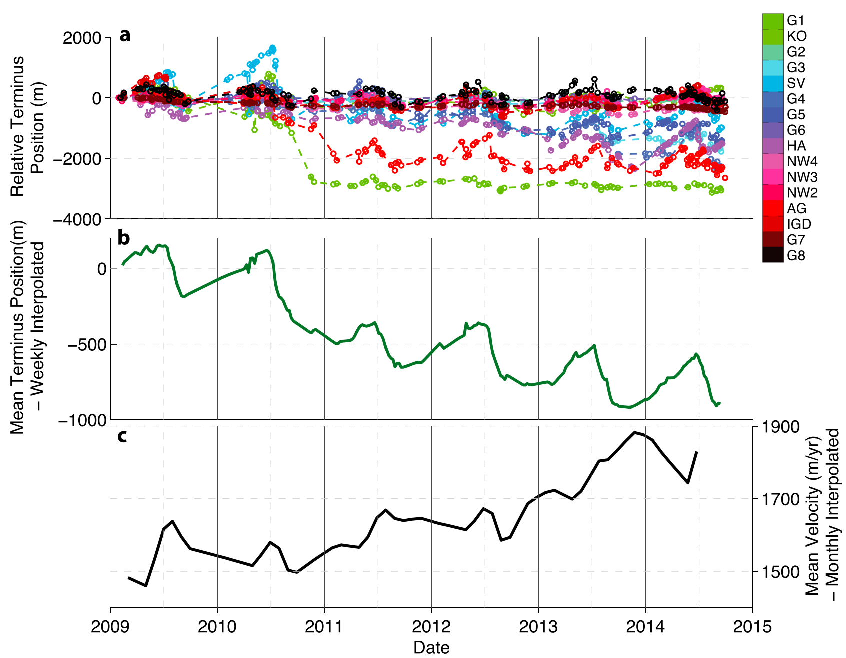

Figure 5. Time series with (a) full record of terminus positions for all 16 glaciers (displayed by color in north to south order), (b) total mean terminus position using weekly interpolated data, and (c) total mean velocity using monthly interpolated data (late 2014 not shown because of missing data for glacier G3).

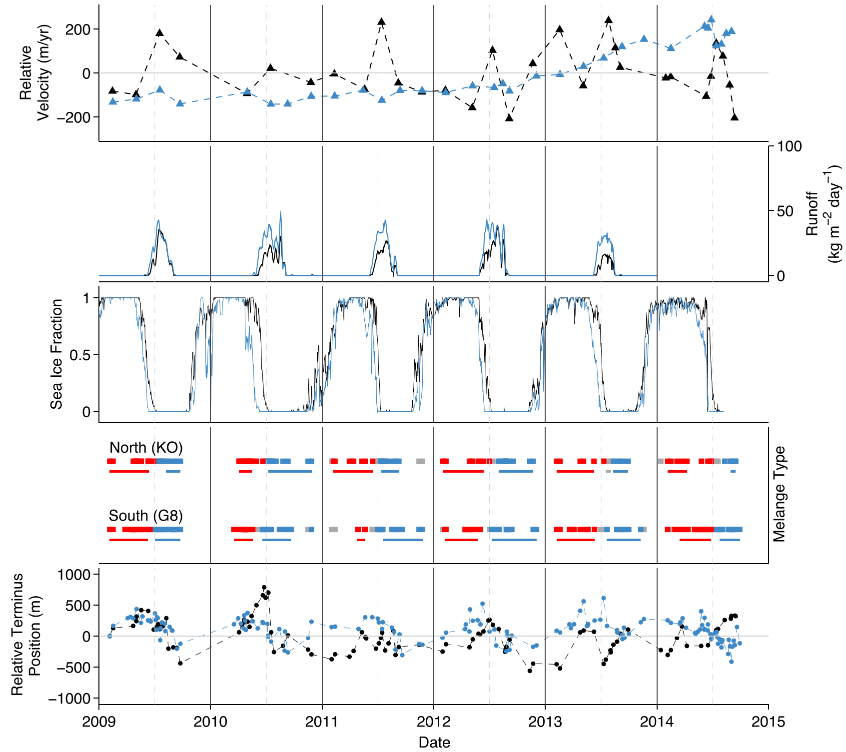

Figure 6. Data for the second most northern (KO, black) and most southern (G8, blue) study glaciers during 2009–2014 for (a) relative ice flow velocity (normalized by subtracting 6 year mean velocity), (b) runoff from RACMO2.3 (2014 not available), (c) sea ice fraction from OSTIA, (d) mélange type from 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.

subsequent slowing in 2009–2012. Even the large slowdown on HA from late 2013 to mid-2014 did not return the velocity to early 2013 speeds (Figure 4).

All but one exception to the pattern of spring to summer speedup occurred in the four southernmost glaciers. In most cases, however, these southern glaciers sped up during the preceding winter to spring measurement. The seasonal patterns for the four southernmost glaciers may be connected to differences in their hydrologic systems, as discussed in *Moon et al*. [2014]. Their velocity patterns in many years are consistent with early speedup due to increasing water pressure and a subsequent large slowdown during the melt season, likely due to development of an efficient subglacial drainage system. The same is not true of the more northern glaciers, which lack anomalous velocity lows in middle to late summer.

3.2. Terminus Change

Using the Landsat and TerraSAR-X data sets from 2009 to 2014, we produced an average of 125 terminus measurements for each glacier. In addition to the results shown in Figures 3 and 4, Figure 5a shows the complete terminus records for every individual glacier. Measurements are sparse during late 2009 to early 2010 due to a lack of available TerraSAR-X or Landsat 7 images, but we otherwise have relatively consistent year to year coverage. Thirteen glaciers retreated between the first measurement in 2009 and the final 2014 measurement. The largest changes occurred at G1 and AG, and G3, G4, G5, and HA also retreated more than 1 km (Table 1 and Figure 5a).

Seasonally, there is a strong signal of advance and retreat for all years. This is apparent in the mean regional terminus behavior (Figure 5b) and in individual glacier records (Figures 3 and 4). Longer, more continuous winter through spring advance is followed by a sharp retreat roughly coincident with the onset of the summer quarter (July). We find a mean annual difference between maximum and minimum terminus positions of 610 m (Table 1). Looking only at the glaciers also studied by *Carr et al*. [2013a], our mean

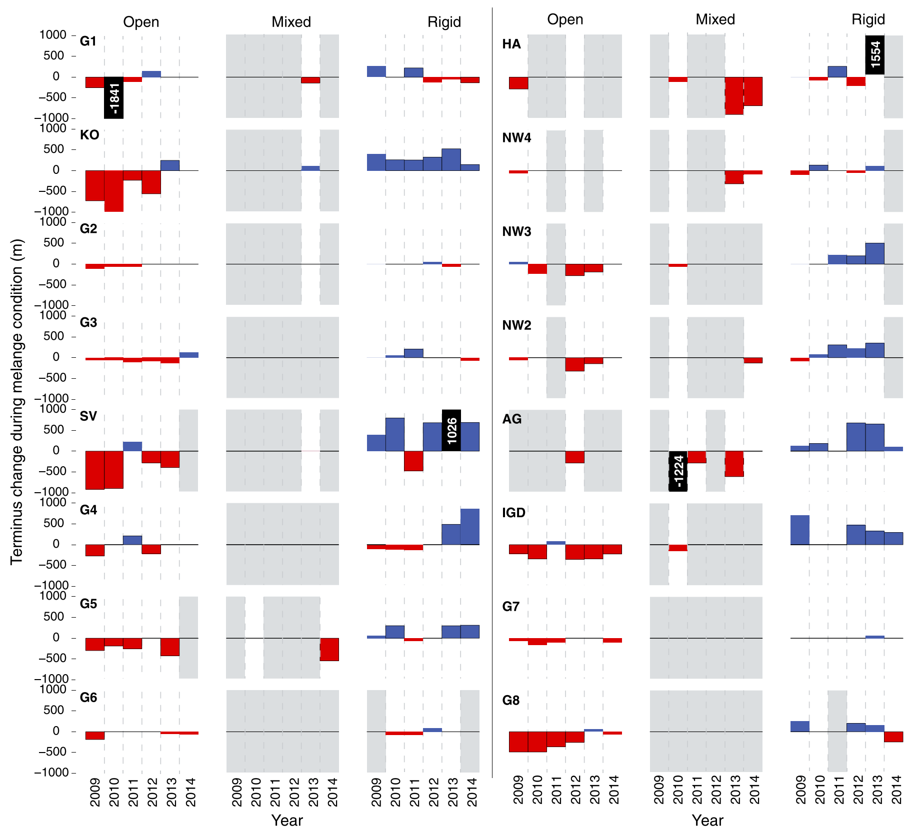

Figure 7. Observed terminus change during open, mixed, and rigid mélange conditions. Consistent mélange conditions must be observed for at least 2 weeks and have >2 terminus position observations during the period; grey indicates that no observations met these requirements. On average, mélange/terminus observation windows cover ~50% of each year, and terminus changes during the remainder of each year are not shown. The black bars show advance/retreat >1000 m, with value labeled. No bar indicates that terminus change was <50 m.

annual terminus variation is 590 m, substantially larger than the 400 m range they found for 2004–2010. This increase is due largely to a rough doubling in terminus position range for HA during 2013 and 2014 (Table 1).

Carr et al. [2013a] noted two prominent modes of terminus retreat: (1) large, stepwise retreat often in an isolated instance and (2) slower, more gradual retreat. We also observe evidence of this dichotomy. On glaciers that retreated more than 900 m, four (G4, G5, HA, and AG) retreated steadily and three (G1, G3, and SV) had a notable stepwise recession (Figures 3 and 4). Examining Landsat images for each of these glaciers, we find that all three instances of stepwise retreat are linked with topographic changes (e.g., glacier lost contact with pinning point) that are clearly visible in the satellite data.

3.3. Mélange Condition and Terminus Change

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 consistent mélange conditions, we only examined periods for which (1) the observed mélange condition, as recorded in our analysis data set, continued for at least 2 weeks, and (2) more than two 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., Figures 3 and 4 and Figure 6d).

Using the above criteria, we compiled between 9 and 15 mélange/terminus observation intervals for each glacier during 2009–2014, with an average of 13 intervals per glacier (e.g., Figure 6d). Most commonly, we recorded one period with open conditions and one with rigid conditions each year (the complete data set includes 83 open periods, 24 mixed periods, and 99 rigid periods). Figure 7 summarizes the terminus

Table 2. Velocity and Retreat Data for Extended Record Glaciers

Glacier	2000/2001 Winter Velocity (m/yr)	Last Measured 2014 Velocity (m/yr)	Velocity Increase (% of 2000/2001 Velocity)	1999–2014 Total Retreat (m)	Mean Retreat Rate (m/yr)
G1	382	857	125%	2550	169
SV	1255	2276	81%	4140	275
HA	1887	3185	69%	2030	135
G7	133	278	109%	770	51

position changes measured during observation windows for each mélange type. The mélange observation windows cover ~50% of each year, so additional changes in terminus position occurring during the remainder of the year are not shown. A quarter to a third of the observation windows (depending on mélange type) coincided with no notable terminus change.

During periods with significant terminus fluctuations (>50 m), we find a strong correspondence between mélange condition and terminus advance or retreat. During open conditions with notable terminus change, retreat occurred 86% of the time and advance only 14%. By contrast, during rigid conditions with terminus change greater than 50 m, 72% coincided with advance and 28% with retreat. The average length of our observation window for open conditions was 65 days with mean retreat of 170 m. For rigid conditions, the average advance was 350 m over 124 days of observation.

There are only a few instances of mixed mélange in our data, primarily during 2010, 2013, and 2014 (Figure 7). Within this sample, most periods (63%) of mixed conditions coincided with retreat greater than 50 m, with five instances surpassing 500 m. In only three cases did the glacier terminus advance more than 50 m during mixed mélange conditions.

3.4. Extended Records

Turning our attention to the more expansive 15 year records, we found that G1, Sverdrup, Hayes, and G7 all receded substantially between 1999 and 2014, with simultaneous increases in velocity (Table 2 and Figure 8). The data indicate open and rigid mélange conditions for each glacier during most years (Figure 8). Although fewer mélange/terminus observation windows met our strict criteria for persistent mélange conditions

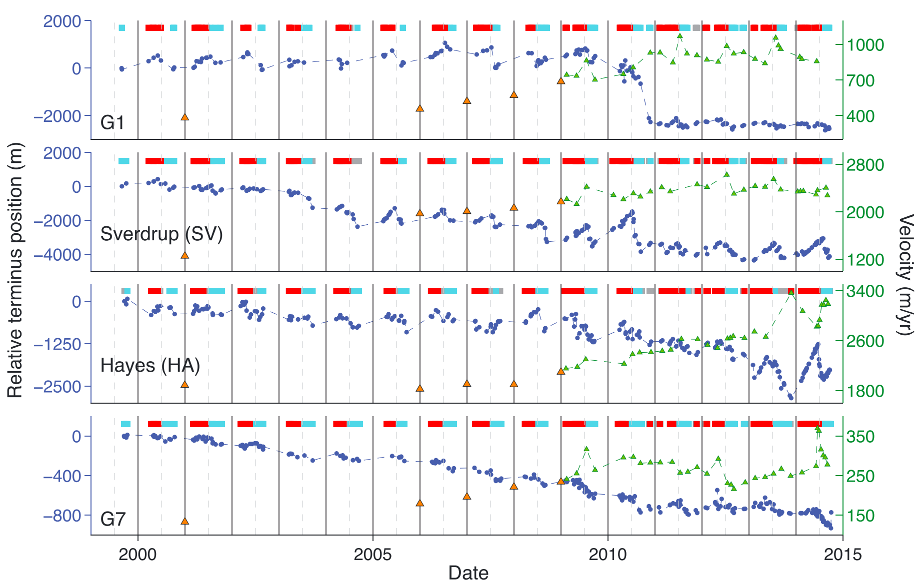

Figure 8. Terminus position (blue circles), annual winter velocities for 2000/2001 and 2005/2006–2008/2009 (orange triangles with bars indicating sample period), TerraSAR-X seasonal velocities for 2009–2014 (green triangles), and mélange conditions (red = rigid, grey = mixed, and blue = open) for late 1999 through 2014. Note different scales used for each glacier.

(Table S1 in the supporting information), the onset of retreat generally coincided with the end of the winter rigid ice period (Figure 8).

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, although winter velocity measurements show interannual speedup beginning by 2006 (Figure 8). 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, and interannual velocity was also relatively stable after 2010. We observed only four intervals of continuous (>2 weeks) open water during 1999–2008, with notable (>50 m) retreat during two periods and advance during one period (Table S1 in the supporting information). Of eight pre-2009 rigid intervals, five coincide with terminus advance and two with retreat.

Sverdrup Glacier retreated ~4 km from summer 1999 to late 2014, with relatively steady retreat through at least 2012 (Figure 8). Velocity increased steadily through 2011, with a potentially higher rate during 2001–2006 than for 2006–2011. Beginning in about 2004, the amplitude of the spring/summer terminus change increased and the late summer terminus position retreated for 2006 through 2012. The largest seasonal advance occurred in 2010, followed by small seasonal advances in 2011 and 2012 and a return to higher amplitude fluctuations in 2013 and 2014. 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 S1 in the supporting information).

Hayes Glacier retreated steadily from 1999 to 2013, although at a somewhat reduced rate from late 2005 to late 2008 (Figure 8). The glacier advanced ~1.5 km in early 2014 but then retreated ~1 km during summer 2014. The largest increases in interannual velocity were after 2008, with considerable velocity fluctuations (at least 700 m/yr) in 2013–2014 that correspond to terminus change. Unlike the other glaciers with long-term records, HA fluctuated seasonally by at least 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 S1 in the supporting information). 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 four extended record glaciers, G7 retreated the least (Figure 8). Comparing late summer terminus position from 1999 until 2011, G7 consistently retreated (~50–150 m) during summer with minimal (~0–50 m) spring readvance, producing ~720 m of total retreat. The location of farthest retreat was relatively consistent from 2011 to early 2014, 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). In the summer of 2014, however, the velocity of this glacier spiked as it retreat further. 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 S1 in the supporting information).

For an additional perspective on longer-term changes, we also compared 2009–2014 retreat rates to 1993–2010 rates for glaciers examined by *Carr et al.* [2013a]. We found that retreat rates for AG remained high during 2009–2014, stayed less than 50 m/yr for NW2 and IGD, dropped to zero for NW3, and increased for HA and NW4.

4. Discussion

Previous observation and modeling work indicates that multiple mechanisms may induce ice flow speedup [e.g., *Howat et al.*, 2008; *Joughin et al.*, 2008b; *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.*, 2002]. 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]. In some instances, 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 hydrological changes inducing speedup in Greenland [e.g., *Zwally et al.*, 2002; *Joughin et al.*, 2008b; *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 terminus retreat 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]. Some modeling work [e.g., *Nick et al.*, 2009; *Vieli and Nick*, 2011] 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) time scales [*Nettles et al.*, 2008; *Joughin et al.*, 2008b; *Podrasky et al.*, 2012].

Terminus retreat may be initiated or enhanced 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.*, 2010; *Xu et al.*, 2013]. Finally, some research suggests that substantial ice mélange can suppress calving, and loss of mélange may increase calving [*Joughin et al.*, 2008a; *Amundson et al.*, 2010; *Carr et al.*, 2013b]. However, there is not a clear understanding of how these separate elements connect at different temporal scales and across broad regions, including for glaciers that do not have long, narrow fjords such as those found at Jakobshavn Isbræ and Helheim Glacier. We address this need by examining ice flow speed, terminus position, runoff availability, and ice mélange over seasonal to multiyear periods.

4.1. Mélange Control on Seasonal Terminus Change

Examination of mélange conditions during 2009–2014 reveals strong correspondence between open conditions and glacier retreat and rigid conditions and advance. These results agree well with findings from other studies along the western Greenland coast. Studies on Jakobshavn Isbræ and in the Uummannaq region also found that (1) mélange may inhibit calving and support terminus advance and (2) calving may increase as mélange breaks up [*Sohn et al.*, 1998; *Joughin et al.*, 2008a; *Ahn and Box*, 2010; *Amundson et al.*, 2010; *Howat et al.*, 2010]. *Carr et al.* [2013a] also found a strong connection between terminus advance and retreat and the formation and breakup of mélange during much of the last decade at AG. However, they 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; *Carr et al.*'s [2013a] study focused on monthly measurements, whereas we generally have higher-resolution data for terminus position and mélange condition. Our results also expand the geographic scope over which a terminus and mélange connection has been documented, including a broad range of glaciers with varying velocities and fjord geometries.

Two important additional findings come from our examination of ice mélange. First, our 6 year records and 15 year records show that the onset of retreat commonly coincides with the seasonal decline of the rigid mélange. Our observations do not capture the transition from open to rigid conditions as well as the rigid to open transition (e.g., Figure 6). However, records from SV, NW3, and IGD show evidence that the onset of advance corresponds with the development of rigid mélange (Figures 3 and 4). Future study of the transition from open water to rigid mélange is warranted based on our initial results. Second, the iceberg and bergy bit concentration of the rigid mélange conditions we observe varies, suggesting that full sea ice coverage (i.e., no icebergs) may be sufficient for influencing seasonal terminus behavior.

Other studies have suggested that seasonal subglacial discharge may influence terminus retreat by substantially increasing melt at the terminus [*Motyka et al.*, 2013; *Sciascia et al.*, 2013]. In our study region, seasonal runoff commonly begins before the full loss of sea ice cover (e.g., Figures 6b and 6c). In many instances, terminus advance, which generally corresponds with rigid mélange conditions, continues after the onset of runoff. Subglacial discharge and melt from warmer ocean temperatures, however, may still affect the magnitude of retreat we observe for multiple reasons. First, there may be a lag in a retreat signal associated with runoff. RACMO2.3 results provide data on surface runoff availability, but this melt may not be influencing the subglacial and basal terminus conditions for weeks to months depending on development of each glacier's hydrologic system. Second, the effects of increased melt from discharge may act to increase terminus retreat at a time coincident with the effects of mélange breakout, blending the signal from both changes. Finally, subsurface terminus melt (either from subglacial discharge or warmer ocean water) before the loss of mélange may act to weaken and thin the terminus without causing calving, but increasing the extent of recession after rigid mélange is lost.

4.2. Mechanisms Affecting Seasonal Velocity Change

Spring runoff may be a strong influence on seasonal velocity due to effects on subglacial hydrology. The mean per glacier summer speedup was ~145 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.*, 2008b; *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 these marine-terminating glaciers suggest that the same mechanism—subglacial hydrology—may play a significant role in the observed seasonal velocity changes for our glacier group.

Moon et al. [2014] include examination of the seasonal velocity patterns for our study glaciers during 2009–2013. The results suggest that glaciers in this region have a velocity pattern indicative of high sensitivity to limited input to the subglacial hydrologic system. Velocity behavior for most glaciers in our region is consistent with speedup and slowing related to an increase and lowering of water pressure that matches the rise and fall in seasonal runoff (e.g., Figures 6a and 6b). Only a few glaciers in our study, concentrated in the southern end, appear to develop efficient subglacial drainage during the summer, which is identified as a substantial late summer velocity low that occurs during the melt season. Our results from 2014 are consistent with this analysis and suggest that the seasonal velocity of our study glaciers is largely determined by subglacial hydrology.

4.3. Mechanisms Affecting Interannual Velocity and Terminus Change

Overall, we observe many instances of interannual speedup coincident with large-scale sustained retreat as expected for grounded termini with reverse-slope glacier beds (bed depth increases up glacier from terminus) [e.g., *Howat et al.*, 2008; *Nick et al.*, 2009; *Podrasky et al.*, 2012; *Joughin et al.*, 2012a]. The four glaciers that sped up at least 100 m/yr^2 during 2009–2014 all retreated more than 1 km over our record. Glacier G1 also retreated more than 1 km but had a smaller speedup. In addition, all of our 15 year records show substantial retreat along with notable sustained speedup. However, our 2009–2014 data includes some exceptions. Glacier G5 retreated more than 1 km while slowing, and three other glaciers slowed despite some retreat (Table 1). Other factors, including glacier thinning and local topography, may cause this anomalous behavior.

While G1 did speedup, it serves as an excellent example to demonstrate the potential influence of glacier-specific factors. The long-term record for G1 indicates steady speedup beginning in at least 2006 (the data gap between 2001 and 2006 precludes determination of the onset of speedup prior to 2006), well before the onset of the ~2 km of retreat, which was largely concentrated in 2010 (Figure 8). 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 (based on size and surface features) from G1 prior to 2010, which suggests that the terminus was at or near floatation before retreat. Subsequent to retreat, interannual velocity remained relatively steady. Imagery from 2013 and 2014 shows new bedrock exposed along the north edge of the glacier. This suggests that the glacier may have retreated from one topographic pinning point to another, with early thinning-induced speedup. The higher ice velocity was then sustained in the new recessed position.

We also examined the role that mélange may play in multiyear 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 (Figure 6d). This extended ice-free period coincided with particularly large retreat events for G1 and SV (Figure 3). There was a similar stepwise retreat for G3 in 2013 as the southern end of the terminus lost contact with a rock island. However, while full sea ice cover developed fairly late in winter 2012/2013, our observations do not necessarily suggest an anonymously short period of rigid mélange for the year. Thus, we see some, but not overwhelming, evidence that longer mélange-free periods may play a role in relatively large glacier retreat, with lasting effects on mean terminus position. Results from Uummannaq and Jakobshavn also support the link between longer calving seasons and larger interannual retreat [*Joughin et al.*, 2008a; *Howat et al.*, 2010]. In addition, *Carr et al.* [2013a] 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 2009–2014 record may be too short for identifying SIF trends, others' work finds that the ice-free season throughout Baffin Bay lengthened from 1979 to 2012 (Laidre et al., manuscript in preparation, 2015). This may have had an influence on the widespread retreat in this region, which began by at least 1992–2000 [*Moon and Joughin*, 2008; *McFadden et al.*, 2011], and perhaps leading to the present elevated speeds for many of these glaciers [*Moon et al.*, 2012]. Although predicting retreat is dependent on a wide set of factors that must include bed topography and ice sheet thinning rates, continued lengthening of the ice-free period may portend further terminus retreat.

The corresponding timing of sea ice-free periods and large retreat events is not necessarily causal, however, but may be an important indicator of the combined effects of multiple environmental changes. For example, in both late 2010 and late 2012, delayed development of sea ice came on the heels of record summer ice-sheet surface melt [*Tedesco et al.*, 2011; *Nghiem et al.*, 2012]. As a result of this anomalous summer melt, there may have been higher than normal glacier thinning from surface melt and increased basal terminus melt due to greater subglacial discharge. Surface thinning, subglacial melt, and poor mélange development may all act together to decrease terminus stability and promote larger than normal glacier retreat.

As a final note, the daily SIF product is not always in agreement with our record of mélange condition. In many cases, we observe rigid mélange conditions throughout the annual springtime decline in SIF, and in cases where we have observations, rigid mélange may not form again until after the full build up of sea ice in fall and winter (e.g., Figure 6). This disagreement suggests that studies focused on precise timing of ocean and ice sheet events may still require high-resolution measurements beyond that available in many broad-scale remote sensing products.

5. Conclusion

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. Our results are consistent with earlier findings from other Greenland glaciers [*Sohn et al.*, 1998; *Joughin et al.*, 2008a; *Ahn and Box*, 2010; *Amundson et al.*, 2010; *Howat et al.*, 2010]. Overall, 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. Longer ice-free periods and/or shorter periods of rigid mélange, perhaps also in combination with increased glacier thinning from melt, may also allow large-scale terminus retreat past previous annual retreat locations, potentially by creating a small initial perturbation that is enhanced by dynamical feedback associated with retreat down a reverse bed slope [e.g., *Howat et al.*, 2008; *Nick et al.*, 2009]. Thus, mélange presence and rigidity appear to influence both seasonal and interannual evolution of glacier terminus behavior.

The dominant seasonal velocity pattern for our study glaciers has a consistent increase in speed between spring and summer (mean of 145 m/yr), and the pattern and magnitude of seasonal changes in ice-flow velocity are consistent with observations and theory linking velocity changes to seasonal melt modifying subglacial conditions [e.g., *Joughin et al.*, 2008b; *Schoof*, 2010; *Sole et al.*, 2011; *Moon et al.*, 2014]. On interannual time scales, however, relatively large retreat is accompanied by multiyear 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. Assuming reverse-slope beds for most glaciers, however, our results suggest that if the sea ice- free season continues to lengthen, whether it acts as the primary driver or in combination with other changes, we can expect further glacier retreat and speedup to contribute to increasing ice sheet mass loss.

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