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Extensive retreat of Greenland tidewater glaciers, 2000–2010

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Abstract

Overall mass loss from the Greenland ice sheet nearly doubled during the early 2000s resulting in an increased contribution to sea-level rise, with this step-change being mainly attributed to the widespread frontal retreat and accompanying dynamic thinning of tidewater glaciers. Changes in glacier calving-front positions are easily derived from remotely sensed imagery and provide a record of dynamic change. However, ice-sheet-wide studies of calving fronts have been either spatially or temporally limited. In this study multiple calving-front positions were derived for 199 Greenland marine-terminating outlet glaciers with width greater than 1 km using Landsat imagery for the 11-year period 2000–2010 in order to identify regional seasonal and inter-annual variations. During this period, outlet glaciers were characterized by sustained and substantial retreat summing to more than 267 km, with only 11 glaciers showing overall advance. In general, the pattern of mass loss detected by GRACE (Gravity Recovery and Climate Experiment) and other measurements is reflected in the calving record of Greenland glaciers. Our results suggest several regions in the south and east of the ice sheet likely share controls on their dynamic changes, but no simple single control is apparent.

Introduction

The Greenland ice sheet has been one of the largest contributors to sea-level rise during the past two decades (IPCC, 2013). Large-scale changes and increased mass loss have been observed in many regions of the Greenland ice sheet. The rates of mass loss have varied regionally with the most negative trends coinciding with regions where ice is discharged through marine-terminating outlet glaciers, which have thinned, sped up, and retreated (Pritchard et al., 2009; Rignot and Kanagaratnam, 2006; van den Broeke et al., 2009; Joughin et al., 2010; Moon et al., 2012). Iceberg calving from marine-terminating glaciers accounts for between 36% and 58% of Greenland's overall mass loss in the period 2000–2009 (Enderlin et al., 2014), and calving is known to dominate mass loss in regions of the ice sheet such as the southeast (SE) and northwest (NW) (e.g., Pritchard et al., 2009; van den Broeke et al., 2009). Changes in the calving-front position of marine-terminating glaciers are a good indicator for dynamic mass loss, as typically speedup-induced thinning is coupled to frontal retreat (Howat et al., 2005, 2008a; Joughin et al., 2008).

Studies of calving-front positions (or studies that include such data) have used a small number of temporal snapshots of ice-front positions (Moon and Joughin, 2008; Howat and Eddy, 2011), have been regionally specific (Howat et al., 2008a; Joughin et al., 2008; McFadden et al., 2011; Murray et al., 2010; Seale et al., 2011; Walsh et al., 2012), or have only sampled a small number of glaciers (Box and Decker, 2011). In what is one of the most extensive published studies, McFadden et al. (2011) considered 59 glaciers in west Greenland, and this study showed no apparent synchronicity in glacier behavior in this region of the ice sheet. In contrast in the SE, synchronicity of retreat and subsequent restablization/advance of the fronts of tidewater glaciers during the 2000s has been reported (Rignot and Kanagaratnam, 2006; Howat et al., 2008a; Murray et al., 2010; Walsh et al., 2012) and attributed to regional forcing such as air or ocean temperature changes (e.g., Luckman et al., 2006; Moon and Joughin, 2008). Differences in the behavior of the calving fronts of glaciers north and south of 69°N in the SE has been suggested to be controlled by the patterns of ocean circulation (Seale et al., 2011; Walsh et al., 2012).

However, to date no ice-sheet-wide study has been published that quantifies calving losses with both high spatial and temporal coverage. In this paper, we present the first complete time series of terminus fluctuations for all Greenland tidewater glaciers wider than 1 km that are visible in Landsat data in order to resolve both the seasonal and inter-annual changes during the period 2000–2010. We also investigate various environmental conditions in each region thought to be plausible as explanatory controls on glacier calving and frontal position: namely sea surface temperature (SST), melt days, and sea ice coverage.

Methods

We compiled a record of terminus positions for all tidewater glaciers with width larger than 1 km visible on Landsat-7

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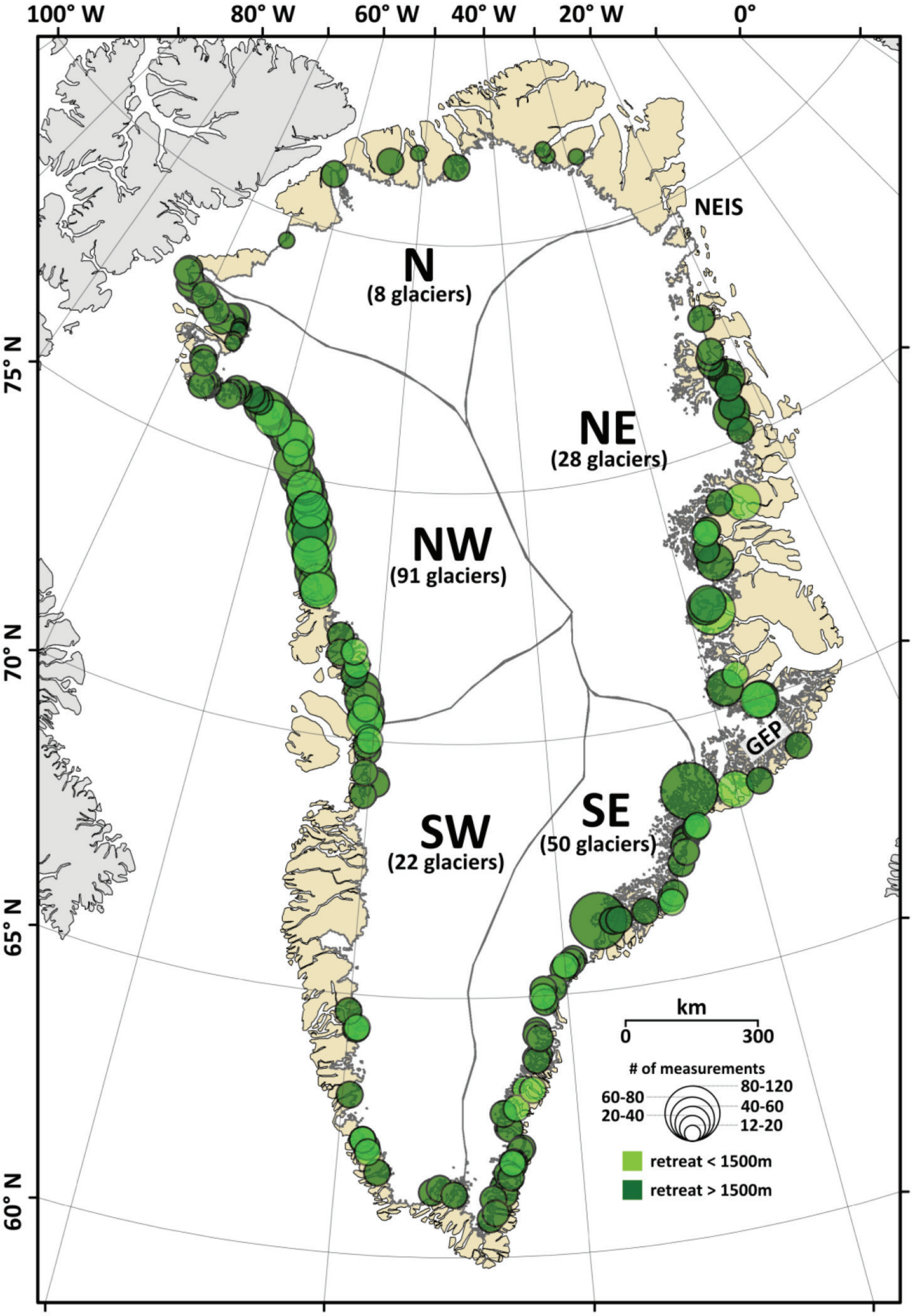

FIGURE 1. Location of the glaciers included in the data set. The circle size indicates the number of measurements between 2000 and 2010. Note that circle symbols are plotted with the largest symbols lowest and smallest symbols on top, meaning that there are no fully obscured symbols on the figure. Dark green indicates glaciers with more than 1500 m retreat (which form those glaciers in the red class in Fig. 6). Numbers are the total number of glaciers in each region of the ice sheet, GEP is the Geikie Plateau region, NEIS is North-East Greenland Ice Stream.

data around the Greenland ice sheet during the 11-year period 2000–2010 (Fig. 1), thus capturing 199 tidewater outlets in a time period where extensive changes have been reported (Howat and Eddy, 2011). In common with all studies of this nature, a cut-off size below which fronts were not considered was needed to enable digitization of the fronts within a practical time scale. The orbital limit of Landsat-7 data is 81°N (NASA, 2014), although in some places data up to 81.7°N are obtainable. This data limit means that some regions of northern Greenland are sparsely or not covered by the data, but the majority of Greenland's coast has good coverage. Ice caps in contact with the Greenland ice sheet, such as the Geikie Plateau (GEP in Fig. 1) are taken as part of the main ice sheet. We omit several outlets along the GEP known to be surge-type glaciers because this region is a surge cluster (Jiskoot et al., 2003). The frontal positions of surge-type glaciers respond to an internally driven cycle rather than climatic changes (Clarke, 1987) and a region with a high percentage of surge-type glaciers could affect the results. Two further surge-type glaciers, one in the NW and one in the northeast (NE) (Harald Moltke Bræ [76.6°N, 67.85°W] and Storstrømmen [76.7°N, 22.45°W] [Rignot and Kanagaratnam, 2006]) were included. No new surge-type glaciers were identified during our analysis, however, the data set likely also contains a small number of unrecognized surge-type glaciers. Furthermore, the record of the Northeast Greenland Ice Stream (NEIS in Fig. 1) comprising the outlets Nioghalvfjerdsbræ and Zachariæ Isstrøm was not included in our analysis due to ambiguities in identifying the actual calving cliff locations in imagery.

We used Landsat thematic mapper (TM) and enhanced thematic mapper (ETM+) images downloaded from the National Aeronautics and Space Administration (NASA). These images were orthorectified by the method presented by Tucker et al. (2004) and geolocation errors were minimized by using only data of the same Worldwide Reference System (WRS) path/row for each glacier. Furthermore, we visually inspected the alignment of several images for each glacier along the steep fjord-walls, and found no image with irregularities larger than one pixel, translating on the ground to <30 m for Landsat-5 TM, and <15 m for Landsat-7 ETM+ (band 8). Glacier-front positions were then manually digitized on-screen from the Landsat scenes. Since 2003, a hardware fault in the Scan-line Corrector of the Landsat-7 satellite means that there is an ~22%–25% data loss in the form of parallel stripes varying in width across each image (Wijedasa et al., 2012), however, it was still possible to map calving front positions from these images: front positions were simply digitized either side of the missing data.

There are a number of methods by which glacier frontal change can be calculated (e.g., Walsh et al., 2012; Lea et al., 2014): all have limitations, some of which are detailed by Lea et al. (2014). The commonest method is the center-line method; however, more recently the more complex and time-consuming box method has been increasingly used (e.g., McFadden et al., 2011; Moon and Joughin, 2008; Howat and Eddy, 2011), because of its ability to account for asymmetric changes in front geometry. However, the box method is problematic unless the box width is equal to the glacier width (Lea et al., 2014), and so is inappropriate for data where segments of fronts are regularly missing or where the glacier front changes width: both occur in our data. We chose to use a modified center flow-line method where the flow-line follows the fjord orientation. This center flow-line method of measuring frontal positions was shown by Walsh et al. (2012) to be equivalent in accuracy (to ±100 m, which is the measurement error) to the box method. In this study, center flow-lines were manually drawn and where necessary segments followed changes in fjord orientation. We considered the width of the respective outlet, its surface velocity field (Rignot and Kanagaratnam, 2006) close to the calving front, as well as choosing a more-or-less perpendicular orientation compared to the digitized calving fronts. Using this modified center flow-line method, the distance between front positions was measured along the center flow-line of each outlet relative to the position of furthest retreat. Measurement accuracies on the flow-lines are estimated to be better than ±76 m (Bevan et al., 2012), and each center-line location was chosen to avoid any gaps due to the Scan-line failure.

To validate this choice of method we randomly chose 10 glaciers and compared Lea et al.'s (2014) extrapolated center-line method with our method for all measured fronts at these glaciers. The extrapolated center-line method uses inverse distance weighting to extrapolate positions from the glacier center line across the fjord width and allows for both changing fjord width (unlike the box method) and frontal geometry (Lea et al., 2014). The median difference between frontal changes using the absolute value of retreat or advance using our method and the extrapolated center-line method was 77 m and the interquartile range was 107 m across 357 measured frontal positions. Furthermore, neither method was demonstrably better than the other: our center-line method does not deal with changes in across-front geometry (such as a glacier front changing from concave down-glacier to convex down-glacier), but the extrapolated center-line method is problematic when fronts are sometimes partially obscured by cloud or the Scan-line hardware fault, as is the case in our data.

In order to ensure measured frontal changes are not in fact simply seasonal variations, we aimed for a minimum of three measurements per year (covering spring, summer, and autumn whenever possible, although limited imagery prevents a regular seasonal survey), subject to satellite data coverage (Fig. 1). We discuss regional seasonal variations in the frontal position of the glaciers and their timing; however, there are limitations on these results and they should be taken as minimum values of seasonal variation as it is unlikely that our sampling records either the maximum or the minimum position of individual glaciers. We grouped the outlet glaciers into five sectors around the ice sheet (Fig. 1) based on previous studies (e.g., Luthcke et al., 2006; Wouters et al., 2008; van den Broeke et al., 2009; Sasgen et al., 2012). We incorporated Kangerdlugssuaq Gletscher (68.6°N, 32.48°W) into the SE sector, as it is known to have behaved in concert with other SE Greenland glaciers (Luckman et al., 2006; Howat et al., 2008a; Murray et al., 2010). Figure 1 shows the number of glaciers in each region and summarizes the overall number of measurements we made at each glacier. On average there are two measurements per year for glaciers in the north (N) sector, four in the NE, three in the SE, two in the southwest (SW), and four in the NW. There are only two glaciers in the database with measurements completely missing in any particular year (i.e., zero measurements in a year): for both glaciers this occurs for just a single year. Nevertheless, because we present averaged positions, there are 45 occurrences within the database without a recorded annual frontal position because fewer than three measurements could be made in that year, and one glacier (Steensby Gletscher, 81.6°N, 54.64°W) has no average position for the five-year period 2000–2004 (Table 1). The orbital limit means many more of the glaciers with missing averaged positions are in the northern sector than are further south, which together with the small number of glaciers measured in the N region (Fig. 1) means that results in the N can be affected by the variable data coverage. In total, the inventory comprises 6688 ter-

TABLE 1

Glaciers that advance or are stable relative to their first recorded position during the period 2000–2010. Steensby Gletscher (81.6°N, 54.63°W) is also recorded in the database as advancing 186 m during the period 2005–2010, but there are no frontal positions for this glacier within the database prior to 2005.

Glacier name	Longitude	Latitude	Sector	Advance 2000–2010 (m)
Akugdlerssup	–49.60	64.3	SW	20
Eqalorutsit	–45.79	61.3	SW	159
Guld Rimfaxe	–42.17	63.2	SE	131
Heimdal	–42.57	62.8	SE	41
Koge_c	–41.14	65.0	SE	13
Magga Dan	–27.28	70.0	NE	186
Rolige Brae	–28.26	70.6	NE	103
Sermeq Kujatdleq	–50.22	70.0	SW	13
Skinfaxe	–41.84	63.2	SE	24
Store Gletscher	–50.57	70.4	NW	30
Ussing_b1	–55.87	73.9	NW	155

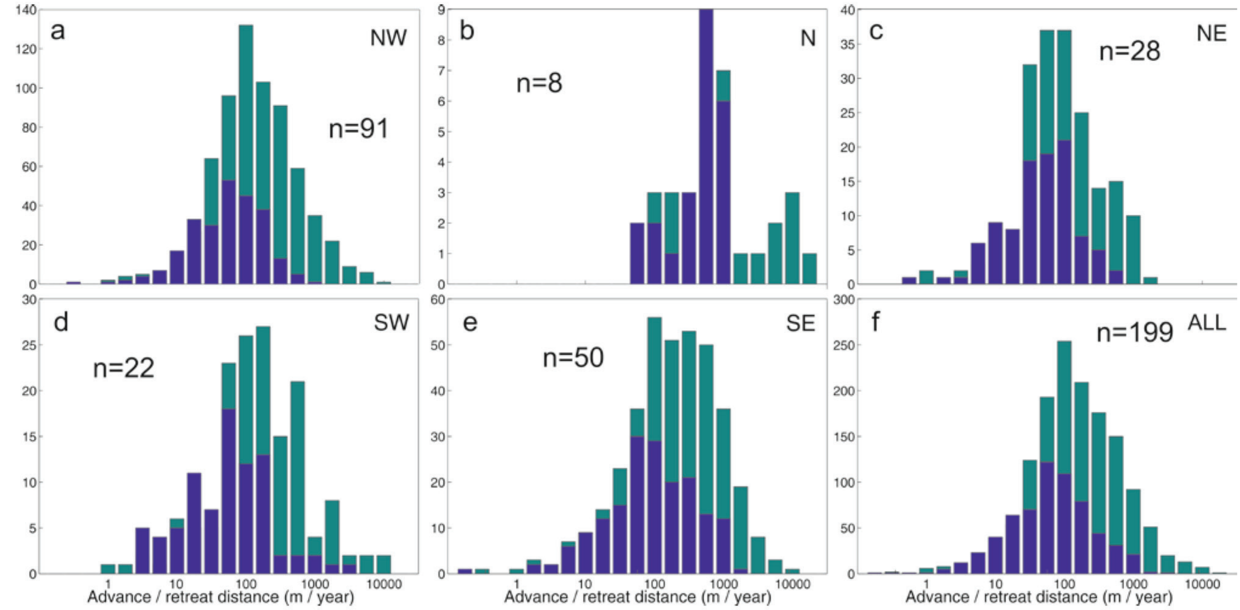

FIGURE 2. Histograms showing number of occurrences of annual frontal change of different magnitude in: (a) northwest; (b) north; (c) northeast; (d) southwest; and (e) southeast regions. Figure 1 shows the regions and locations of glaciers measured, along with the number of measurements. (f) Histogram of annual frontal change for all glaciers measured. Note that in all cases the horizontal axis is logarithmic and that vertical axes vary between regions. *n* is the number of glaciers in each region. Advances in blue, retreats in green.

minus positions with satellite coverage varying significantly for the different areas around the ice sheet (Fig. 1). Values when stated for a particular year are calendar years (1 January to 31 December). In this paper, we present regional summaries of the data collected: information for all individual glaciers is presented in Appendix Table A1, and the locations and fronts themselves are presented in a Google Earth Keyhole Markup (.kmz) file provided as Appendix supplementary file A1, which is available online as an open access file.

Because the frontal changes measured are not normally distributed (small changes are more common and the distributions are positively skewed; Fig. 2), both the mean and median values of retreat for the glaciers in each of the different sectors were computed: in order to achieve this, a daily frontal record was interpolated from the measured data points for each glacier and used to calculate the mean or median position across each sector. For one figure, glaciers within each sector were also separated by the overall magnitude of their frontal change. In common with analysis in Murray et al. (2010), those glaciers with overall retreat exceeding 1500 m over the time period were considered "large" retreats, and those with retreats less than 1500 m were considered "small" retreats (Fig. 1). All overall advances (Table 1) were less than 1500 m and therefore were considered "small."

We also examined possible environmental controls on glacier frontal position, specifically sea surface temperature, melt days, and sea-ice extent.

A number of studies have shown or implied that the delivery of heat by ocean water to the fronts of calving glaciers in Greenland is an important control on frontal retreat (e.g., Holland et al., 2008; Murray et al., 2010; Straneo et al., 2010; Christoffersen et al., 2011), whether by weakening the ice mélange (Amundson et al., 2010) or undercutting the ice front directly (Motyka et al., 2003). Satellite-measured sea surface temperature (SST) has been used as a proxy for this heat, albeit that it reflects the temperature of the very surface waters. In this paper, we present Moderate Resolution Imaging Spectroradiometer (MODIS)–derived SSTs (Brown and Minnett, 1999) for comparison to glacier behavior. SST in the SE has been used to explain glacial retreat (Howat et al., 2008a; Hanna et al., 2009; Murray et al., 2010). An analysis by Sutherland et al. (2013) has subsequently shown SST is significantly correlated with water temperatures in the upper 50–250 m; however, there is no significant correlation at greater depth. SST may therefore only be a suitable proxy for the integrity of the ice mélange rather than the influx of deeper warm water. In the SE only, we also use temperatures measured at depth by using the westernmost station (64.2°N, 27.58°W) of the quarterly measured Faxaflói-line, an Icelandic long-term hydrographic standard section (http://www.hafro.is/~argos/snid/snid.php?stod=FX9&dypi=200). This station captures the core of the Irminger Current (IC) prior to its recirculation southward and before it interacts with the waters on the East Greenland shelf. We use mean values of temperature for a depth range of 200–500 m (H. Valdimarsson, personal communication) to capture the full depth of the IC while minimizing any seasonal influence.

We also used the Greenland Daily Surface Melt 25 km EASE-Grid 2.0 Climate Data Record from NSIDC to compute melt day anomalies for each catchment (Mote, 2012), essentially summing the number of days on which melt occurs in each catchment as a proxy for melt intensity. Finally, the coverage of sea ice in the coastal region was taken from the Sea Ice Index (Fetterer et al., 2002).

Results

In general, Greenland's tidewater glaciers experienced large and widespread retreat during the period 2000–2010 (Fig. 2): retreat is dominant around the entire ice sheet margin. In total, the 199 outlets measured retreated more than 267 km over the 11-year period (Table 2; Fig. 3). The largest annual retreat of any glacier (14.9 km) occurred at Hagen Bræ in N Greenland (81.5°N, 28.72°W). Annual rates show strong variation, with maximum to-

TABLE 2

Summary results for period 2000–2010 by sector. Columns 4–7 are normalized by the number of glaciers in the sector.

Sector	Summed retreat for sector (km)	No of glaciers	Mean change (m yr^{-1})	Standard deviation (m yr^{-1})	Median change (m yr^{-1})	Interquartile range (m yr^{-1})
N	31.4	8	–700	2800	–60	1500
NE	13.6	28	–50	180	–30	150
SE	72.3	50	–145	520	–65	370
SW	35.0	22	–170	730	–50	240
NW	114.8	91	–130	360	–60	230
All	267	199	–140	620	–50	250

tal retreat in 2009 (–44 km), 2004 (–42 km), and 2005 (–41 km), whereas there was an overall advance in 2006 (+4 km) (Figs. 4 and 5). However, only 11 of 199 outlets show minor advance over the whole 11-year period (Fig. 2; Table 1). There is no obvious regional clustering of the glaciers that advance and they occur across four of our five sectors.

The mean retreat rate per glacier per year was ~355 m a^{-1} in the N, ~145 m a^{-1} in the SE, ~130 m a^{-1} in the SW, ~115 m a^{-1} in the NW, and ~45 m a^{-1} in the NE. However, because the number of glaciers in each sector differs, the NW was the main contributor to the overall retreat, followed by the SE, and SW (Fig. 4, part a). There is considerable inter-annual variability in both the overall retreat rate and the regional pattern of retreat (Table 3; Figs. 4 and 5, part b). Overall retreat rates in Greenland were highest during 2009 (Fig. 5, part b). During 2009, no region showed overall advance and the northern glaciers retreated strongly (due primarily to the retreat of Hagen Brae). However, only the northern glaciers were retreating at their fastest rate during this year. Overall retreat rates were almost as high in 2004 and 2005 despite the northern glaciers advancing slightly in those years (Fig. 5, part b). Glaciers in Greenland showed overall advance during 2006 (Figs. 4 and 5, part b), driven by low retreat in all sectors with a slight advance in the NE and strong advance in the SE. Other years with overall low retreat rates were 2001, 2008, and 2007: glaciers in the SE continued advancing into 2007 (Fig. 4).

Regionally, glaciers in the NW showed overall retreat every year in the record, whereas all of the other regions had at least one year with advance (Fig. 5, part b). The glaciers in the NW retreated most strongly of all the regions in 6 out of the 11 years in the record, with 4 of these years occurring since 2006. The NW also contained the largest number of glaciers retreating more than 1500 m during 2000–2010. Glaciers in the SE retreated more than those in the other regions in 2002, 2005, and 2009, with the SW dominating in 2003 (Fig. 5, part a). Glaciers in the SE showed the greatest variability in frontal position: both the greatest overall retreat (during 2005) and greatest overall advance (during 2006) are shown by the glaciers in this region. The region contained the second largest number of glaciers retreating more than 1500 m over the period.

Figure 6 shows both the inter- and intra-annual variability in glacier frontal position in each region broken down by size of retreat. Seasonal variations in frontal position are evident in all regions except the north. In those regions with seasonal variation, the pattern revealed is slow advance of glaciers during the winter and more rapid and shorter-lived retreat during the summer period. This pattern is revealed in both the mean and the median behavior for regions (Fig. 6). Seasonal changes are larger for the glaciers with larger overall retreats.

Glaciers in the NE with small overall retreats did so at an almost constant rate, punctuated by seasonal fluctuations (Fig. 6). Those outlets with large retreats showed higher retreat rates during 2002–2005 with subsequent stabilization (Fig. 6). A similar pattern to the NE (rapid retreat to a minimum in 2005, followed by stabilization or readvance) is apparent in the SE across both size classes. Smaller retreats in the SW also follow a similar pattern; however, here the glaciers are most retreated in 2004. Larger retreats in the SW are dominated by the behavior of Jakobshavn Isbræ, which retreated rapidly in the early part of the record, causing the mean and median retreat rates to differ substantially. Seasonal variations are increased after 2005, and much of the advance in the latter part of the period results from the lack of summer retreat during 2008. In contrast, in the NW the outlets with larger retreats show a rather constant mean and median retreat superimposed by seasonal fluctuations, while the outlets with smaller retreats reduced their retreat after 2004. Both size classes increased the magnitude of their seasonal fluctuations 2005 onward (Appendix Table A2).

Figures 7, b–e, summarize the overall potential environmental controls in comparison to the glacier frontal record (Fig. 7, part a), although none of these appears to correlate strongly with overall frontal position. Pearson product-moment correlation shows no relationships between these environmental controls and frontal position that are significant at the 95% significance level. If just the SE glaciers are considered, there is a significant correlation between the SE glaciers frontal position and the temperature of the IC lagged by one year (Pearson correlation—0.70 significant at 95% confidence level).

Figure 7, part e, shows melt day anomalies for each region. The highest melt day anomaly occurs during 2010 in the SW, although all other areas except the north were also affected (Fig. 7, part e, Tedesco et al., 2011). Other high melt years were 2002 and 2008 (N and NE), 2005 (N, NE, NW), and 2007 (SW, SE, NW). Low melt years were 2001 (NE and SW) and 2006 (all areas).

In the SE, SST was high in 2003 and low in 2002 and 2006 (Fig. 7, part d). SST in SW Greenland follows similar trends in most years: both the SE and SW are affected by warm water from the Irminger Current flowing southward along the SE Greenland shelf edge and subsequently northward along SW Greenland (e.g., Straneo and Heimbach, 2013). Cooler waters in the SW during 2009 provide an exception as the SE is relatively warm in that year. SST in the NE is warmest during 2002 and 2008.

Figure 7, part f, shows that inter-regional differences in sea ice coverage are much larger than temporal intra-regional differ-

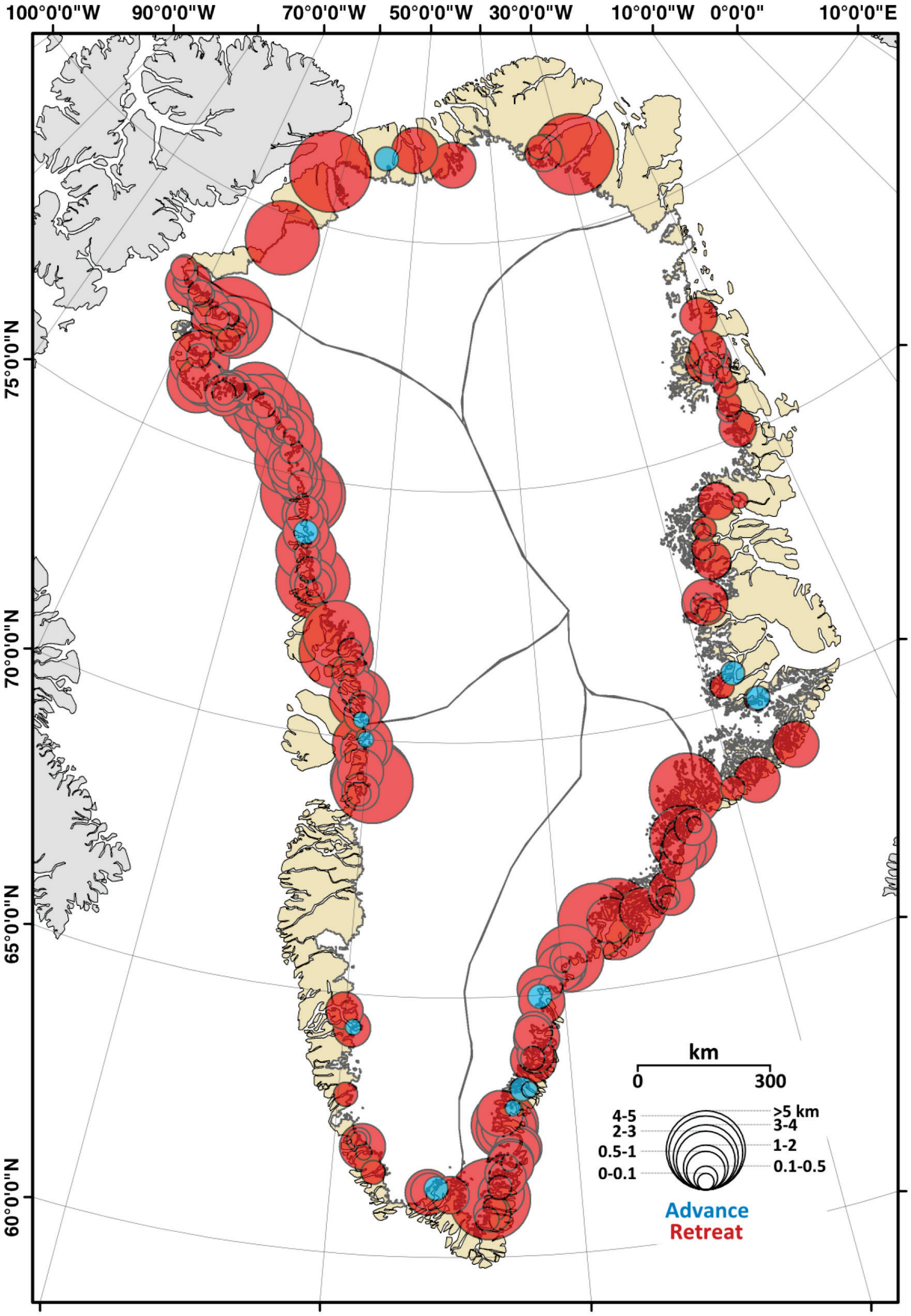

FIGURE 3. Overall change in frontal position of sampled glaciers for the period 2000–2010. Note that symbols are plotted with the largest symbols lowest and smallest symbols on top, meaning that there are no fully obscured symbols in the figure. The advances in blue are plotted on top of retreats (in red) where they fall in the same size category.

ences. There are sea ice lows in the SE during 2003 and 2005 that correlate to higher SST, but coverage in the SW does not follow a similar trend. Coverage in the SW is low 2004–2006 and peaks in 2008.

Discussion

Overall, Greenland tidewater glaciers experienced large and widespread retreat during the observation period 2000–2010 with strong regional and temporal variations around the ice sheet. Studies of ice sheet mass balance that use a surface mass balance minus discharge method assume a constant grounding line or front position, which given the ubiquitous retreat around Greenland is clearly a potential source of error. Our data could be used to assess the impact of such an assumption.

Dividing the ice sheet into five sectors based on glaciological considerations and published GRACE measurements (Sasgen et al., 2012), a clear pattern with high retreat rates during 2002–2005 and subsequent stabilization becomes clear for the NE, SE, and SW sectors, while outlets in the NW show a relatively constant retreat over the entire period (Fig. 6). The pattern of temporally consistent retreat in the NE and around the southern region of the ice sheet suggests related controls on glacier behavior, possibly originating from warming North Atlantic ocean waters (e.g., Holland et al., 2008; Straneo and Heimbach, 2013). The correlation between the front positions in the SE and the IC temperature reinforces this suggestion.

TABLE 3

Median glacier change in meters for each year by sector. Yearly values in the north where the number of glaciers is small and there are few images available are based on small samples and are therefore not presented.

	NE (m)	SE (m)	SW (m)	NW (m)
2000–2001	–10	–20	–27	–110
2001–2002	–60	–120	–90	–50
2002–2003	–40	–130	–90	–80
2003–2004	–20	–240	–120	–90
2004–2005	–90	–160	–100	–10
2005–2006	+50	+130	0	–20
2006–2007	–30	+50	0	–90
2007–2008	–30	–30	+10	–30
2008–2009	–30	–120	–30	–70
2009–2010	–40	+10	–140	–60

There is also a clear seasonal signal in all areas except the north showing fast retreat in summer and slow advance during winter (Fig. 6). Some caution should be made in interpreting this result, as the lack of daylight means that Landsat data are not available during winter months in northerly locations. However, a similar pattern of summer retreat and winter advance was found for five of the largest glaciers in Greenland (Schild and Hamilton, 2013). The seasonal signal suggests that the glacier fronts are stabilized by the presence of sea ice or lack of surface melting in winter. Summer retreat is likely initiated by melting causing some combination of sea ice and mélange breakup (Amundson et al., 2010), faster glacier flow causing increased surface crevassing and hence calving (Benn et al., 2007), or increased fjord circulation (Motyka et al., 2003; Sciascia et al., 2013). However, Schild and Hamilton (2013) emphasize that the timing of these effects are modulated by glacier geometry in individual cases.

CHANGE IN EAST GREENLAND

In SE Greenland our results show both size classes of glaciers retreating rapidly until 2005 and then subsequent advance and stabilization (Fig. 6). Published GRACE results show mass loss increased in the period 2005–2007 and then decreased again by August 2007 (Chen et al., 2011; Sasgen et al., 2012). The ranges of spatial and temporal sampling chosen by particular GRACE studies make it difficult to pin down the exact time of the change shown in GRACE data, but broad agreement in the timing of changes between published GRACE results (e.g., Chen et al., 2011; Sasgen et al., 2012) and the calving record shown in Figures 4 and 6 suggest that the mass loss is dominated by the dynamics of the major tidewater glaciers in the southeast. Measurements of ice dynamics in the area indeed show the majority of glaciers accelerating and then decelerating in this period (Howat et al., 2008a; Murray et al., 2010; Joughin et al., 2010), and a recent mass budget study (Enderlin et al., 2014) shows rapid increase in discharge from the SE to 2005, followed by a drop during 2006 and then stable or slowly increasing discharge to 2010. The correlation between frontal position of the SE glaciers and the temperature in the IC lagged by one year provides further support for an ocean control for the dynamics of these glaciers.

Two studies (Seale et al., 2011; Walsh et al., 2012) have discussed differences in the behavior of glaciers in the SE of Greenland compared to glaciers on the east coast but situated further north. A change in behavior is reported for glaciers north and south of 69°N, with both studies showing that glaciers north of this remained stable in frontal position, whereas those farther south displayed the widely reported pattern of retreat to a minimum in 2005 and subsequent readvance. The change is hypothesized to be controlled by the presence of warm waters transported in the IC in the southern fjords, and its absence in those farther north, rather than warmer air temperatures. Our results show that this division holds for the data set as a whole, and that the glaciers in the SE retreated much more strongly and advanced more strongly than those in the NE (Tables 2 and 3; Figs. 4–6). However, the glaciers with the largest retreats in the NE sector do show a similar pattern of retreat to a minimum in 2005 and subsequent stabilization (Fig. 6) as those in the SE, suggesting a common forcing factor or factors.

CHANGE IN WEST GREENLAND

The glaciers in the NW region show rather constant retreat rates throughout the period with the smaller retreat glaciers showing retreat slowing after 2005 (Fig. 6). In common with other areas, the NW sector showed large losses during 2004 and 2005, and 2006 was a year when many glaciers in the NW advanced (Fig. 4). GRACE analyses suggest acceleration in mass loss in the NW since late 2005 or 2007 (Chen et al., 2011; Khan et al., 2010; Schrama and Wouters, 2011; Harig and Simons, 2012; Sasgen et al., 2012), with the highest mass loss rates at the end of the period, (i.e., since 2009). In contrast, Enderlin et al. (2014) showed glaciers in the NW having a slowly increasing discharge over the period with a decrease in discharge acceleration during 2006–2008 and an increase in 2008–2010. Our data show retreat was almost ubiquitous in the region over the period. Thus there is no convincing frontal response that would match the GRACE signal acceleration.

McFadden et al. (2011) studied 59 glaciers combining those in the NW with the SW during 2000–2009. Their study showed that while most of these glaciers retreated, the majority retreated less than 1 km and that retreats were asynchronous across the region. Our data show that between 2000 and 2010 most glaciers in the NW (59 out of 91) retreated more than 1.5 km, whereas most glaciers (13 from 22) in the SW retreated less than 1.5 km (Figs. 1 and 6). McFadden et al. (2011) also analyzed the relationship of retreat with SST and in accordance with our larger study found no relationship between retreat rates and this variable.

The NW region is dominated by marine-terminating glaciers (McFadden et al., 2011). Moon et al. (2012) reported that one-third of these glaciers increased in speed throughout 2000–2010, one-third showed no trend, and a quarter slowed: a further 15% of the region's glaciers slowed in 2000–2005 and then accelerated substantially. This complex pattern is summarized by Moon et al. (2012) as a general trend of speedup throughout 2000–2010, with the rate increasing toward the end of the period, especially during 2007–2010.

Our data confirm that there is no strong and synchronous signal in frontal position from the glaciers, which show a rather constant retreat through the period. There is an indication

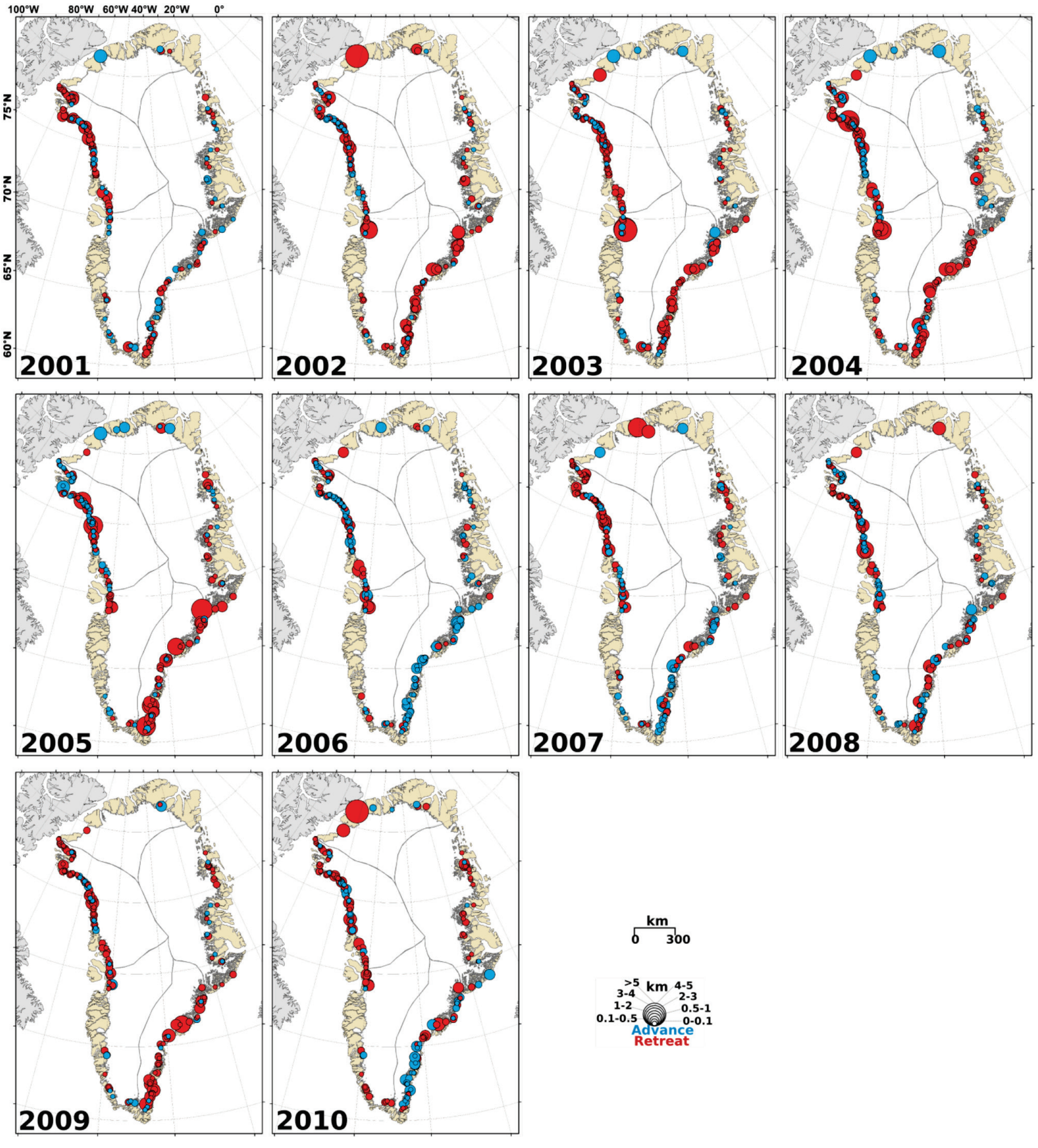

FIGURE 4. Annual changes in calving front position. Note that symbols are plotted with the largest symbols lowest and smallest symbols on top, meaning that there are no fully obscured symbols in the figure. The advances in blue are plotted on top of retreats (in red) where they fall in the same size category.

in the retreats of the smaller glaciers of a slowdown in retreat rate (Fig. 6) starting in 2005–2006 as reported by Enderlin et al. (2014). There is no strong indication of a strong increase in retreat rates. Overall, we suggest that at least a component of the clear GRACE signal of accelerated mass loss results from changes in surface mass balance or thinning at higher elevations (e.g., Howat et al., 2008b) rather than simply reflecting dynamic loss. This conclusion is supported by the study by Sasgen et al. (2012), which found that part of the acceleration in mass loss seen by GRACE in the NW was a consequence of higher precipitation prior to 2005 and lower precipitation after that date.

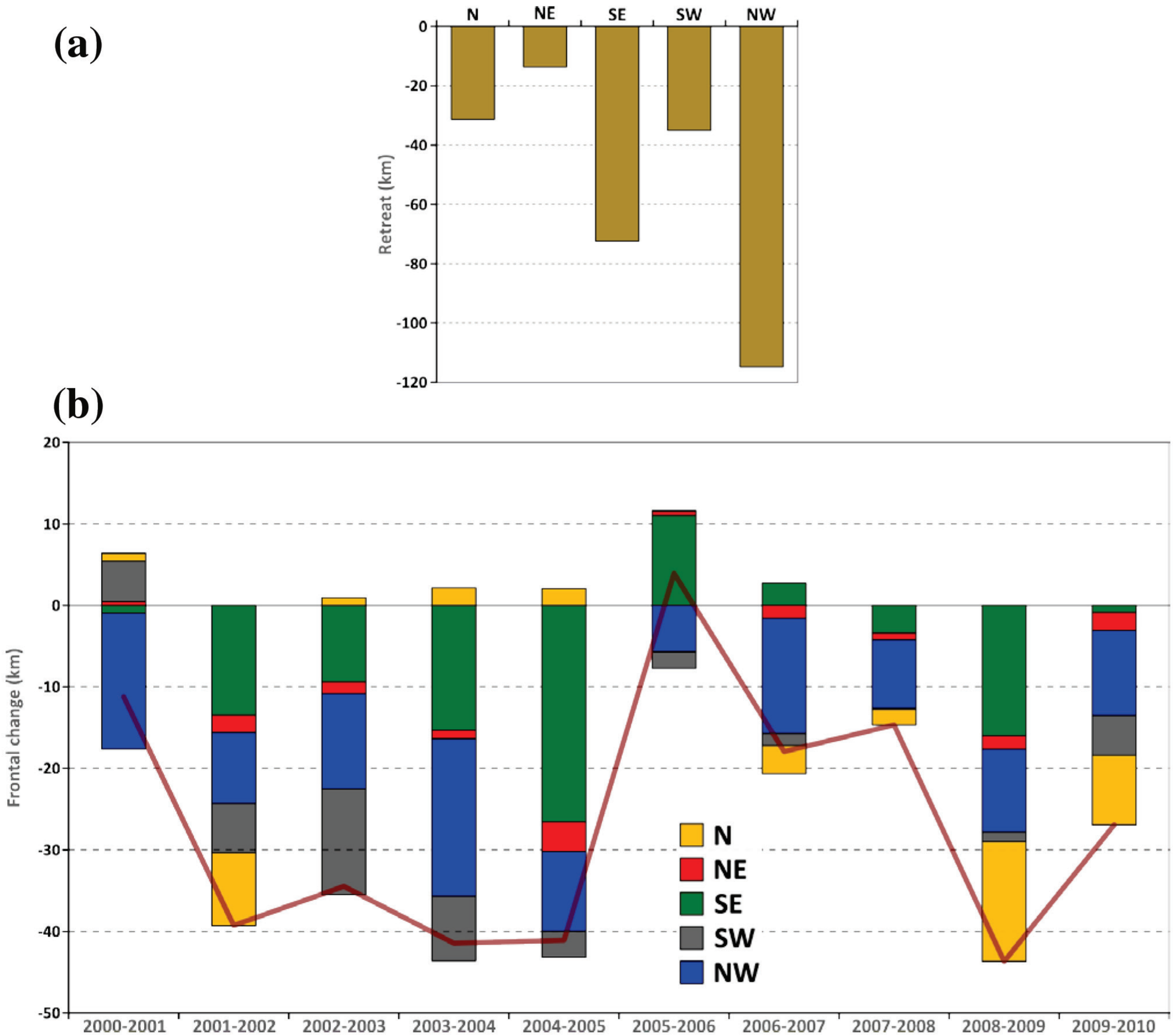

FIGURE 5. (a) Summed changes over the period 2000–2010 for each sector. (b) Annual contributions of each sector with the brown line following the overall change for each year. A line graph version of part b using the same color scheme is included as Figure 7, part a.

Conclusions

Greenland's marine-terminating glaciers are an important interface between ice and ocean, and their frontal position acts as an indicator for dynamic thinning of the Greenland ice sheet: retreat indicates increased calving flux corresponding to an increased contribution to sea-level rise. We have measured the front positions of 199 Greenland marine-terminating glaciers located in all regions around Greenland over the period 2000–2010 using Landsat satellite data. All regions of the ice sheet are affected by sustained and substantial glacier retreat during this period (Fig. 3). Over the whole period, the 199 glaciers retreated more than 267 km in total, with only 11 glaciers (5.5%) showing overall advance. Only one year of the 11-year record, 2006, was characterized by overall minor advance (Fig. 5). There were considerable inter-annual and inter-regional differences (Fig. 4). In general, the pattern of mass loss detected by GRACE and other measurements is reflected in the calving record of Greenland glaciers.

Glaciers in the SE sector of Greenland show very high retreat rates (–325 m a^{-1}) during the period 1999–2005, and subsequent stabilization and readvance (+161 m a^{-1}) during following years: glaciers in the SW show a similar pattern of pre-2005 retreat and subsequent stabilization. In contrast, outlets in the NE show mean retreat of 300 m over the entire 11-year period, with stabilization of glaciers with large retreat from 2005 but those with smaller retreats showing slow retreat punctuated with clear annual variations over the entire period. In the NW, outlets show continuous retreat (–83 m a^{-1}), with seasonal fluctuations. Our results suggest several regions in the south and east of the ice sheet are synchronized in their behavior and thus likely share controls on their dynamic changes: this is probably oceanic in origin. In the case of the SE, we show a significant correlation between ocean temperature lagged by one year and the frontal position of the glaciers.

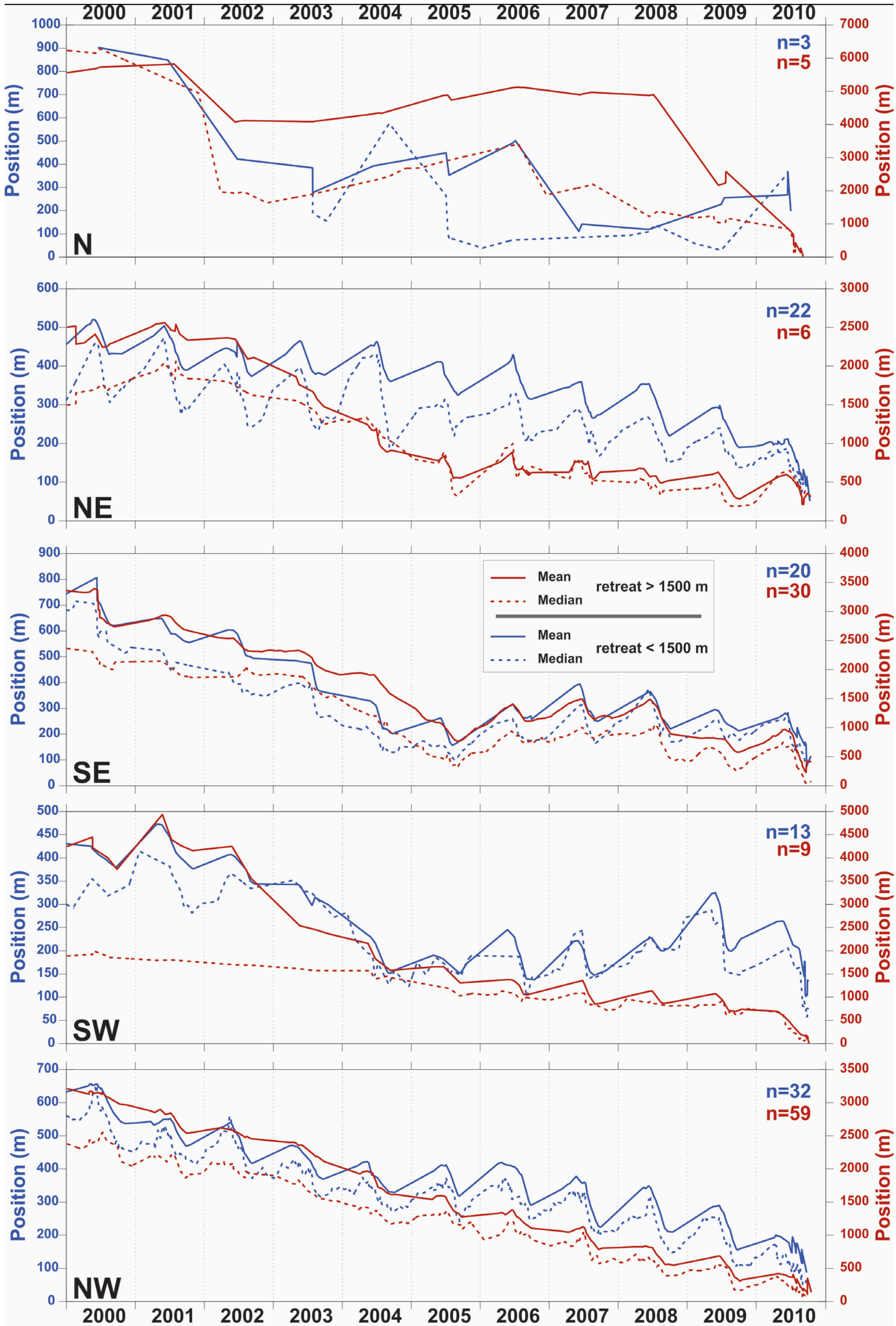

FIGURE 6. Calving front location of outlet glaciers separated on the basis of the range of advance/retreat exhibited by region. Glaciers that retreat less than 1500 m in blue and those that retreat more than 1500 m in red during the period 2000–2010 (the regions and location of glaciers is shown in Fig. 1). Note that the scales for the two classes of glaciers are different (smaller retreats on the left-hand axis; larger retreats on the right-hand axis) and that the scales vary among regions. Lines show monthly running mean (solid line) and median (dashed line).

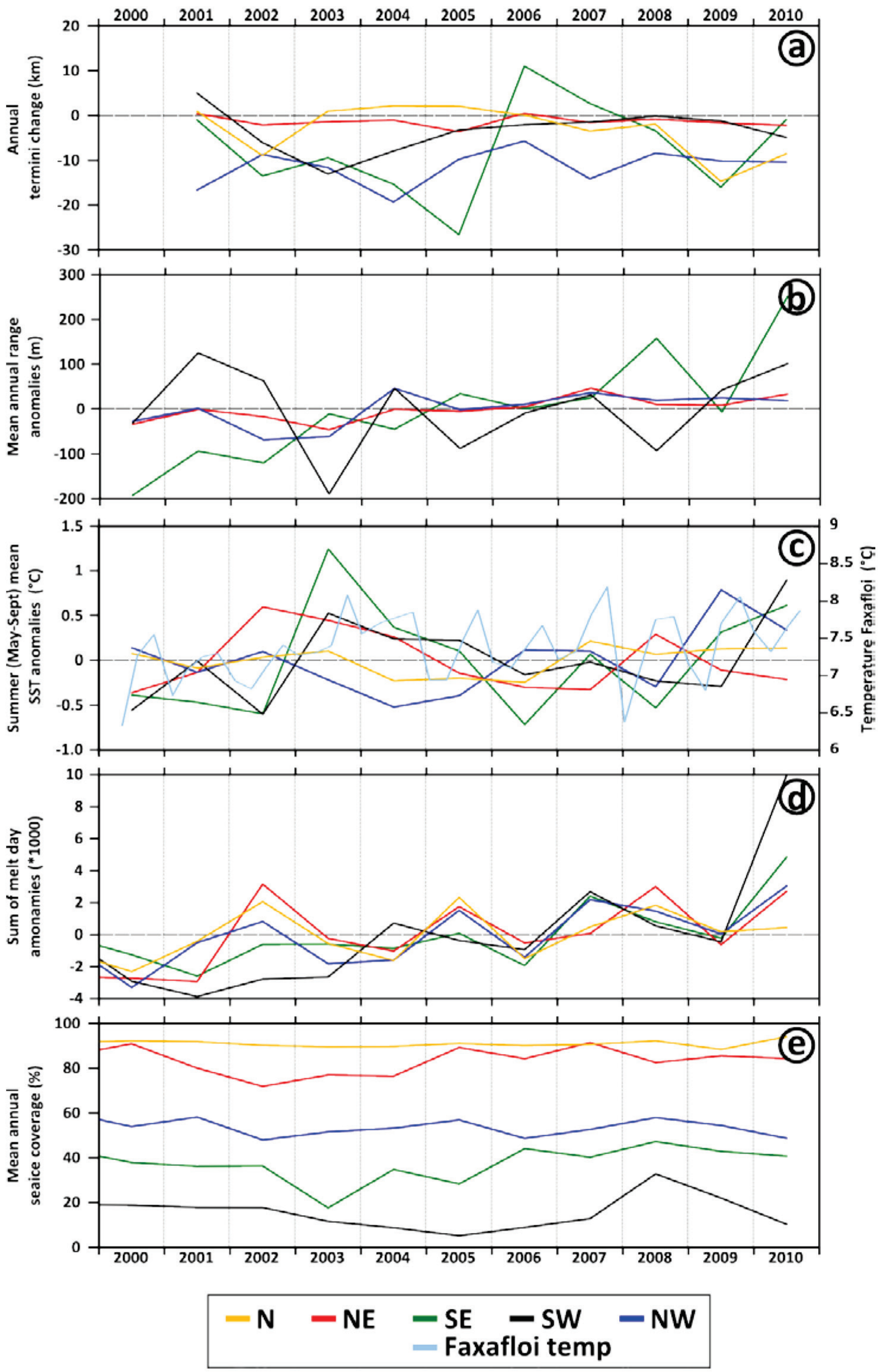

FIGURE 7. Different data sets for comparison. (a) Glacier annual frontal position change for each region. (b) Mean annual range anomalies, which show how the mean annual range (maximum – minimum frontal position for each glacier) in each region differs from the long-term average range. (c) MODIS-derived sea surface temperatures (SSTs) (Brown and Minnett, 1999) and temperature for depth range of 200–500 m at the westernmost station of the Faxaflói-line. (d) Melt day anomalies from Greenland Daily Surface Melt 25 km EASE-Grid 2.0 Climate Data Record (Mote, 2012). (e) Coastal sea ice coverage from the Sea Ice Index (Fetterer et al., 2002). SST and sea ice coverage were calculated for the entire continental shelf area for each region.

The record of behavior of the fronts of tidewater glaciers we present has the potential to be used in future studies of controls on calving losses from the Greenland ice sheet. Furthermore, our data could be used to assess the impact of assuming a constant groundling line or front position for studies of ice sheet mass balance that use the surface mass balance minus discharge method. In order to make these sorts of studies as simple as possible, we provide the data as supplementary material (.kml file S2) to this paper. Understanding the nature, distribution, and controls on dynamic change of Greenland's tidewater terminating glaciers are essential for predicting Greenland's future sea-level contribution.

Acknowledgments

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APPENDIX

TABLE A1

Annual and total frontal change in meters for each glacier in the data set ordered by sector and name. Sector 1 = SE; Sector 2 = NE; Sector 3 = NW; Sector 4 = SW; Sector 5 = N. Some names are informal and the stated location should be used to determine data for each glacier.

Name	Sector	Longitude	Latitude	Width (km)	2001-2000	2002-2001	2003-2002	2004-2003	2005-2004	2006-2005	2007-2006	2008-2007	2009-2008	2010-2009	SUM
A.P. Bernstorf Gletscher a	1	–41.485	63.857	2.9	285	–599	–545	–1	11	5	120	–156	–125	61	–944
A.P. Bernstorf Gletscher b	1	–41.624	63.789	3.9	334	–318	–409	–441	–219	469	243	–242	–485	604	–463
A.P. Bernstorf Gletscher c	1	–41.598	63.759	2.8	–136	–122	–109	–281	–161	–188	55	–126	–62	–650	–1779
Danell Gletscher	1	–43.470	60.921	2	–424	62	36	–210	111	255	136	–5	64	–133	–108
Fenrisgletscher	1	–37.487	66.324	2.7	–37	–587	–280	–373	–53	627	–387	–73	–23	–133	–1319
Glacier de France	1	–35.848	66.422	2.9	17	–7	–150	–207	–163	–17	67	–403	–113	–161	–1138
Guldfaxe/Rimfaxe	1	–42.165	63.204	3	67	30	–78	–53	36	62	–64	88	–4	47	131
Gyldenlove a	1	–41.507	64.326	2.6	285	–599	–556	10	–42	58	120	–156	–125	61	–944
Gyldenlove b	1	–41.554	64.257	2.9	334	–318	–409	–441	–219	469	243	–242	–485	554	–514
Gyldenlove c	1	–41.401	64.181	2.9	–136	–122	–109	–281	–161	–188	55	–126	–62	–650	–1779
Heimdal Gletscher	1	–42.574	62.848	2.9	–21	–38	–105	–77	–8	48	–6	131	–8	123	41
Helheimgletscher	1	–38.188	66.356	5.7	258	–1918	–544	–1233	–2553	2332	–840	327	–988	692	–4469
Ikertivaq a	1	–39.592	65.669	3.2	114	–60	–372	–389	–251	20	–282	–494	–1356	–860	–3930
Ikertivaq b	1	–39.668	65.621	4.5	–77	–97	–73	–205	–117	193	42	–128	60	–192	–594
Ikertivaq d	1	–39.932	65.532	2.4	–19	–128	–146	–85	–298	131	–337	–16	–165	–108	–1172
Ikertivaq c	1	–39.991	65.560	3.1	–2	0	–23	–66	24	167	–143	34	–36	–47	–91
Ikertivaq e	1	–40.090	65.496	2.7	–7	–91	–194	–395	–1434	771	–417	535	–444	–167	–1845
Kangerlussuaq Gletscher	1	–32.477	68.574	6.6	154	–1257	551	–310	–4224	251	413	832	–117	–502	–4211
Koge Bugt a	1	–40.614	65.137	1.9	–128	–107	–56			36	–48	–27	–21	22	–328
Koge Bugt b	1	–41.092	65.122	3.3	–32	–186	–27	–1011	–142	29	1092	–1263	–127	–84	–1750
Koge Bugt c	1	–41.135	64.978	2.4	–150	–24	–2	–552	–459	692	184	–232	–38	768	186
Koge Bugt d	1	–41.064	64.876	3	–255	–136	–170	–663	–91	50	19	–173	2	2	–1415
Kruuse	1	–33.663	67.217	2.4	91	–271	–124	–193	–466	449	171	239	–526	108	–521
Lindenow Gletscher	1	–43.779	60.727	1.2	–103	–83	48	–334	–25	20	132	84	32	–68	–297
Midgårdsgletscher	1	–37.181	66.326	3.7	–14	–111	–527	–1237	–439	–315	–439	–44	–2916	–1775	–7817
Mogens Heinesen a	1	–42.950	62.519	2.1	–317	–507	–251	–42	–1706	351	–260	–58	–362	144	–3007
Mogens Heinesen b	1	–42.972	62.483	1.9	48	–260	–757	–88	–50	130	–8	–76	–60	–16	–1136
Mogens Heinesen c	1	–42.902	62.458	2.3	85	–446	–1282	1233	–2712	809	1174	226	–1286	84	–2115
unnamed a	1	–33.151	67.693	2.3	–5	–842	1232	–874	–1023	1163	103	–316	–674	479	–757
unnamed b	1	–33.188	67.652	3.9	–192	–1443	–894	–579	–557	547	–773	4	12	50	–3826

TABLE A1
Continued

Name	Sector	Longitude	Latitude	Width (km)	2001-2000	2002-2001	2003-2002	2004-2003	2005-2004	2006-2005	2007-2006	2008-2007	2009-2008	2010-2009	SUM
unnamed c	1	–33.355	67.538	2.8	–220	–404	–276	–78	–38	115	144	–125	–114	10	–985
unnamed d	1	–33.314	67.418	4.2			–710	–335	–455	233	348	–537	–63	–269	–1789
Polaric Gletscher a	1	–32.445	67.873	9.5	168	–100	–243	–207	352	–335	80	157	–17	111	–34
Polaric Gletscher b	1	–32.541	67.846	3.9	–97	–290	–483	–40	–57	323	63	100	–413	–55	–949
Puisortoq a	1	–42.404	62.073	2.2	–122	–71	–201	–660	–834	177	–127	312	–461	14	–1972
Puisortoq b	1	–42.501	62.029	2	70	–157	–67	–204	–933	331	–150	10	–1392	649	–1842
Skinfaxe	1	–41.842	63.186	4.2	6	–45	–24	9	–9	56	65	28	–133	71	24
Avaqqat Kangerlua	1	–43.244	61.326	2.1	–22	–82	–332	74	–9	–62	49	–15	42	13	–344
Igutsaat	1	–43.187	61.205	1.3	–3	–144	–269	–777	–920	83	86	–12	–193	201	–1947
Kangerluluk	1	–43.650	61.111	1.9	–249	7	–15	–142	–3866	–308	225	–1191	–1039	102	–6475
Paatusoq	1	–43.568	60.837	1.2	–104	52	–36	–383	–310	–27	53	–29	–67	–19	–872
K.J.V. Steenstrups Nordre Bræ a	1	–34.503	66.582	3.8	–2	–5	–92	–63	–67	–12	27	15	–42	21	–219
K.J.V. Steenstrups Nordre Bræ b	1	–34.489	66.502	4.3	–107	95	43	–268	58	273	203	–208	128	–287	–68
Napasorsuaq a	1	–42.769	61.811	1.7	–123	9	–134	–745	–242	184	95	6	–139	–49	–1139
Napasorsuaq b	1	–42.840	61.790	1.9	–48	29	–71	–13	6	66	7	34	–34	–12	–36
Napasorsuaq c	1	–42.770	61.768	2.2	–62	–199	3	–243	–426	–134	17	–131	–185	–77	–1437
Kangikitsua a	1	–43.069	61.592	2.5	–107	–769	51	–66	–555	122	381	751	–544	18	–717
Kangikitsua b	1	–42.927	61.524	1.9	–67	–6	–37	–609	–46	91	20	0	–65	9	–711
Østre Tasiisaq	1	–34.291	66.673	1.8	–77	–187	–37	–200	–90	140	–143	–133	–80	–361	–1167
Timmiarmiut	1	–43.129	62.750	2.8	170	–635	–174	–1010	–749	288	900	–573	–761	770	–1775
Nunatakgletscher	2	–25.791	73.946	3.3	9	–11	–36	–16	–83	–428	–89	–35	7	64	–618
L.Bistrup Bræ a	2	–22.332	76.513	2.5	–6	–96	105	–21	–103	5	15	–27	–209	–494	–832
L.Bistrup Bræ b	2	–22.385	76.539	2.7	–158	–46	48	7	122	91	–507	–79	–27	–30	–578
L.Bistrup Bræ c	2	–22.438	76.565	1.2					–130			–34	–26	–178	–367
L.Bistrup Bræ d	2	–22.495	76.615	4					–13	112	–194	–184	–432	–531	–1241
Charcot Gletscher	2	–28.864	72.052	1.9	30	–47	–83	72	–43	–1	6	–47	84	–123	–153
Christian IV Gletscher	2	–30.038	68.399	9.5	–83	–69	–27	27	–110	138	–27	18	–41	–118	–291
Daugård-Jensen Gletscher	2	–28.550	71.921	5.8	467	–537	–94	–59	–246	404	318	–453	–124	–63	–387
Ejnar Mikkelsen Gletscher a	2	–22.490	75.552	1.2	–27	–82	–64	–23	–52	7	–1	–34	–171	–38	–485
Ejnar Mikkelsen Gletscher b	2	–22.259	75.657	1.2	46	–120	–92	1	81	44	–30	–21	–26	–17	–134
Kronborg Gletscher	2	–28.652	68.430	2.3	199	–272	–332	–38	–780	108	–278	–88	–3	178	–1306

TABLE A1
Continued

Name	Sector	Longitude	Latitude	Width (km)	2001-2000	2002-2001	2003-2002	2004-2003	2005-2004	2006-2005	2007-2006	2008-2007	2009-2008	2010-2009	SUM
Storbræ	2	–26.080	68.862	3.2	45	–253	–293	11	–134	–139	–200	–305	–497	507	–1258
F. Graae Gletscher	2	–28.683	72.094	2.3	340	–59	36	–1215	–445	–123	135	–76	43	–42	–1406
Heinkel Gletscher	2	–22.345	75.154	2.2	28	32	–92	–32	–72	–38	–134	–45	–130	–25	–507
Hisinger Gletscher	2	–27.403	72.839	2.1	–30	–98	–64	–54	–4	–282	–200	–31	42	–153	–873
Kista Dan	2	–27.418	69.966	3.1	–97	–110	38	57	–168	150	34	85	–122	–18	–150
Kofoed-Hansen Bræ	2	–21.719	77.529	11.7	–205	–59			–136	–54	–42	–163	–9	–98	–766
Magga Dan	2	–27.281	69.966	4.3	40	2	27	–52	9	–27	22	108	23	34	186
Rolige Bræ	2	–28.263	70.583	3.2	68	–403	60	252	–96	112	–185	264	78	–46	103
Akuliarutsip Sermerssua	2	–27.712	73.132	2.5	–9	–33	–42	10	–34	–63	–32	7	–55	–62	–312
Jættegletscher	2	–27.418	73.454	2.5	27	–56	74	–86	–119	123	–5	79	25	–126	–64
Gerard De Geer Gletscher	2	–27.253	73.496	4.2	–63	33	–96	–50	32	75	–143	15	62	–22	–158
Soranerbræen a	2	–21.922	76.035	1.6	–24	–13	–5	–12	3	49	–85	–8	–42	–53	–190
Soranerbræen b	2	–21.691	76.243	3.6	–70	46	21	–63	18	70	–129	87	–29	–40	–89
Storstrømmen a	2	–22.450	76.744	20.1	13	100	–397	122	–167	65	127	103	–48	–622	–705
Storstrømmen b	2	–22.167	76.842	4.9					–837	67	–101	32	42	10	–788
Vestfjord	2	–29.082	70.394	3.9	–57	8	–43	161	–128	10	84	–92	–64	–41	–161
Waltershausen Gletscher	2	–24.203	73.800	10.7	–60	23	–73	–36	13	26	44	83	–8	–50	–39
Alángorssûp Sermia	3	–55.168	73.182	2.1	–2	–44	0	–30	–47	0	–22	75	–35	–42	–145
Cornell Gletscher a	3	–56.171	74.231	2.9	–119	–61	–164	–278	17	–73	–75	–61	–82	–20	–916
Cornell Gletscher b	3	–56.189	74.275	2.1	–74	–149	–183	51	–9	–74	–252	–55	–122	–252	–1121
Dietrichson Gletscher	3	–58.211	75.448	3.4	–40	–73	–20	–124	14	187	–286	65	–151	51	–378
Sverdrup Gletscher	3	–58.311	75.547	6.8	–462	–99	–134	–1235	–114	257	–268	–375	–367	509	–2287
Døcker Smith Gletscher a	3	–61.862	76.205	3.7	193	–356	89	–296	173	–18	–75	–148	24	–56	–470
Døcker Smith Gletscher b	3	–62.189	76.254	3.9	233	–258	1	–4607	–164	41	–93	109	110	–300	–4928
Dodge Gletscher	3	–72.745	78.189	3.4		–42	–89	–82	–27	–17	–49	11	–58	–35	–388
Morell Gletscher	3	–62.536	76.268	3.9	–192	10	–219	–156	–52	101	–331	–1	–47	–661	–1548
Gade Gletscher	3	–63.018	76.331	5.2	–207	125	0	–278	–194	79	166	–27	–88	–14	–437
Nunatakavsaup Sermia a	3	–56.485	74.632	5	–350	–1035	–1521	–1341	–3943	–869	–385	–1120	–106	–454	–11124
Nunatakavsaup Sermia b	3	–56.772	74.672	4.2	–208	48	–310	–231	–886	–270	–1158	–408	–1275	–843	–5540
Nunatakavsaup Sermia c	3	–56.931	74.777	3.9	–46	–28	56	–116	115	–41	–146	32	–77	13	–240
Hayes Gletscher a	3	–56.837	74.830	3.4	–149	–979	–214	90	19	236	–556	–242	6	23	–1767
Hayes Gletscher b	3	–57.002	74.871	3.2	–39	–151	–89	4	–25	61	–105	191	–293	–2	–448

TABLE A1
Continued

Name	Sector	Longitude	Latitude	Width (km)	2001-2000	2002-2001	2003-2002	2004-2003	2005-2004	2006-2005	2007-2006	2008-2007	2009-2008	2010-2009	SUM
Hayes Gletscher c	3	–57.096	74.915	4.9	–26	–117	–528	–202	459	281	–1043	358	–572	–13	–1405
Heilprin Gletscher a	3	–66.071	77.549	4	–539			225	–381	–404	–125	178	–16	–75	–1136
Heilprin Gletscher b	3	–66.004	77.498	1.5	–21			–140	56	–69	–82	23	–69	18	–284
Heilprin Gletscher c	3	–66.020	77.477	1.7	–96			–104	–5	–142	–195	17	–90	–40	–656
Illullip Sermia	3	–56.150	74.396	5.1	109	–270	–71	254	–175	103	105	–75	–10	–224	–254
Inngia Isbræ	3	–52.707	72.009	3.6	3	69	–257	–980	418	–850	–403	–395	–248	–641	–3283
Kakivfait Sermiat a	3	–55.319	73.433	2.3	–76	–143	–64	28	–10	70	–125	49	7	28	–236
Kakivfait Sermiat b	3	–55.530	73.501	3.1	–164	80	–31	–136	–119	500	–382	–34	92	–155	–348
Kangerdlugssûp Sermerssua	3	–51.427	71.460	5.5	–513	3	–93	–183	457	–93	65	–205	–100	216	–448
Kangerdluarssûp Sermia	3	–51.535	71.271	3.8	–175	3	–60	–81	–64	–130	55	–81	–103	–88	–723
Kangilleq	3	–50.665	70.719	2.3	–128	–75	–143	83	–43	72	49	79	–129	–25	–259
Knud Rasmussen Gletscher	3	–68.058	76.686	4.3	–19	16	–58	–79	45	–28	–77	–32	–61	–72	–363
Kong Oscar Gletscher a	3	–59.629	75.921	2	–31	–356	30	–10	26	–12	21	–139	–29	18	–483
Kong Oscar Gletscher b	3	–59.985	75.938	4.4	–1746	–545	–1012	–462	289	–468	–341	–525	147	136	–4528
Kong Oscar Gletscher c	3	–60.115	75.989	3.5	14	22	–102	44	170	73	–158	51	123	–555	–318
Kong Oscar Gletscher d	3	–60.281	76.026	3	–221	–77	–193	25	–192	93	–98	–46	57	–184	–836
Yngvar Nielsen Gletscher a_l	3	–64.169	76.316	4.9	–110	–11	–21	–132	–54	62	39			–185	–411
Yngvar Nielsen Gletscher a_r	3	–64.169	76.316	4.9	–533	–29	46	–138	–75	263	–96	–82	–45	–82	–770
Yngvar Nielsen Gletscher b	3	–64.338	76.351	2.3	–96	321	–408	189	–212	22	–18	–98	–13	42	–272
Helland Gletscher b	3	–64.596	76.250	2.6	18	34	–68	–110	27	–47	–314	–139	–162	–59	–821
Helland Gletscher a_l	3	–64.907	76.173	5.1	–99	–63	–294	–89	–90	–50	–120	–107	–125	–156	–1193
Helland Gletscher a_m	3	–64.907	76.173	5.1	–98	153	–155	–64	77	–16	–136	–114	–187	–243	–783
Helland Gletscher a_r	3	–64.907	76.173	5.1	–133	37	–31	–104	87	130	–246	–77	–94	–8	–438
De Dødes a	3	–66.811	76.219	3.2	–307	–257	–182	–316	18	–4	–45	–78	–16	–18	–1205
De Dødes b_l	3	–66.891	76.249	3.2	–220	–158	140	–222	–28	–169	–141	–56	–229	–46	–1128
De Dødes b_r	3	–66.891	76.249	3.2	–192	–187	139	–213	–113	–73	–334	–65	–35	–25	–1098
De Dødes c	3	–67.116	76.239	2.8	–510	–66	–80	–133	–71	–30	–126	–126	–297	–133	–1570
De Dødes d	3	–67.296	76.174	5.3	–741	–49	88	–519	–193	189	–447	–78	–234	–406	–2390
Lille Gletscher	3	–50.545	70.486	2.4	75	–105	–148	–124	–53	–101	–62	13	–121	–28	–653
Leidy Gletscher	3	–66.117	77.266	3.7	–60	–57	5	–161	109	–86	–183	–143	–30	–87	–693
Marie Gletscher	3	–66.121	77.196	3.3	10	–31	–31	–121	57	89	–87	27	–71	–79	–237
Harald Moltke Bræ	3	–67.848	76.606	6.8	–258	–618	–303	–492	1168	–458	–534	–246	–690	–454	–2886

TABLE A1
Continued

Name	Sector	Longitude	Latitude	Width (km)	2001-2000	2002-2001	2003-2002	2004-2003	2005-2004	2006-2005	2007-2006	2008-2007	2009-2008	2010-2009	SUM
Morris Jesup Gletscher	3	–71.241	77.870	3.2	–79	0	10	–51	25	116	–71	–44	–154	–44	–291
Diebitsch Gletscher	3	–71.668	77.915	3.5	–262	–95	–130	–4	64	2	–200	–131	–179	–67	–1002
Clements Markham Gletscher	3	–72.055	77.921	1.7	–79	–38	–41	–85	–33	–11	–82	–11	–40	–31	–451
Bamse Gletscher	3	–72.310	78.039	2.1	–77	–54	–89	–73	–30	41	–97	11	–35	–36	–439
Verhoeff Gletscher	3	–69.993	77.836	3.1	–67	6	–16	46	30	–41	21	–27	–3	–62	–113
Iterdlagssûp Qíngua	3	–69.456	77.756	1.1	–133	35	–24	5	–32	–76	–99	13	–108	–109	–528
Nansen Gletscher a	3	–58.510	75.723	7.5	–39	22	14	–29	34	–68	52	–31	50	–45	–39
Nansen Gletscher b	3	–58.998	75.712	4.5	–354	–50	–278	–322	–703	365	85	–437	150	–475	–2021
Nordenskiöld Gletscher a	3	–59.230	75.800	3.9	–14	–33	11	–75	65	–19	–129	–9	–11	–98	–312
Nordenskiöld Gletscher b	3	–59.160	75.842	3	–301	39	42	–68	–93	42	86	–69	–42	41	–323
Nordenskiöld Gletscher c	3	–59.208	75.869	3	–151	–77	–45	–18	14	12	–131	–59	–105	–31	–590
Nunatakavsaup Sermia	3	–55.173	73.215	2.7	–67	–116	–184	11	58	14	61	151	–125	–136	–332
Igssûssarssuit Sermia	3	–60.701	76.005	3.4	17	166	187	–386	43	–53	–56	88	–68	–102	–165
Peary Gletscher	3	–60.859	76.147	2.4	–137	–68	–330	25	–104	–19	–94	66	–25	–94	–779
Perlerfiup Sermia	3	–50.948	70.990	2.8	–338	–11	–115	–83	–39	20	29	12	–98	–186	–806
Qeqertarsuup Sermia	3	–55.635	73.563	3.3	8	–29	23	16	–13	2	–91	–238	–394	–1370	–2088
Rink Gletscher a	3	–61.064	76.162	2.9	–63	185	–266	–599	–2187	–289	–58	47	–69	–66	–3364
Rink Gletscher b	3	–61.064	76.162	2.3	–63	185	–266	–1078	–2039	–97	–274	8	–40	–75	–3737
Rink Gletscher c	3	–61.261	76.173	1.7	–66	–60	–20	–323	19	45	–6	–22	–74	–75	–584
Rink Gletscher d	3	–61.393	76.169	3.1	–214	55	15	–95	58	216	–311	13	–22	–16	–300
Rink Isbræ	3	–51.704	71.726	4.8	73	–63	–599	211	55	–350	332	89	–25	–138	–415
Sermeq Silarleq	3	–50.821	70.792	4.4	–217	–37	–266	–711	–177	–68	–162	165	–394	–326	–2193
Sermilik	3	–50.625	70.628	2.7	–88	–54	14	–64	31	–53	–30	116	8	–43	–163
Kjer Gletscher a	3	–57.574	74.973	4.2	–389	–24	252	–631	226	–948	–143	–122	56	–21	–1745
Kjer Gletscher b	3	–57.984	75.135	5.4	–136	–62	–36	35	76	–3	–73	–274	–819	128	–1163
Kjer Gletscher c	3	–57.938	75.174	5.1	–151	–27	–106	–1	–35	67	–90	–86	–26	–111	–566
Steenstrup Gletscher	3	–58.300	75.240	5.4	–1370	–798	–642	–167	28	25	–611	–311	–173	189	–3830
Storm Gletscher	3	–72.836	78.135	2.1		–78	–79	22	62	–135	–77	–66	–49	–24	–423
Store Gletscher	3	–50.570	70.379	5.3	–153	89	–72	108	35	–81	177	98	–158	–13	30
Tracy Gletscher	3	–66.582	77.647	8.3	–1915	–1875	291	–1592	–62	–825	–25	85	–142	31	–6028
Melville Gletscher	3	–66.665	77.714	1.6	–62	64	–271	478	–125	35	–611	136	–97	–185	–639
Sharp Gletscher	3	–66.968	77.686	1.5	139	–183	–127	27	90	–83	–47	8	1	–28	–201

TABLE A1
Continued

Name	Sector	Longitude	Latitude	Width (km)	2001-2000	2002-2001	2003-2002	2004-2003	2005-2004	2006-2005	2007-2006	2008-2007	2009-2008	2010-2009	SUM
Hart Gletscher	3	–67.085	77.675	2.1	–2	–67	–10	19	–21	16	–33	62	–139	–59	–235
Hubbard Gletscher	3	–67.832	77.528	2.5	–13	–163	–61	–107	19	–27	–19	–66	–22	–22	–481
Bowdoin Gletscher	3	–68.671	77.655	3.1	–160	–16	86	–42	–60	–63	–27	102	–286	–249	–715
Meehan Gletscher	3	–70.311	77.868	1.2	–124	6	–127	–207	44	13	–28	–18	–3	17	–428
Umiámáko Isbræ	3	–52.576	71.671	4.2	–588	208	–335	–514	–445	–1505	–65	–522	–344	–94	–4203
Upernavik Isstrøm a	3	–54.611	72.833	3.1	–301	68	–317	175	217	68	163	–611	284	167	–86
Upernavik Isstrøm b	3	–54.694	72.899	3.6	–149	121	–84	155	–132	73	–171	51	–203	–590	–930
Upernavik Isstrøm c1	3	–54.783	72.981	4.2	–170	–194	–130	96	–32	–85	–1516	–2642	53	–253	–4873
Upernavik Isstrøm c2	3	–54.783	72.981	3.6	–219	–107	–330	–109	–350	–208	–350	101			–1571
Ussing Bræer a	3	–55.649	73.850	4.1	111	–136	–183	195	–52	161	–44	107	–172	–149	–162
Ussing Bræer b1	3	–55.871	73.920	2.9	34	–1	–37	59	50	–5	–58	75	–88	127	155
Ussing Bræer b2	3	–55.871	73.920	2.8	8	123	–268	–474	–793	–229	–36	–85	–103	6	–1852
Akugdlerssûp Sermia	4	–49.601	64.353	3.5	–103	–74	–125	–100			14	119	162	125	20
Alángordliup Sermia	4	–50.224	68.956	2.5	21	–85	–149	–69	–251	71	3	–71	–30	51	–507
Eqalorutsit Kitdlít Sermiat a	4	–46.058	61.257	0.9	–95	–103	–209	–129	–71	–10	64	3	3	–6	–553
Eqalorutsit Kitdlít Sermiat b	4	–46.102	61.242	1.3	–509	–370	–518	–393	–21	462	–180	149	–139	–389	–1909
Eqalorutsit Kangiglít Sermiat	4	–45.785	61.314	3.5	81	–63	85	95	–104	51	–58	53	36	–17	159
Eqip Sermia	4	–50.272	69.786	4.5	–75	–154	–105	–97	–181	–50	–181	130	–261	–455	–1430
Nakaissorssuaq	4	–49.684	63.046	1.9	11	–67	–74	–60	19	–131	137	48	–16	–16	–149
Avannarleq Bræ	4	–49.015	62.201	1.9	97	–12	150	–297	23	97			–99	–11	–53
Jakobshavn Isbræ N	4	–49.715	69.214	5.8	2355	–2045	–5974	–1745	–626	–732	20	–450	632	–688	–9255
Jakobshavn Isbræ S	4	–49.623	69.157	5.5	2667	–2346	–5668	–3052	–974	–1415	–551	–163	–484	–944	–12930
Kangiata Nunâta Sermia	4	–49.659	64.333	4.4	72	–117	–172	–220			–373	238	179	–191	–583
Kangilerngata Sermia	4	–50.371	69.895	4.3	187	–85	–309	–161	–167	–1034	280	–242	–122	–846	–2499
Narsap Sermia	4	–50.059	64.658	4.5	–51	–57	49	7			–39	38	–143	–473	–670
Sermilik	4	–48.757	61.965	3.7	146	29	103	–464	188	39	56	–28	51	–172	–53
Nigerlikasik Bræ	4	–48.830	62.065	1.9	–51	–104	–100	–74	–296	–207	68	–329	–388	–130	–1610
Avannarleq Bræ	4	–49.014	62.198	1.8	81	–106	5	–111	29	45	9	233	–185	–125	–124
Qôrqup Sermia	4	–45.204	61.193	1.6	138	–99	–224	–426	78	–3	–42	–52	225	–181	–586
Sarqardliup Sermia	4	–50.308	68.907	5.1	16	18	3	–186	–139	14	7	6	–35	52	–244
Sermeq Avannarleq	4	–50.339	69.351	3.6	62	–155	192	–603	–352	–43	–181	–661	–47	–102	–1889
Sermeq Avannarleq	4	–50.313	70.051	6.1	33	–66	22	31	–53	47	–2	–72	63	–17	–13

TABLE A1

Continued

Name	Sector	Longitude	Latitude	Width (km)	2001-2000	2002-2001	2003-2002	2004-2003	2005-2004	2006-2005	2007-2006	2008-2007	2009-2008	2010-2009	SUM
Sermeq Kujalleq	4	–50.224	69.998	5.2	–68	–9	–11	116	–342	871	–581	858	–607	–215	13
Sermiligaarsuk	4	–48.334	61.585	3.6	11	22	–2	3	–1	–129	50	43	8	–144	–140
Academy Gletscher	5	–32.638	81.653	8.3	–233	–275			–530	–59			587	–486	–995
Hagen Bræ	5	–28.718	81.481	11.2	–77	78	597	1250	922	406	546	–1049	–14940	–165	–12432
Humboldt Gletscher	5	–64.646	79.512	98.6			–1206	–534	–294	–674	501	–883	–257	–1044	–4391
Marie Sophie Gletscher	5	–33.054	81.788	4.4	125	–578			60	–105			–79	346	–232
C. H. Ostenfeld Gletscher	5	–45.410	81.599	12.6							–1173			68	–1104
Petermann Gletscher	5	–61.676	81.096	15.2	1127	–8163	1143	1005	1098					–7498	–11287
Ryder Gletscher	5	–50.894	81.850	9.9			439	426	569	521	–3354				–1399
Steensby Gletscher	5	–54.635	81.601	4.2					229					240	470

TABLE A2

Seasonal variations in regional glacier front positions calculated by detrending the data presented in Figure 6 on an annual basis. Values are missing in 2010 as data for 2011 are not included and no extrapolation was undertaken. (a) Seasonal variation in median postion; (b) seasonal variation in mean position. In each case the subscript “<“ denotes glaciers with an overall retreat less than 1500 m and “>” glaciers with an overall retreat greater than 1500 m. Locations and numbers of glaciers in each region/group shown in Figure 1.

(a) Median	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Mean
$\mathrm{SE}_{<}$	310	70	60	130	60	100	90	150	190	80	120
$\mathrm{SE}_{>}$	620	160	140	190	180	320	320	210	480	320	300
$\mathrm{NE}_{<}$	160	170	140	130	220	90	110	100	100	90	130
$\mathrm{NE}_{>}$	140	260	70	170	220	490	450	330	180	250	260
$\mathrm{NW}_{<}$	150	100	170	80	70	130	90	130	150	130	120
$\mathrm{NW}_{>}$	380	300	210	140	160	270	320	380	200	310	270
$\mathrm{SW}_{<}$	50	70	50	30	70	50	80	110	60	110	70
$\mathrm{SW}_{>}$	150	20	10	40	160	130	180	330	200	330	160
$\mathrm{N}_{<}$	—	90	100	200	200	190	20	0	70	110	110
$\mathrm{N}_{>}$	290	750	1750	20	100	50	990	450	340	300	490

(b) Mean	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	Mean
$\mathrm{SE}_{<}$	150	60	90	90	80	100	70	130	120	70	100
$\mathrm{SE}_{>}$	910	260	150	200	300	410	380	400	540	190	370
$\mathrm{NE}_{<}$	90	90	80	80	90	70	110	80	100	100	90
$\mathrm{NE}_{>}$	250	220	200	100	200	250	290	230	140	240	210
$\mathrm{NW}_{<}$	90	60	90	60	60	90	100	110	130	110	90
$\mathrm{NW}_{>}$	100	190	100	130	190	210	220	260	190	270	190
$\mathrm{SW}_{<}$	50	80	50	30	70	50	90	70	40	110	60
$\mathrm{SW}_{>}$	620	880	580	270	330	240	250	420	240	290	410
$\mathrm{N}_{<}$	—	90	100	110	20	90	150	120	30	40	80
$\mathrm{N}_{>}$	70	540	540	80	90	180	160	100	720	660	310