JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, F02022, doi:10.1029/2007JF000927, 2008

Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007

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Received 24 October 2007; revised 4 February 2008; accepted 27 March 2008; published 7 June 2008.

[1] Previous studies in Greenland show that retreat of tidewater glaciers may be linked to recent increases in ice loss, raising Greenland's contribution to sea level rise. We examined ice front changes of 203 tidewater glaciers, land-terminating glaciers, and glaciers terminating with ice shelves to understand Greenland glacier behavior over three periods: 1992–2000, 2000–2006, and 2006–2007. We observed synchronous, ice sheet–wide increases in tidewater retreat during 2000–2006 relative to 1992–2000, coinciding with a 1.1°C increase in mean summer temperature at coastal weather stations. Rates of retreat for the southeast and east slowed during 2006–2007 when temperatures were slightly cooler than the 2000–2006 average. Our work suggests that regional Greenland tidewater retreat responds strongly to climate change, with higher temperatures corresponding to increasing retreat, and helps confirm a link between ice thickness, velocity, and ice front position.

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

1. Introduction

[2] Recent studies of the Greenland Ice Sheet reveal rapid changes in ice dynamics around most of the margin, increasing the ice sheet's contribution to sea level rise [*Rignot and Kanagaratnam*, 2006; *Shepherd and Wingham*, 2007; *Thomas et al.*, 2006]. *Krabill et al.* [2000] found that 70% of the coastal ice sheet thinned appreciably before 2000. Thinning rates of >1 m a^{-1} were typical between 1994 and 2003, and the thinning accelerated after 1999 [*Krabill et al.*, 2004]. During the same period, Jakobshavn Isbrae, the largest outlet glacier on Greenland's west coast, retreated rapidly, and its near-terminus region almost doubled in speed [*Joughin et al.*, 2004; *Thomas*, 2004]. Major speedups followed on the two largest outlet glaciers along Greenland's east coast, Kangerdlugssuaq and Helheim [*Howat et al.*, 2007, 2005; *Luckman et al.*, 2006]. Over the same period, nearly all of the glaciers along Greenland's southeast coast sped up by 50% or more [*Rignot and Kanagaratnam*, 2006]. Collectively, these accelerations increased ice discharge to the ocean by 133 Gt a^{-1} from 1996 to 2005, an equivalent added sea level rise of 0.34 mm a^{-1} [*Rignot and Kanagaratnam*, 2006].

[3] Work on Jakobshavn [*Joughin et al.*, 2004; *Thomas*, 2004], Kangerdlugssuaq [*Howat et al.*, 2007; *Luckman et al.*, 2006], and Helheim [*Howat et al.*, 2005; *Luckman et al.*, 2006] shows that along with speedups and thinning, the ice fronts of these glaciers retreated rapidly. Collectively, studies of these three glaciers suggest that glacier retreat may be part of a cycle: (1) conditions change near the glacier terminus, such as thinning to flotation or increasing occurrence of full ice thickness fracture, allowing for initial glacier retreat; (2) a loss of ice buttressing from glacier retreat causes an increase in near-terminus ice velocity; (3) thinning near the terminus increases the inland surface slope, causing speed to increase up glacier; and (4) dynamic thinning propagates up glacier with the velocity increase. Once in process, the dynamic changes act as a positive feedback to further destabilize the near-terminus ice. Since thinning at the terminus and retreat may serve as initial indicators for this progression, observations of retreat or thinning can provide an early indication of other dynamic changes. While thinning data are unavailable for many outlet glaciers, retreat can be observed around the entire ice sheet with current satellite images.

[4] Tidewater glaciers, which end in the ocean at either a grounded calving front or a short floating ice tongue, are classically thought to advance slowly as they build a sediment shoal in front of their terminus ice and then retreat quickly when they can no longer maintain a terminus position [*Meier and Post*, 1987]. Traditionally, this cycle has not been directly linked to climate changes but has been thought to depend on factors including topography, mass balance distribution, and bed character [*Meier and Post*, 1987]. These traditional theories of tidewater glacier dynamics come from observations of glaciers emanating from smaller ice fields, primarily Alaskan. While tidewater glaciers are abundant in Greenland, they have not been studied as extensively as their counterparts in Alaska and other locations.

[5] Recent studies of glacier retreat and advance in Greenland have focused on single glaciers or limited

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0148-0227/08/2007JF000927$09.00

regions [*Howat et al.*, 2007; *Luckman and Murray*, 2005; *Warren*, 1991]. We used synthetic aperture radar (SAR) images from 1992 [*Fahnestock et al.*, 1993], 2000, 2006, and 2007 and Landsat satellite images to create a comprehensive spatial database of ice front changes. This database presents a pan-regional view of glacier variation during a period of change in ice dynamics and climate.

2. Data Sets

[6] SAR mosaics, created by compiling many images over most of Greenland, are the primary image set used to locate glacier ice fronts. We used mosaics from 1992, 2000, 2006, and 2007. For 1992, we used two mosaics to maximize coverage. The two 1992 mosaics represent different seasons and have different image quality. The earlier 1992 mosaic [*Fahnestock et al.*, 1993] contains images from 2 August 1992 to 9 September 1992 and has 100-m resolution. This mosaic was made from C band SAR images from the ERS-1 satellite [*Fahnestock et al.*, 1993]. The later, nominally 1992 mosaic contains ERS-1 images from 19 December 1992 to 24 March 1993 and has a resolution of 40 m. Of these two mosaics, we used the 40-m resolution 1992 mosaic wherever possible because the data were collected at roughly the same time of year (approximately winter) as the later mosaics. In addition, it was georeferenced and terrain corrected using the same digital elevation model and algorithms that were used to produce the subsequent mosaics.

[7] The 2000 mosaic contains images from 21 September 2000 to 23 January 2001, with most of the images acquired in December. The 2006 mosaic contains images from 24 December 2005 to 21 March 2006, with most images from January, and the 2007 mosaic is also created primarily from January images, with a range from 20 December 2006 to 4 February 2007. For simplicity, we refer to these as the 2000, 2006, and 2007 mosaics. These three mosaics were created from RADARSAT fine-beam resolution images and have 20-m resolution and almost complete coverage of Greenland (Figure 1). All the data used in these mosaics are fine-beam RADARSAT-1 data with a narrow incidence angle range (36.8° to 39.9°), which helps minimize relative geometric errors. The mosaics are coregistered such that relative geometric errors between the RADARSAT mosaics are less than a single 20-m pixel, although absolute error after using a digital elevation model [*Bamber et al.*, 2001] to remove terrain distortion [*Joughin*, 1995] can be larger. We have verified the coregistration by cross-correlating image patches on stationary regions at several locations around the ice sheet margin.

[8] To supplement our 1992 and 2000 data, we used a limited amount of Landsat satellite images in the lower half of the southwest and southeast regions (south of 62°N) and in the eastern region (between 68°N and 72°N) (Figure 3). The Landsat images that we included were collected within the periods of 10 July 1992 to 11 August 1992 and 4 August 2000 to 10 November 2000. Landsat images were used as the source only if there were no SAR data available, and the Landsat image registration was compared with the SAR mosaics to ensure error of less than approximately 100 m. These images allowed us to add measurements for 33 glaciers during 1992–2000 (in the southeast, southwest, and east regions) and three glaciers during 2000–2006 (in the southwest and southeast regions). None of the eight glaciers with Landsat measurements in the southwest and southeast have measurements for all three periods, and thus they are not included in the discussion of southeast regional changes.

3. Methods

[9] All mosaics were overlaid in a geographical information system, and ice fronts were digitized in the same reference frame (Figure 2). Rather than using a single midglacier reference line to measure retreat or advance, we used an open-ended box that approximately delineated the sides of the glacier and an upflow, arbitrarily chosen reference line (Figure 2). We digitized the ice front position in each mosaic, and the mean retreat was calculated as the area change divided by the mean glacier width for the time period of interest. Because this method accounts for uneven changes along the ice front, we can better assess ice front position changes than if we used only a single along-flow reference line. This process also accounts for the changing width of the terminus, allowing us to approximate the area loss or gain between the two periods.

[10] We attempted to digitize all glacier fronts wider than 2 km (Figure 3). Reliable digitization was not possible for a few glacier fronts because of intense fracturing that can make it difficult to distinguish the true terminus from the adjacent mix of glacier and sea ice. In some cases, image distortion due to extreme local topography of the fjord or an inability to distinguish an ice front in the imagery can prevent reliable digitization. These problems, however, affected fewer than 20 glaciers, and in section 4.1 we discuss the behavior of some of these, primarily northern, glaciers.

[11] The main source of uncertainty is measurement error, which includes manual digitization error, geometric distortion, and resolution limits. To evaluate the error, we digitized 20 locations on the ice sheet edge at locations where there is no discernable change in the margin position (note that there are areas on the ice sheet margin where the mosaics reveal significant retreat, and we have avoided those for this comparison). At each location we digitized a section of, on average, 3.5-km width to match the average width of glaciers in our study data set. Since we digitized a nearly stationary feature, all changes are assumed to be due to error from manual digitization, orthorectification, and resolution limits. For the difference between the 1992 mosaic and 2000 mosaic, we used the 100-m resolution 1992 mosaic because it has greater error associated with resolution and geolocation and therefore provides an upper limit to our errors involving the 1992 data. The mean change and standard deviation between each set of mosaics is shown in Table 1. The calculated error is less than 1 m a^{-1} for data comparisons between 2000–2006 and 2006–2007, with standard deviation less than 2 m a^{-1}, while the mean difference between 1992 and 2000 is -1 m a^{-1} and standard deviation is 24.4 m a^{-1}. Because we digitized over the width of the ice front, the digitization errors are reduced to subpixel levels by averaging approximately 175 pixels over the 3.5-km digitized width. This is another advantage of using a box measurement method as opposed to a single reference line.

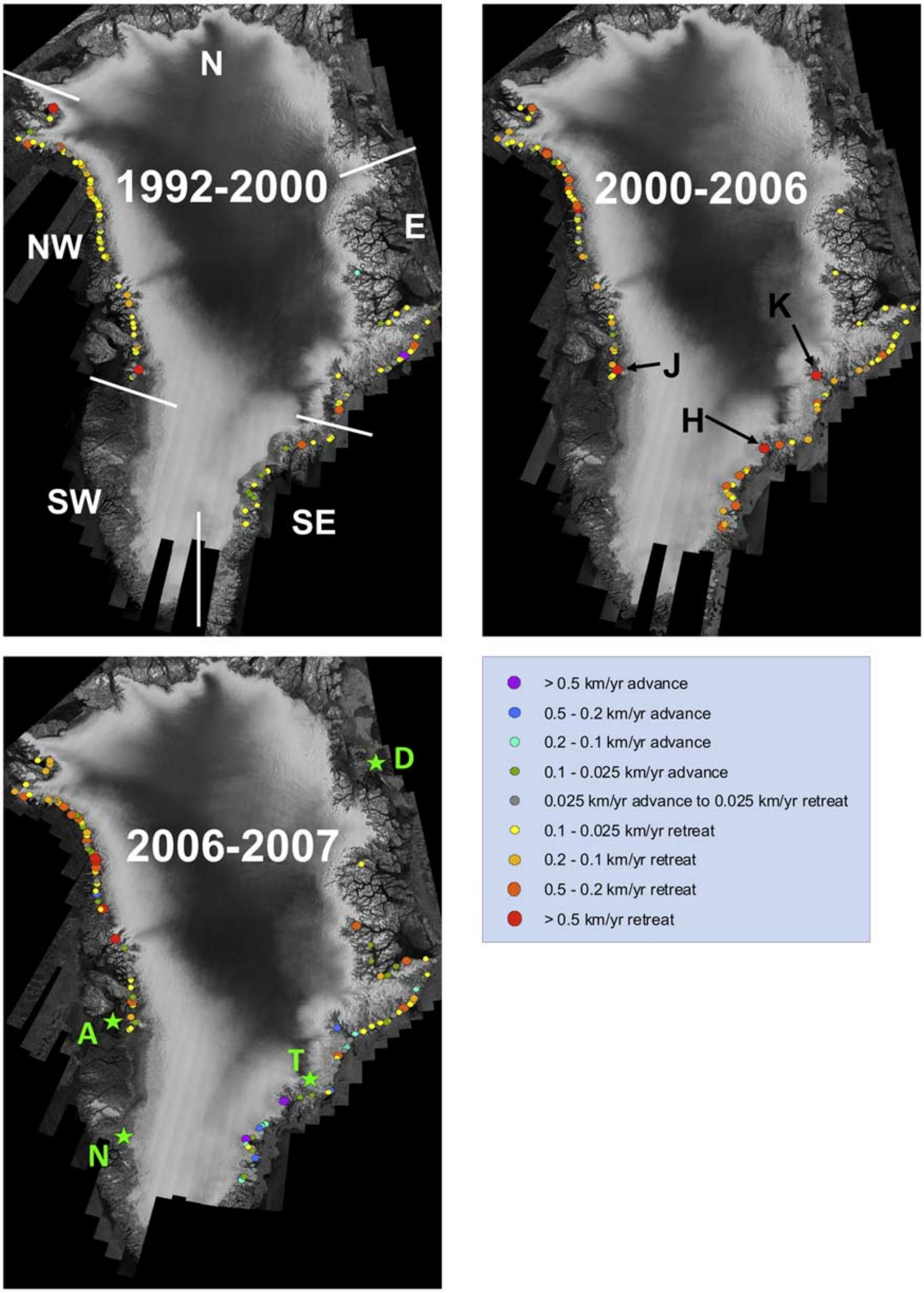

Figure 1. Magnitude and location of retreat and advance. Results show retreating (warm colors) and advancing (cold colors) outlet glaciers for (top left) 1992–2000, (top right) 2000–2006, and (bottom) 2006–2007. The locations of Jakobshavn (J), Kangerdlugssuaq (K), Helheim (H), and weather stations at Nuuk (N), Aasiaat (A), Danmarkshavn (D), and Tasiilaq (T) (green stars) are indicated. White lines show the extent of the five geographic regions: north (N), east (E), southeast (SE), southwest (SW), and northwest (NW). The results are overlaid on the (top left) 2000, (top right) 2006, and (bottom) 2007 SAR mosaics.

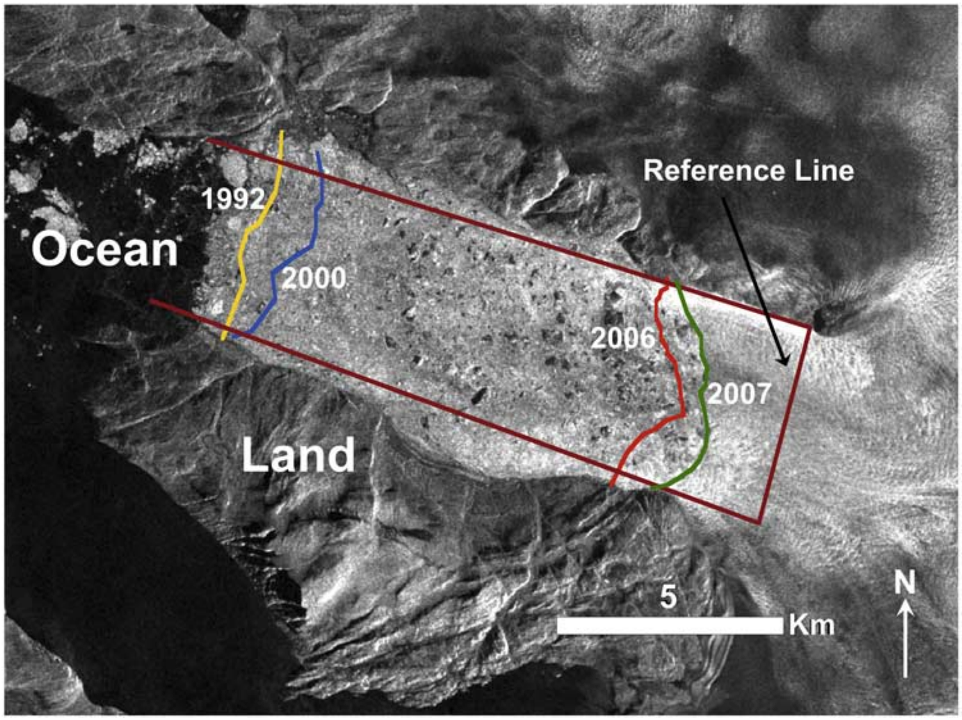

Figure 2. A digitized outlet glacier front 650 km north of Jakobshavn (74.62°N, 56.27°W). Straight lines (dark red) designate the approximate glacier margins and an arbitrary upstream reference line, with the ice front positions digitized for 1992 (yellow), 2000 (blue), 2006 (bright red), and 2007 (green). This glacier retreated 952 m from 1992 to 2000, 8706 m from 2000 to 2006, and 89 m from 2006 to 2007. Location is shown in Figure 3.

[12] Greenland's tidewater glaciers generally have an annual cycle of advance and retreat, with the farthest advance likely during late winter/early spring and the farthest retreat at the end of the summer (approximately August) [*Dwyer*, 1995; *Sohn et al.*, 1998]. To evaluate the expected changes in ice front location due to the annual cycle, we used the two 1992 SAR mosaics, which were collected in different seasons. The temporal separation allowed us to establish the ice front change that might be expected within the range of an annual cycle. We digitized 39 glaciers, including land-terminating and tidewater glaciers that appear in both 1992 mosaics, and calculated the change in ice front position. The result is a mean advance of 40 m and one standard deviation of 220 m from the summer mosaic (100-m resolution) to the winter mosaic (40-m resolution). This compares favorably with 1978–1991 measurements of variability on 10 eastern Greenland glaciers with widths greater than 2 km, which gave a mean annual change of 0 m and a standard deviation of 280 m (210 m if Kangerdlugssuaq is omitted) [*Dwyer*, 1995]. These numbers provide a basis for interpreting the magnitude of change during the three periods we examine here.

[13] To incorporate the potential influence of the annual cycle on our measurements, we set a threshold to distinguish between small and large change. Since our 1992 (40-m resolution), 2000, 2006, and 2007 mosaics were recorded during the same season, steady state should show no change in ice front position, but changes beyond those observed during an annual cycle are particularly important. We set the threshold at 440 m (2σ) of advance or retreat per year for individual glaciers. For regional analysis of glacier behavior, our expected regional change during an annual cycle depends on the number of glaciers. This threshold between small and large change during an annual cycle is $2\sigma/\sqrt{n}$, where σ is the standard deviation (220 m) and n is the number of glaciers in the region. For the tidewater data sets in the northwest, southeast, and east, the threshold between large and small regional change is 55, 96, and 74 m a^{-1}, respectively. Examining periods of 8 years (1992–2000) and 6 years (2000–2006) also reduces this threshold of small change when the data are converted to an annual average rate because the normalized value represents sustained change. Over multiyear periods, small variation for a region is $2\sigma/t\sqrt{n}$, where t is the observation period length, giving regional values of 7 m a^{-1} (NW), 12 m a^{-1} (SE), and 9 m a^{-1} (E) for 1992–2000 and 9 m a^{-1} (NW), 16 m a^{-1} (SE), and 12 m a^{-1} (E) for 2000–2006. Similarly, the individual glacier values can be divided by the observation period to define the threshold for small single glacier advance or retreat. To minimize the influence of the annual retreat/advance cycle on our results, we prioritized use of data from the winter season, as reflected in the dates of our mosaic images.

4. Results

[14] To assess the effect of terminus type on glacier behavior and to better evaluate changes specific to each glacier type, we divided the outlet glaciers into three categories: tidewater, terminating on land, and terminating

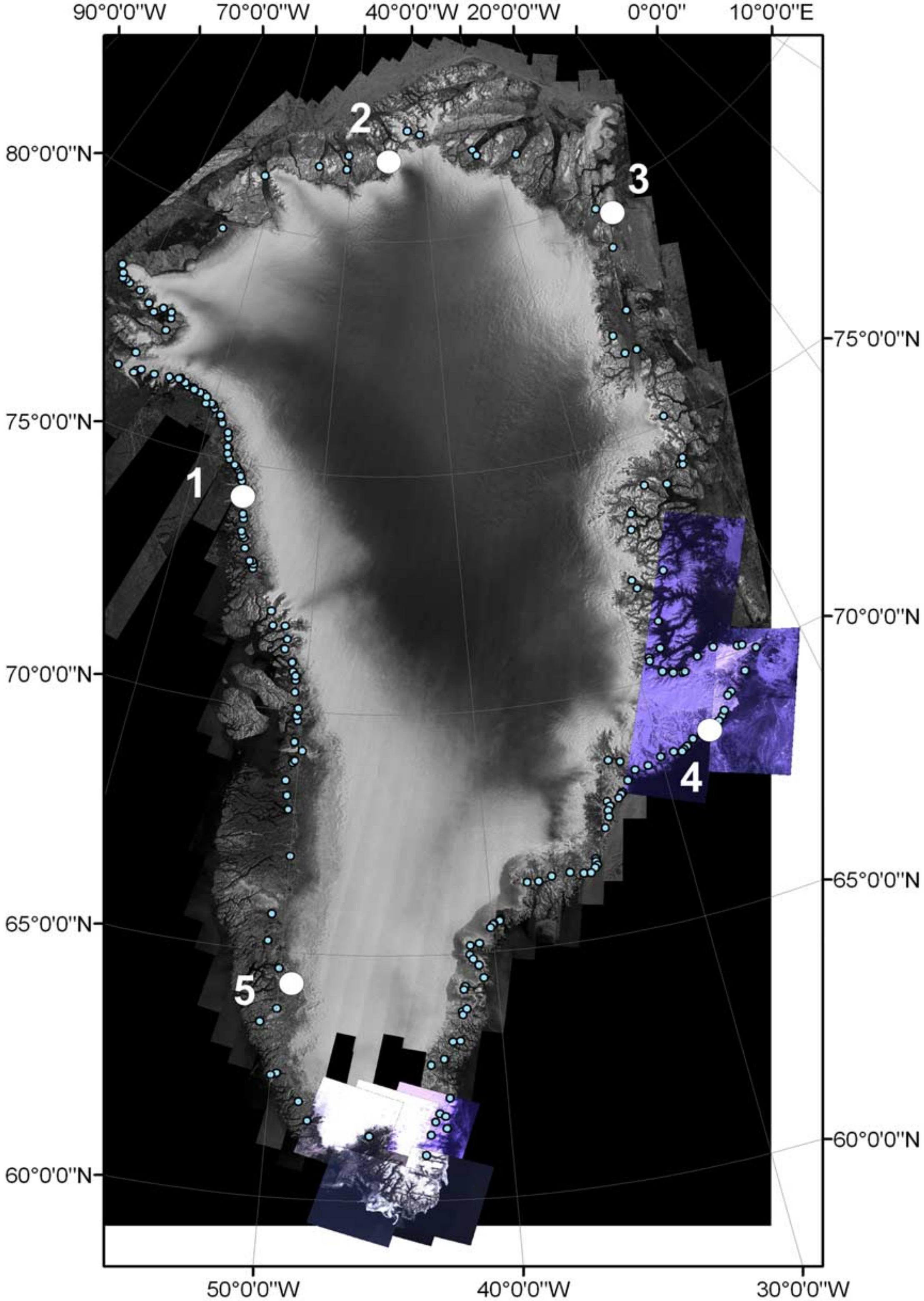

Figure 3. Location of all glaciers considered in the study (small blue points), including glaciers with fronts measured for one or two time periods only. Locations are indicated as follows: 1, the glacier in Figure 2; 2, C. H. Ostenfeld Gletscher; 3, Zachariae Isstrom; 4, the eastern glacier with a 562 m a^{-1} advance during 1992–2000; and 5, Kangiata nunata sermia. The Landsat images we considered are also shown but were only used if the SAR mosaics had no reliable ice front for a given glacier.

Table 1. Error Associated With Measurement Errors for Each Mosaic Pair Used for Data Collection[a]

	1992–2000	2000–2006	2006–2007
Mean change, m a^{-1}	−1.0	−0.1	−0.2
Standard deviation, m a^{-1}	24.4	0.5	1.3

[a] Errors represent measurements from 20 positions on the stable ice sheet edge.

in an ice shelf (>10-km length). If a glacier shifted between groups, we classified it within the most recent configuration; for example, Jakobshavn is classified as a tidewater glacier, though it did have an ice shelf in the 1992 mosaic. We expect the glaciers we measured with an extended ice shelf to behave differently than tidewater or land-terminating glaciers, calving off large tabular icebergs episodically. Indeed, we do observe large advance and retreat events on these ice shelf glaciers, but we treat glaciers with ice shelves separately from the tidewater glaciers because the dynamics of ice shelf calving make it difficult to interpret retreat events without higher-resolution temporal coverage.

[15] Examining the land-terminating glaciers, we found that these glaciers did not change appreciably in any region. The mean and median values for ice front position change in land-terminating glaciers were comparable to the measurement error for all time periods (ice front change $\leq$5 m a^{-1}). In contrast, observations of tidewater glaciers show patterns of retreat or advance that are consistent on the regional scale.

[16] Imagery is not consistently available for all glaciers during all periods. The following number of glaciers were measured within each time period: 153 for 1992–2000, 189 for 2000–2006, 174 for 2006–2007; nine glaciers were identified but not measured. The data include 6 glaciers with ice shelves, 15 land-terminating glaciers, and 182 tidewater glaciers. Of the 182 tidewater glaciers, 122 are measured during all three time periods. In discussion of the northern and southwestern regions, we use all measured glaciers, while for the northwest, east, and southeast we focus only on the glaciers that could be measured during all three periods. We also derive retreat rates from these data to compare retreat per year for all glaciers.

4.1. North Greenland Glaciers

[17] The northern region has 17 glaciers that fit our criteria, including two land-terminating glaciers and nine tidewater glaciers. Of these, four tidewater glaciers were measured during all three periods. These four glaciers retreated at an average annual rate of 94 m a^{-1} during 1992–2000 and 81 m a^{-1} during 2000–2006 and advanced at 40 m a^{-1} during 2006–2007. The two land-terminating glaciers have more limited measurements but show little change.

[18] The remaining six northern glaciers terminate in ice shelves. The regional pattern of retreat in northern Greenland is dominated by relatively large fluctuations of these ice shelf glaciers, on the order of kilometers, as they calve off icebergs. Therefore, our limited temporal coverage may bias ice shelf glacier results, making it difficult to accurately assess long-term trends. Also, many of these glaciers that terminate in ice shelves develop heavily fractured tongues, limiting our ability to define a true ice front. The imagery does, however, reveal large changes on some northern ice shelves. For example, most of the floating ice tongue on C. H. Ostenfeld Gletscher disintegrated between 2000 and 2006 (Figure 4a), with almost no change in ice front position from 2006 to 2007 (and no 1992 data). The images suggest that approximately 350 km^2 of ice shelf were lost, representing an event roughly 4 times larger than the 2005 breakup of the Ayles Ice Shelf in Canada [*Holden*, 2007]. Zachariae Isstrom, on the northeastern coast, also lost ice shelf area between 2000 and 2006 (Figure 4b), with only small changes during 1992–2000 and during 2006–2007. Images from 2000 and 2006 show the loss of about 1400 km^2 of ice shelf area from Zachariae Isstrom. This area was composed of approximately 85% glacier ice and 15% sea ice in the 2000 mosaic.

4.2. Southwest Greenland Glaciers

[19] Southwest Greenland has the highest regional concentration of land-terminating glaciers wider than 2 km. Including data from all time periods, we measured eight land-terminating and seven tidewater glaciers in the southwest. We measured four land-terminating and two tidewater glaciers in all three time periods. Both data sets, of 15 glaciers and of six glaciers, show no appreciable mean retreat or advance. Only one glacier in this region experienced large change (> 440 m a^{-1}) during our study period, with a 580-m retreat of one tidewater glacier, Kangiata nunata sermia (Figure 3), during 2006–2007.

4.3. Northwest, East, and Southeast Tidewater Glaciers

[20] The three remaining regions have relatively high tidewater glacier counts, with 53 noted in the east, 38 in the southeast, and 80 in the northwest. Of these, 35, 21, and 64, respectively, were measured during all three time periods, and we present results using this data set.

[21] The distribution and magnitude of glacier advance and retreat for 1992–2000, 2000–2006, and 2006–2007 are shown in Figure 1. Because of the variety of local factors influencing a glacier (e.g., bed topography and slope), it is necessary to examine larger regional patterns rather than neighboring-glacier correlation. Spatial patterns are apparent on a broad regional scale. Also, because we have a near-complete sampling of the population of interest rather than a random or partial sampling, a significance test to determine differences among the regions is unnecessary, and we, instead, focus simply on the measured results.

[22] Only three tidewater glaciers, two in the east and one in the southeast, advanced by more than 55 m a^{-1} during 1992–2000, with the largest advancing at 562 m a^{-1} (68.75°N, 27.01°W, Figure 3) and the other two advancing at 133 m a^{-1} and 68 m a^{-1}. No glaciers advanced more than 40 m a^{-1} during 2000–2006. Additionally, all of the glaciers advancing in 1992–2000 started retreating during 2000–2006. For example, the eastern glacier with 562 m a^{-1} advance in 1992–2000 switched to 480 m a^{-1} retreat from 2000 to 2006. Likewise, all the glaciers that advanced from 2000 to 2006 had retreated during the earlier 1992–2000 period.

[23] In the east, southeast, and northwest, mean retreat of tidewater glaciers intensified from 1992–2000 to 2000–2006. The southwest had the greatest increase, from 24 m a^{-1} retreat to 175 m a^{-1} retreat. The east made the next

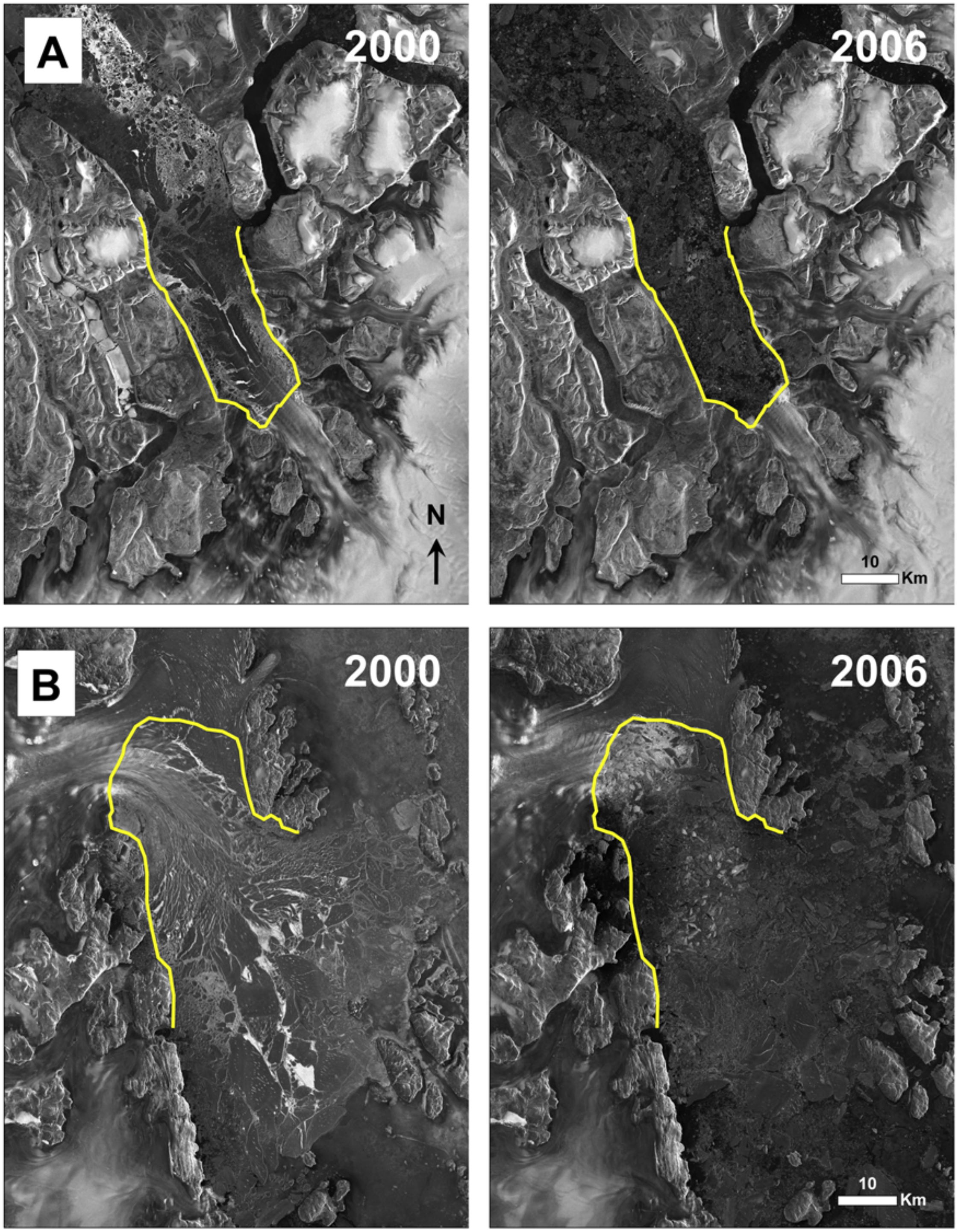

Figure 4. Disintegration of (a) C. H. Ostenfeld Gletscher and (b) Zachariae Isstrom ice shelves between (left) 2000 and (right) 2006, with the yellow line approximately denoting the glacier sides and the 2006 ice front position. The heavy fracturing of the ice shelves in 2000 prevented mapping of the ice front. These images, however, suggest a loss of glacier ice of about 350 km^2 for Figure 4a and 1400 km^2 for Figure 4b. The glacier locations are shown in Figure 3.

greatest increase, from 17 m a^{-1} retreat during the first period to 106 m a^{-1} retreat during the second period. The northwest made only a small change in mean retreat, from 81 m a^{-1} to 118 m a^{-1}, but had the largest 1992–2000 retreat rate initially. During 2006–2007, the northwest retreat rate of 121 m a^{-1} was unchanged, within the threshold of significance, from 2000 to 2006. The 2006–2007 retreat rate in the east slowed to 32 m a^{-1}. Meanwhile, the southeast mean retreat switched to 265 m a^{-1} advance

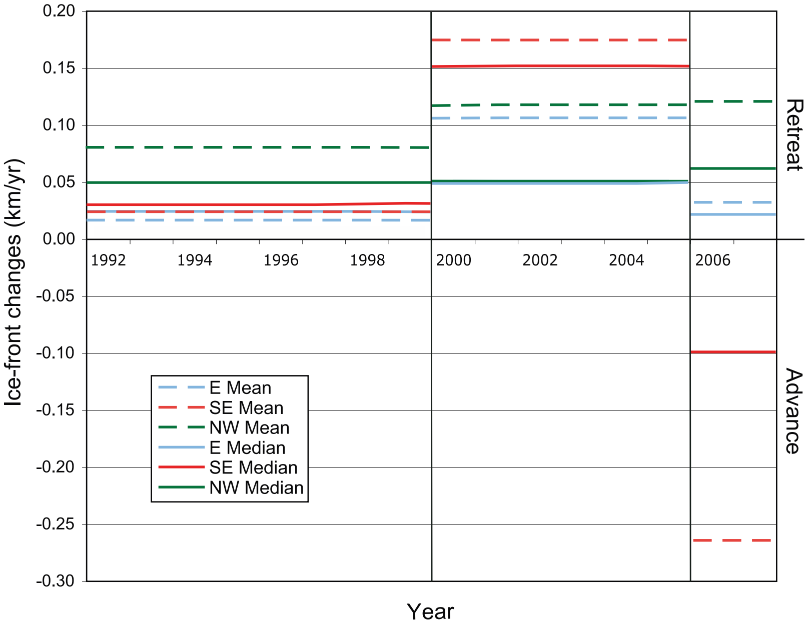

Figure 5. Mean (dashed line) and median (solid line) values for ice front position change. This includes only glaciers measured in all time periods in the northwest (NW), east (E), and southeast (SE) (120 glaciers).

from 175 m a^{-1} retreat, well above the $2\sigma/\sqrt{n}$ threshold of significance of 96 m a^{-1}.

[24] Examining the median value and range of regional retreat allows us to better understand the mean regional behavior (Figure 5). The magnitude of the mean was driven by large changes in a few glaciers (Figure 6). The median for these three regions, however, followed the same trend as the mean. All three regions showed an increase in the rate of front retreat from 1992–2000 to 2000–2006, with the southeast showing the largest increase and the northwest, with the largest initial retreat rate, showing the smallest increase. The northwest median, however, continued to increase during 2006–2007, while the southeast and eastern regions both declined to median retreat rates lower than those sustained during the 1992–2000 period.

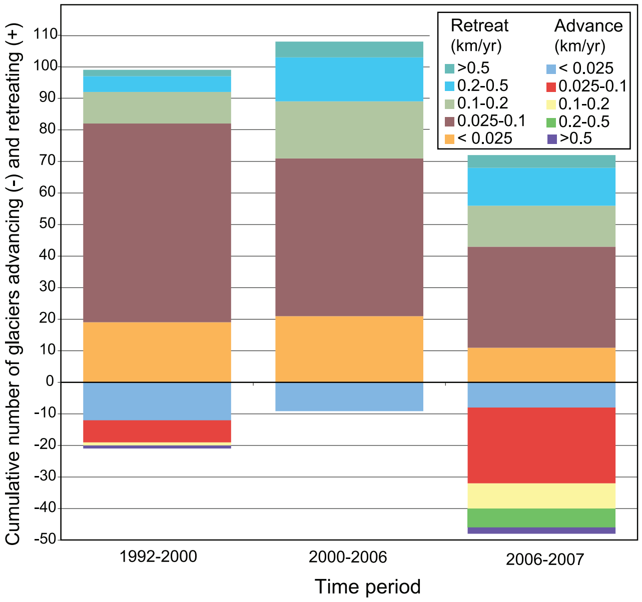

Figure 6. The magnitude of retreat rate (represented by color) and the number of glaciers retreating and advancing (represented by box height) during each time period. Only northwest, east, and southeast glaciers measured in all time periods are included (120 glaciers).

5. Discussion

[25] Several mechanisms may contribute to retreat of tidewater glaciers. These include reduced terminus confinement from decreasing sea ice extent or more water-induced fracturing and calving from meltwater on the surface [*Sohn et al.*, 1998]. Also, warmer ocean temperatures may increase melt of ice below the water level and cause thinning [*Rignot and Jacobs*, 2002; *Thomas*, 2004], or thinning may occur from greater loss of surface ice through melting. In either case, thinning may induce ice flotation or increase calving [*van der Veen*, 1996]. Recent observations on Jakobshavn suggest interannual sea ice variability may exert a strong influence on calving and retreat rates [*Joughin et al.*, 2008]. All of these mechanisms correlate positively with air temperature and suggest that tidewater glaciers can have a quick response to increasing air and ocean temperatures. Thus, we expect that temperature records may correspond positively with the observed retreat patterns.

[26] During the 1970s–1990s, Greenland summer temperatures were relatively cold compared to the previous 3 decades [*Box*, 2002]. Following the 1991 Mount Pinatubo eruption, 1992 was one of Greenland's coldest years in more than a decade [*Box*, 2002]. The multidecade cooling, combined with high accumulation rates in southeast Greenland in the early 1990s [*Hanna et al.*, 2006], may

have created favorable conditions for glacier advance and may explain the advances that we observed in the southeast and east during 1992–2000. This conclusion is also supported by an earlier study that found 14 out of 23 western Greenland tidewater glaciers were advancing during the cooler period between the 1940s and 1980s [*Warren*, 1991].

[27] The cooling trend, however, has reversed over much of the last 15 years, with predominantly increasing temperatures in Greenland [*Chylek et al.*, 2004]. Data from four coastal weather stations (Aasiaat, Nuuk, Danmarkshavn, and Tasiilaq; Figure 1), chosen because they have data covering the entire 1992–2006 period, indicate that average June-July-August (JJA) temperature increased 1.1°C between the 1992–2000 mean (4.4°C) and the 2000–2006 mean (5.5°C) (data available at http://data.giss.nasa.gov). Modeling work by *Box et al.* [2006] also found that mean meltwater production over the entire ice sheet increased by 23% from 1992–2000 to 2000–2004, the most recent year of their reported results. Despite an almost 10% increase in ice sheet–wide average annual accumulation during the same periods, this still resulted in a 13% decrease in surface mass balance from 1992–2000 to 2000–2004. Our results show a significant increase in Greenland tidewater glacier retreat over the warmer period from 2000 to 2006, with retreat concentrated in the northwest, east, and southeast regions.

[28] Although representing only a single year, the 2006–2007 data in the southeast and east are not consistent with the rising rates of retreat observed from 1992–2000 to 2000–2006 (Figure 1). In the southeast there was a mean advance of 265 m during 2006–2007, and in the east the mean rate of retreat slowed from 106 m a^{-1} to 32 m a^{-1}. Though not always outside the range of seasonal variation, 31 glaciers had measurable advance in the southeast and east compared to 25 glaciers with measurable retreat. These changes do track with the annual temperature variation, which shows that the mean temperature during the 2006 summer was lower at the four coastal stations (5°C) than any of the previous 5 years. This suggests that retreat patterns, particularly in the southeast and to some extent in the east, are immediately sensitive to annual temperature changes in addition to longer temperature trends, and we see responses on the multiyear (6 to 8 years) and yearly timescales. The 2006–2007 data may reflect a small annual variation during a cooler summer imposed on a multiyear trend of temperature-correlated retreat.

[29] The disparity often observed in accumulation rates between the northwest and the southeast/east could play a role in the different 2006–2007 responses on the two coasts. During 1988–2004, average annual accumulation along the east coast south of Kangerdlugssuaq was more than double the average annual accumulation for the northwestern coast [*Box et al.*, 2006]. Large accumulation changes over 2006–2007 could potentially outweigh the impact of similar temperature change on the two coasts. These regions may also have fundamental behavior differences, with the northwest showing a consistency between annual and long-term behavior that does not hold true for the east and southeast. The divergence in the tidewater behavior for 2006–2007 between the southeast/east regions and the northwest region should be examined more closely as data for the period continue to be made available.

[30] It is unlikely that synchronous, widespread retreat and advance patterns can be attributed solely to cyclic tidewater dynamics and local conditions operating independently of climate, as might be suggested by traditional tidewater dynamics theories [*Meier and Post*, 1987]. Instead, the correlation between ice front change and temperature suggests that climate is playing an important role and Greenland tidewater glaciers are responding to recent changes in climate.

[31] Comparing our results to other changes in ice dynamics, the regions where we observed the most retreat also showed the most ice thinning and greatest velocity increases. *Krabill et al.* [2004] found particularly large thinning rates in the northwest, in the southeast, and in the Jakobshavn and Kangerdlugssuaq catchments, where we observed the largest retreats. Also, ice velocity doubled on the 21 largest southeast glaciers between 1996 and 2005 [*Rignot and Kanagaratnam*, 2006], where we saw considerable increases in glacier retreat over the same period. The southeast/east region, with relatively large changes in retreat and advance behavior compared to the northwest, also had higher outlet glacier velocities, with greater variation [*Howat et al.*, 2008, 2007]. Synthesizing these results suggests that the cycle including accelerated glacier thinning, velocity speedups, and retreat is occurring around much of the Greenland coast.

6. Conclusions

[32] Examining SAR images from 1992, 2000, 2006, and 2007, we found a marked increase in retreat rate of tidewater glaciers from 1992–2000 to 2000–2006 in the northern, eastern, and southeastern regions. In contrast, land-terminating glaciers saw almost no change, and ice shelf glaciers had large individual changes due to episodic calving behavior. The tidewater glacier changes coincide with a 1.1°C increase in mean JJA coastal temperatures, a substantial increase in mean meltwater production along most of the coast, and a reduction in total ice sheet surface mass balance [*Box et al.*, 2006]. The correlation between retreat and temperature suggests that tidewater glaciers are responding to climate, with a variety of potential mechanisms linking temperature change and retreat. Distinguishing how large a role is played by each of these mechanisms in increasing retreat is an area of active research.

[33] Close observations, such as meteorological, ocean temperature, and satellite data, are necessary to further address changes in Greenland outlet glacier behavior. For example, while the mean retreat rate during 2006–2007 increased slightly for northwestern tidewater glaciers, the eastern retreat rates slowed, and the southeastern region switched to mean advance. The divergent behavior of these two coastal areas may be linked to temperature or precipitation differences or may be a small variation during a long-term trend of retreat. Continued measurements and development of a longer time series of observation are necessary to distinguish between these possibilities.

[34] **Acknowledgments.** Support for T. Moon was provided by a University of Washington Program on Climate Change fellowship, by a National Science Foundation (NSF) Graduate Research Fellowship, and by the Gary Comer Foundation. I. Joughin was supported by NSF Arctic System Science Grant ARC0531270. NASA funded production of the

SAR image mosaics (NNG06GE5SG). We thank P. Christoffersen, B. Csatho, A. Luckman, T. Murray, and E. Waddington for many constructive comments.

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