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Ice-front variation and tidewater behavior on Helheim and Kangerdlugssuaq Glaciers, Greenland

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[1] We used satellite images to examine the calving behavior of Helheim and Kangerdlugssuaq Glaciers, Greenland, from 2001 to 2006, a period in which they retreated and sped up. These data show that many large iceberg-calving episodes coincided with teleseismically detected glacial earthquakes, suggesting that calving-related processes are the source of the seismicity. For each of several events for which we have observations, the ice front calved back to a large, pre-existing rift. These rifts form where the ice has thinned to near flotation as the ice front retreats down the back side of a bathymetric high, which agrees well with earlier theoretical predictions. In addition to the recent retreat in a period of higher temperatures, analysis of several images shows that Helheim retreated in the 20th Century during a warmer period and then re-advanced during a subsequent cooler period. This apparent sensitivity to warming suggests that higher temperatures may promote an initial retreat off a bathymetric high that is then sustained by tidewater dynamics as the ice front retreats into deeper water. The cycle of frontal advance and retreat in less than a century indicates that tidewater glaciers in Greenland can advance rapidly. Greenland's larger reservoir of inland ice and conditions that favor the formation of ice shelves likely contribute to the rapid rates of advance.

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1. Introduction

[2] Greenland's discharge of ice to the North Atlantic through its outlet glaciers has increased dramatically over the last several years. While differing in magnitude, mass-loss estimates from a range of independent methods all show a large increase in the rate of ice loss, starting in about 2000 [*Luthcke et al.*, 2006; *Rignot and Kanagaratnam*, 2006; *Thomas et al.*, 2006; *Velicogna and Wahr*, 2006]. An early contribution to this increase was the near doubling in speed [*Joughin et al.*, 2004] and rapid thinning [*Thomas*, 2004] of Greenland's largest outlet glacier, Jakobshavn Isbrae. In 2002 Greenland's third largest glacier, Helheim, began speeding up [*Howat et al.*, 2005], which was followed in 2005 by the acceleration of Kangerdlugssuaq, the largest glacier along Greenland's east coast [*Luckman et al.*, 2006]. Over the same period, several smaller glaciers, particularly those located along Greenland's southeast coast, sped up by more than 50% [*Rignot and Kanagaratnam*, 2006]. Even in some areas where no speedups have yet been observed, such as along Greenland's northwest coast, airborne altimetry data show substantial rates of thinning [*Abdalati et al.*, 2001; *Krabill et al.*, 2004].

[3] Tidewater glaciers terminate at the ocean, where they lose mass primarily by calving icebergs or by melting of submerged ice. Temperate tidewater glaciers, such as those in Alaska, do not have floating ice tongues (small ice shelves), whereas some polar tidewater glaciers have floating ice tongues with lengths of up to about 10 km [*Meier and Post*, 1987]. The lengths of many temperate tidewater glaciers fluctuate, with slow advance occurring over several centuries followed by more rapid retreats spanning several decades [*Meier and Post*, 1987]. The instabilities driving these fluctuations have been linked to the influence of water depth and bed geometry on calving rates [*Brown et al.*, 1982; *Meier and Post*, 1987; *van der Veen*, 2002]. While this classic tidewater glacier behavior might occur without climatic forcing [e.g., *Alley*, 1991; *Meier and Post*, 1987], changes in mass balance and other climate-related factors may play a role, particularly when the glaciers are in their advanced position [*Calkin et al.*, 2001; *Meier and Post*, 1987].

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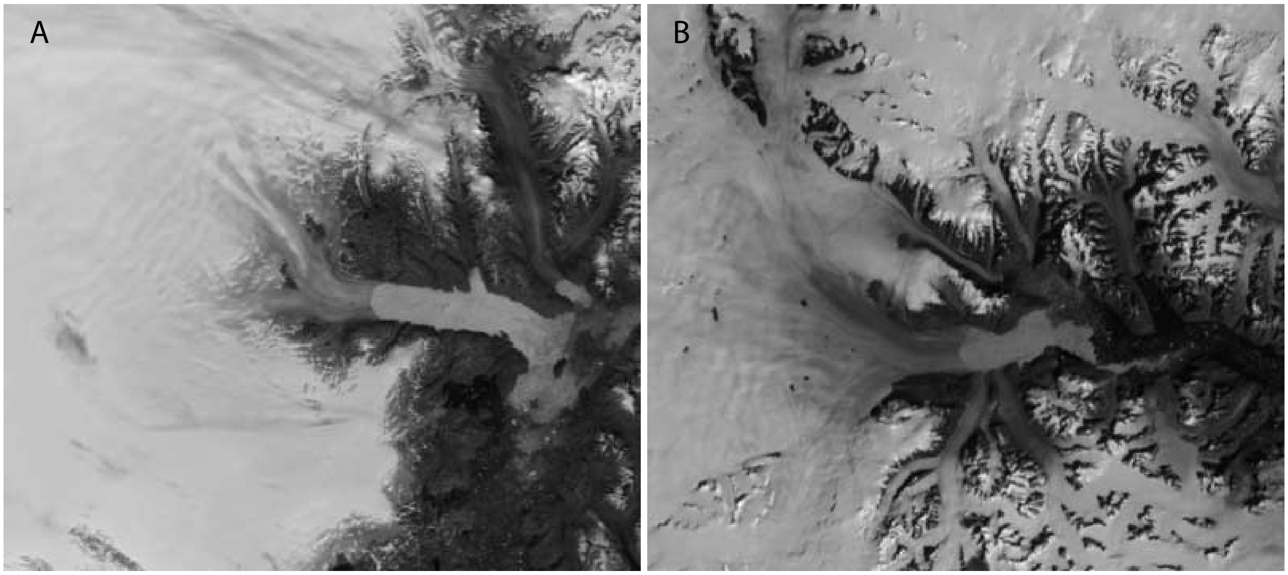

Figure 1. Examples of MODIS images used to determine front positions for (a) Helheim (19 July 2005) and (b) Kangerdlugssuaq (24 August 2005). Note different polar stereographic projections were used so that the glacier flow direction would be aligned approximately with the horizontal direction.

[4] More than 160 tidewater glaciers with widths greater than 2-km discharge ice from the Greenland Ice Sheet. Greenland's tidewater glaciers share many characteristics with temperate tidewater glaciers, including sensitivity to bedrock and fjord geometry. While polar (nontemperate) tidewater glaciers are often assumed to flow more slowly than temperate tidewater glaciers [*Meier and Post*, 1987], dozens of Greenland's tidewater glaciers flow at speeds ranging from roughly 5–40 m/day, which is comparable to the range for Alaskan tidewater glaciers.

[5] Tidewater glaciers are highly sensitive to variability in geometry and hydraulic conditions at the bed, which produce dynamic instabilities [*Meier and Post*, 1987]. Surface meltwater is one contributor to seasonal variability in flow speed on temperate and some polar tidewater glaciers [*Meier and Post*, 1987; *Vieli et al.*, 2004]. Although small variations in flow speed in response to surface melt have been observed at some locations on the slow-moving ice sheet [*Zwally et al.*, 2002], previous observations suggested little sensitivity to surface melt for Jakobshavn Isbrae, one of Greenland's fastest moving outlet glaciers [*Echelmeyer and Harrison*, 1990]. An exception to this apparent insensitivity to surface melt is Ryder Glacier, which sped up by more than a factor of three during a period when the lakes on its surface drained [*Joughin et al.*, 1996]. It is important to note that many estimates of surface motion in Greenland are based on observations spaced several days or weeks apart, so they may not resolve short-term fluctuations similar to those observed on some other Arctic glaciers [e.g., *Vieli et al.*, 2004].

[6] Tidewater glacier flow also has a strong sensitivity to longitudinal-stress gradients, which are large near the calving front [*Meier and Post*, 1987]. The speedups of Jakobshavn [*Joughin et al.*, 2004], Helheim [*Howat et al.*, 2005], and Kangerdlugssuaq [*Luckman et al.*, 2006] all followed the several-kilometer retreat of their calving ice fronts. Force balance analyses suggest that loss of grounded ice for Helheim and floating ice for Jakobshavn removed resistive stresses. To compensate for this loss, the glaciers appear to have sped up to produce the additional longitudinal and lateral stress gradients (resistive stresses) that were necessary to restore force balance [*Howat et al.*, 2005; *Thomas*, 2004]. Similarly, model results show a strong correlation between flow-speed increase and ice-front retreat for Hansbreen, which is one of the larger tidewater glaciers on Spitsbergen [*Vieli et al.*, 2002].

[7] Both temperate and polar tidewater glaciers can respond to changes in the effective pressure at the bed [*Meier and Post*, 1987; *Vieli et al.*, 2004], which is the difference between the ice overburden and the basal water pressure. A variety of sliding laws relate the basal shear stress, τ_b, to the effective pressure, often with a nonlinear relationship [*Paterson*, 1994]. Thus transient conditions linked to ice thinning might reduce basal friction more than driving stress, speeding ice flow [*Meier and Post*, 1987; *Pfeffer*, 2007].

[8] Teleseismic data from 1993 to 2005 reveal nearly 200 large but, slow, earthquakes located beneath several large tidewater glaciers in Greenland [*Ekstrom et al.*, 2003; *Ekstrom et al.*, 2006; *Tsai and Ekstrom*, 2007]. The number of events per year began to increase in 2002, with 2005 producing more events (30) than the combined 1993-to-1996 total. There is a strong seasonality in the rate of occurrence of these events, with nearly five times more events in summer than in winter. The exact mechanism responsible for these earthquakes is unclear, but processes related to calving have been suggested [*Joughin*, 2006; *Tsai and Rice*, 2006].

[9] The speed-ups of Kangerdlugssuaq and Helheim occurred during or immediately following retreats of several kilometers [*Howat et al.*, 2005; *Luckman et al.*, 2006]. Following these increases in flow speed, the combined discharge from these glaciers peaked in 2005 and then

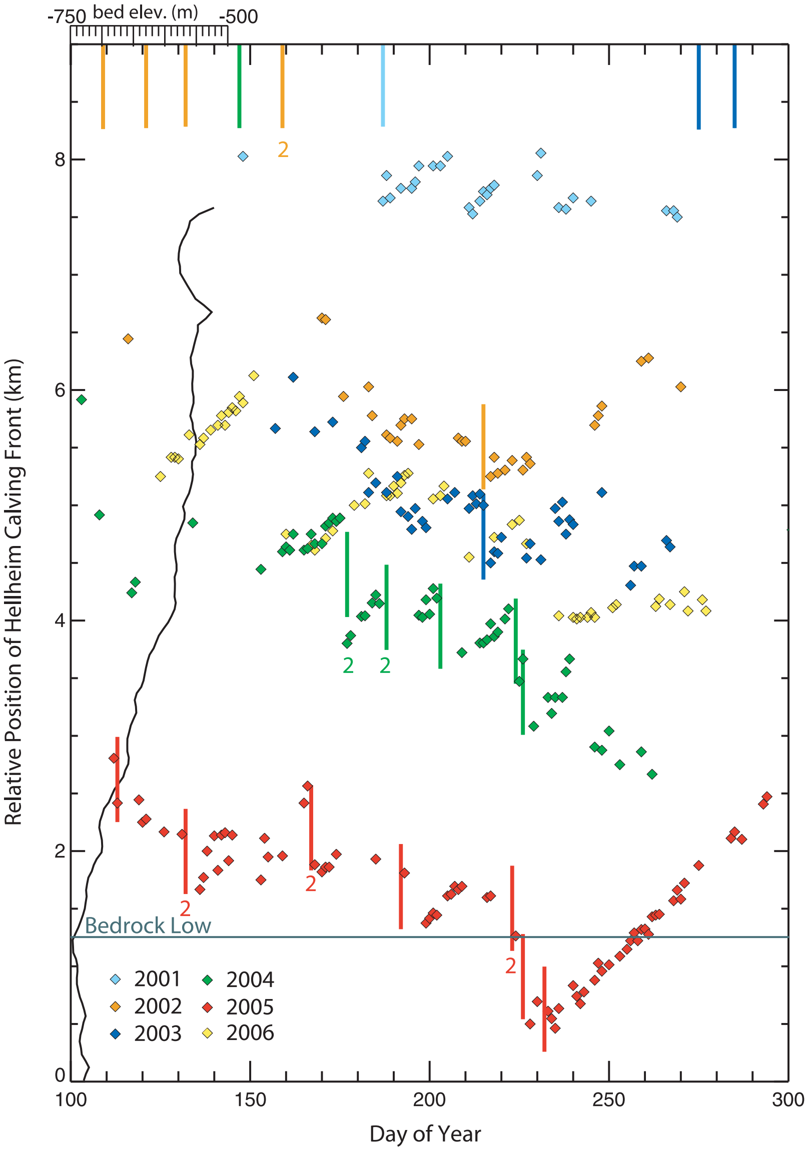

Figure 2. Positions (diamonds) for the Helheim ice front for 2001 through 2006. Vertical lines indicate times when earthquakes occurred and are located near the plotted ice-front position when the event occurred. A number by a line indicates more than one event occurred that day. Earthquakes that occurred during periods where we have no front-position data are plotted as vertical lines along the top axis. The solid black line shows the bedrock topography with the depth indicated by the scale at the top of the plot.

declined in 2006 as the glaciers thinned and slowed [*Howat et al.*, 2007]. The speed-ups of Kangerdlugssuaq and Helheim coincided with the increases in seismicity, with these two glaciers producing more than half of the observed glacial earthquakes [*Ekstrom et al.*, 2006].

[10] The patterns of retreat, acceleration, and seismicity for Kangerdlugssuaq and Helheim suggest that dynamic instabilities, inherent to tidewater glaciers might play a role in these rapid and large-scale changes. The possibility that such instability was triggered by recent higher summer temperatures in Greenland [*Chylek et al.*, 2006] offers a potential link between climate and tidewater glacier behavior. To better understand the factors controlling the tidewater behavior of these two glaciers, we have used a time series of daily ice-front position at each glacier to study the calving and retreat during and immediately following their speedup between 2001 and 2006. We compare these data on frontal position with the concurrent record of seismic events, as well as bed topography, and changes in speed and ice thickness.

2. Methods

[11] We used a variety of image data to examine calving and retreat on Helheim and Kangerdlugssuaq glaciers as described in the following subsections.

2.1. MODIS Ice Front Positions

[12] We used the high-resolution (∼250 m) bands of the Moderate Resolution Imaging Spectroradiometers (MODIS) aboard NASA's Terra (2001–2006) and Aqua (2003–2006) satellites to track the positions of the Helheim and Kanger-

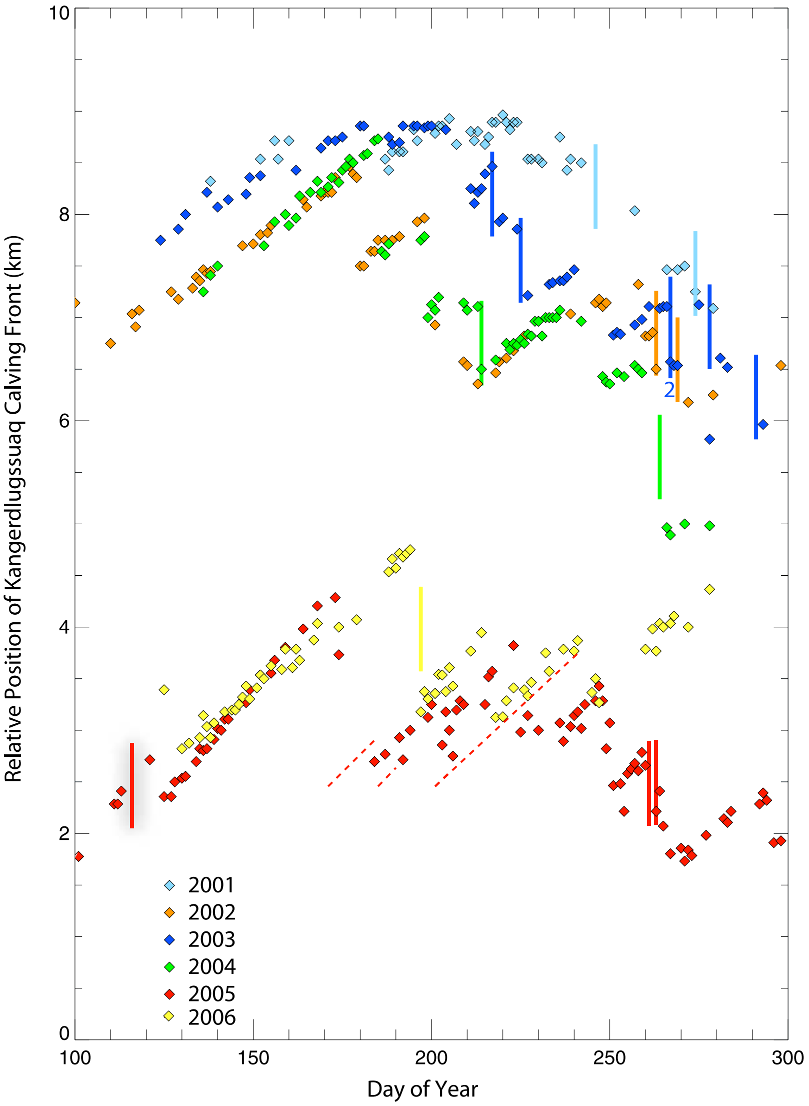

Figure 3. Positions (diamonds) for the Kangerdlugssuaq ice front for 2001 through 2006. Vertical lines indicate times when earthquakes occurred and are located near the plotted ice-front position when the event occurred. A number by a line indicates more than one event occurred that day. Earthquakes that occurred during periods where we have no front-position data are plotted as vertical lines along the top axis. Red diagonal lines are relative displacements from ASTER-derived velocity estimates and show what the rate of advance would be with no calving [*Howat et al.*, 2007].

dlugssuaq ice fronts through time. For each cloud-free image (e.g., Figure 1), we used a simple edge-detection algorithm to automatically determine an ice-front position estimate, which was then accepted or rejected based on a visual inspection. We then obtained mean position by averaging over a 1.5-to-2-km wide band at the center of each ice front. On days when multiple images were available, we averaged the results from 2-to-3 independent ice-front estimates. With this spatial and temporal averaging, we are able to resolve changes in the mean ice-front position to better than the instrument's 250-m resolution. For this analysis, we use ice-front positions acquired only from cloud-free images with high contrast, which provide the most reliable estimates (Figures 2 and 3). The vertical lines on these figures indicate the days when glacial earthquakes were detected at each of these glaciers [*Ekstrom et al.*, 2006; *Tsai and Ekstrom*, 2007].

2.2. ASTER Images and Elevation Data

[13] Because of the limited resolution of MODIS, we used higher-resolution images to study details of the calving process. One source of these data was visible to near-infrared (bands 1–3) 15-m imagery from the Advanced Spaceborne Thermal Emissivity and Reflection Radiometer (ASTER) sensor aboard the Terra satellite launched in December, 1999. Although ASTER does not offer the same temporal resolution as MODIS, for each summer we have several ASTER images for each glacier.

[14] We created Digital Elevation Models (DEMs) for each of several ASTER data sets using the ENVI/IDL DEM Extraction Module, which uses the nadir and backward-looking Band-3 images to construct parallax images. The

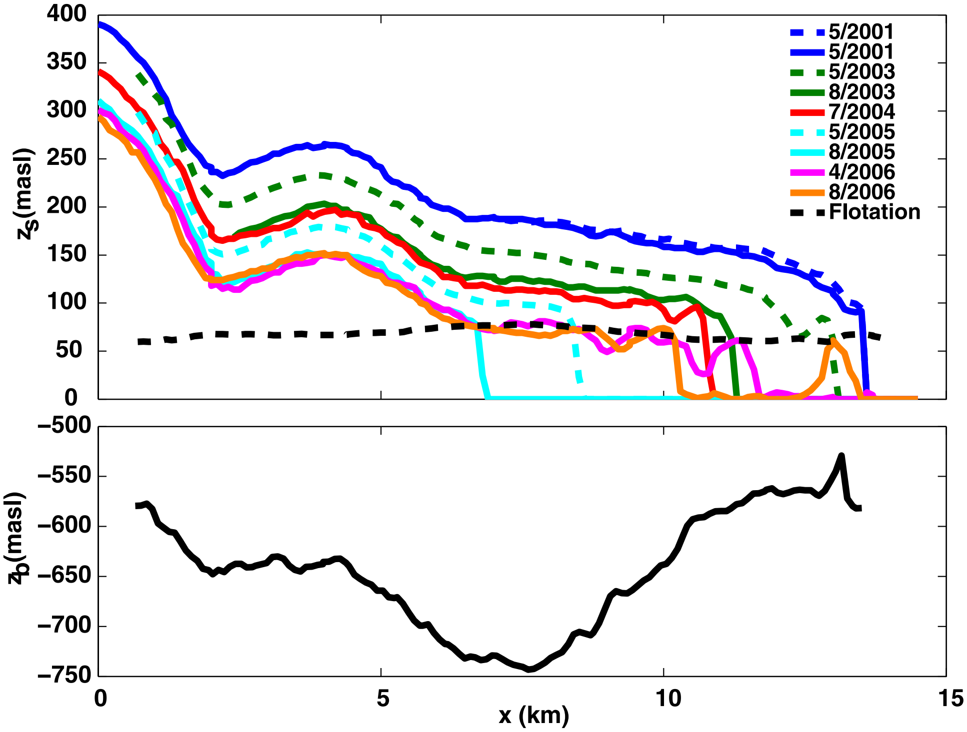

Figure 4. (top) Elevations from the Airborne Topographic Mapper (ATM) lidar (dashed) [*Krabill et al.*, 2004] and ASTER-derived DEMs (solid) [*Howat et al.*, 2007] near the Helheim ice front. The dashed black line shows the flotation threshold, above which the ice is grounded. (bottom) Ice thickness from the University of Kansas Coherent Radar Depth Sounder (CoRDS).

several-meter accuracy of these DEMs allows detection of large thickness changes such as those that occurred on Helheim and Kangerdlugssuaq [*Howat et al.*, 2007]. Figure 4 shows several elevation profiles for Helheim extracted from these DEMs as well as laser altimeter profiles from the Airborne Topograpic Mapper (ATM) [*Krabill et al.*, 2004]. We also used the ASTER DEMs and the satellite ephemeris to orthorectify the images (Figure 5).

2.3. Corona Images

[15] The US Government launched the Corona series of reconnaissance satellites in the 1960s, and high-resolution (∼2 m) data from these instruments were declassified in 1996 (http://edcsns17.cr.usgs.gov/EarthExplorer/). We obtained a Corona image for Helheim glacier from July 1965. No geo-location information is provided with the Corona imagery. Using orthorectified ASTER images as a reference, we selected numerous tie points on fixed bedrock near the glacier, and warped the Corona imagery to match the reference using point-by-point triangulation. This yielded co-registration errors of roughly 100-m or less on the ice-covered regions, which is adequate at the level of comparison we describe below.

3. Results

[16] We applied the methods described above to produce estimates of ice-front position for Helheim and Kangerdlugssuaq glaciers. These observations reveal the pattern of large calving episodes for the period when each of these glaciers retreated by several kilometers.

3.1. Helheim

[17] Figure 2 shows that in 2001 when image coverage was more limited, Helheim's ice-front position remained relatively stable, with short-period advances of roughly 0.5 km balanced by retreats of similar magnitude. By the following spring, the front had retreated by ∼1.25 km, and a series of small calving episodes over the summer yielded an additional 1.25 km of retreat by mid-August. Note that because we can only resolve calving episodes to within at best a 24-h period, we cannot determine whether a single calving episode comprises several small calving events or a single large one. A later-summer advance offset some of the earlier calving, yielding a net retreat relative to 2001 of ∼1.5 k. From this position, the front retreated steadily over the summer of 2003, punctuated by a glacial earthquake at the approximate time of a ∼0.5-km calving episode. By the end of 2003, the ice front had retreated by nearly 3.25 km from its 2001 position, with an increase in glacier speed up of more than 500 m/a [*Howat et al.*, 2005]. Several large calving episodes produced an additional ∼2-km of retreat over the summer of 2004. Nearly all of these calving episodes were accompanied by one or more glacial earthquakes.

[18] Beginning in 2005, Helheim's pattern of retreat changed. In spring 2005 the ice front was near its position from the previous fall and the ice was grounded with its surface height well above the threshold for flotation (e.g., the bathymetry dependent height shown in Figure 4 below which the ice is thin enough to float and above which it is grounded). Over the summer, the front position receded

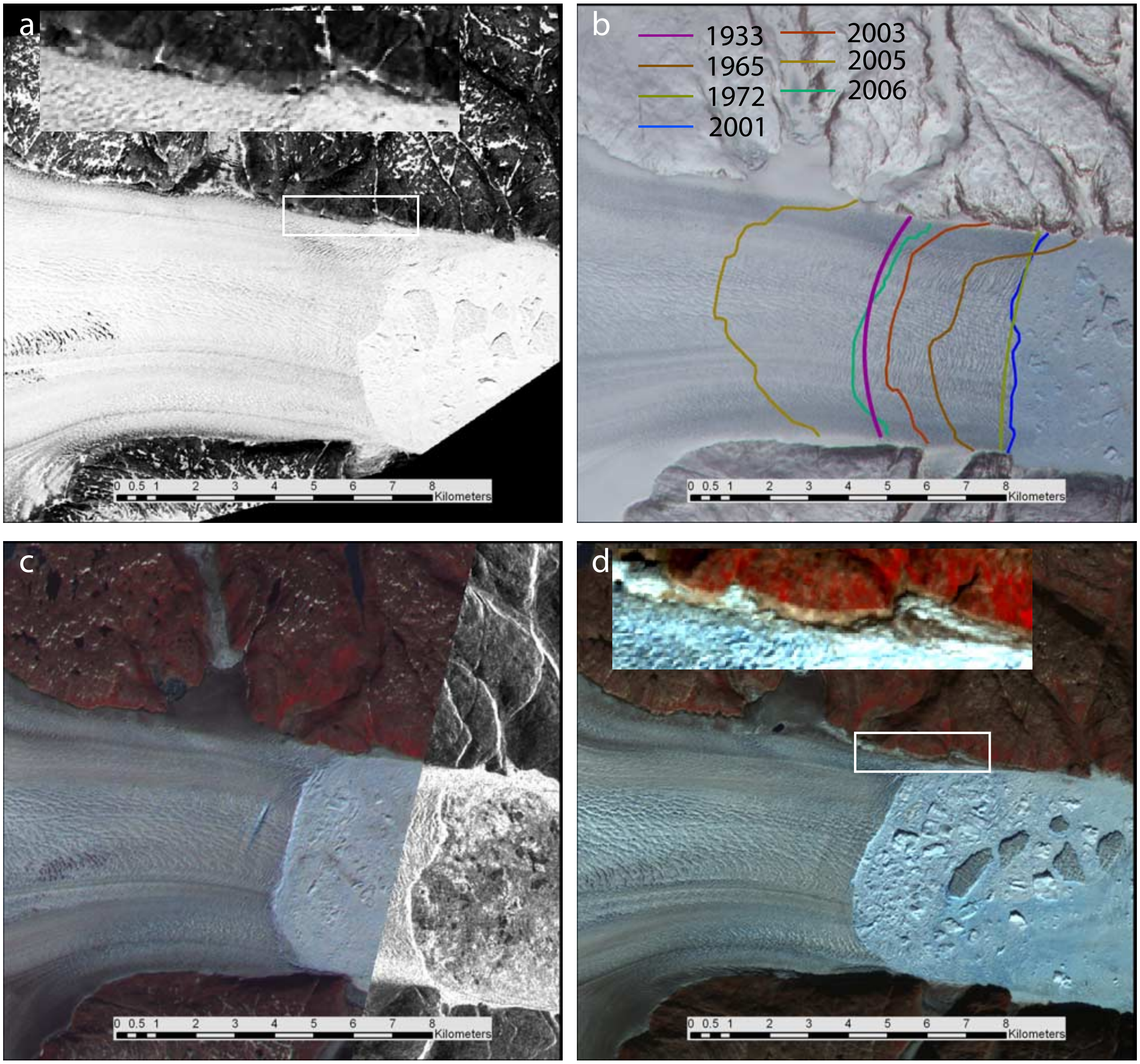

Figure 5. Images of the Helheim front from (a) July 1965, (b) 12 May 2001, (c) 3 August 2004, and (d) 29 August 2006. Insets in Figures 5a and 5d show magnified view of the trimline in the area enclosed by a white rectangle. Positions of the ice front at several times are shown with colored lines over the May 2001 image.

relatively slowly, with glacial earthquakes coinciding with most of the large calving episodes. In mid-August, two large calving episodes accompanied by glacial earthquakes yielded ~1-km retreat past a low in the bedrock topography. At this time the ice front, which was at or near flotation, began an advance, initially into deep water, that was sustained over a period of at least 70 days. By spring 2006 the ice front had advanced by more than 2.5 km to roughly the spring 2003 front position. The front then advanced by another kilometer, but then calved back by more than that amount in late May or early June. This was followed by several large calving episodes that occurred through about late August, after which the position of the calving front remained nearly constant for the remainder of the record. Figure 4 indicates that, unlike in earlier years, during 2006 a several-kilometer long section upglacier of the ice front was either at or near flotation.

[19] To gain some historical perspective on this cycle of retreat and advance, Figure 5 shows the location of the Helheim ice front at several different times. Figure 5b shows that in 1933 the ice front [*Weidick*, 1995] was in a position similar to the late-summer position in 2006. The Corona image in Figure 5a shows that by 1965 the ice front had advanced ~2 km forward of the 1933 position, but it was still located ~1.5-km behind the 2001 ice-front. By 1972 [*Weidick*, 1995], however, the ice front had advanced to the 2001 position.

[20] A prominent trimline (the line on the fjord wall that forms the boundary between areas of recent and past deglaciation as indicated by differences in weathering

patterns or vegetation cover) is visible in the 1965 Corona image, indicating that the ice had recently thinned, probably coupled to retreat. This trimline is not evident in the ASTER images collected before 2004 (e.g., Figure 5b), demonstrating probable thickening and advance between 1965 and 2001, close to or beyond the extent of the ice before the pre-1965 retreat. The trimline is barely exposed in images from 2004 (e.g., Figure 5c) and this feature is clearly visible in images from 2005, following the substantial thinning and retreat that had just occurred. The trimline is also visible in an August 2006 image, when the adjacent ice was at or near flotation (Figure 5d). Given the similarity in the exposed extent of the trimline in the 1965 and 2006 images, we conclude that in 1965 the glacier was at or near flotation. In 2001, however, the ice surface in this region was grounded up to $\sim$100 m (Figure 4) above the flotation threshold. The presence of large tabular icebergs near the ice front provides further evidence for the ice front being at or near flotation in 1965. These icebergs appear to have calved and then grounded as they floated forward into shallower water. If the 1965 ice front was well-grounded, the tabular icebergs could not have floated into shallower water. By 2001, however, the ice was $\sim$60 m above the flotation threshold at the location of the 1965 ice front, indicating substantial thickening.

3.2. Kangerdlugssuaq

[21] From 2001 to 2004, Kangerdlugssuaq's calving front followed a relatively consistent seasonal progression. Sometime prior to mid-April of each year, the ice front began a steady sustained advance with little calving. Starting in about July of each year, the ice front calved back $\sim$2-km in a series of large calving episodes that continued at least through October (the last date when we were able to determine the ice-front position). Glacial earthquakes occurred during several of these calving episodes, and were more frequent in late summer/early autumn when the ice front was near its most seasonally retreated position. During each winter the ice front would re-advance past the previous autumn position. The seasonal variability is roughly consistent with the range of ice-front positions (7 total) measured between 1966 and 1999 [*Thomas et al.*, 2000].

[22] This pattern changed in 2004 when the late-summer ice front retreated by $\sim$1 km relative to the late-summer position of previous years. This was followed by substantial retreat during the following winter [*Luckman et al.*, 2006], so that the spring 2005 ice front was about 4.5 km behind the spring 2004 position. Over this period, the glacier sped up from roughly 20 m/day to 35 m/day [*Luckman et al.*, 2006]. Despite this large retreat, in 2005 the ice front began advancing again in a pattern similar to earlier years: spring/early summer advance followed by mid-summer through early autumn retreat. The ice-front position followed a nearly identical progression in 2006 up through about early September, when the ice front began to re-advance.

4. Discussion

[23] During retreat stages, substantial changes in ice-front position at Helheim and Kangerdlugssuaq occurred through large (0.5-to-1-km), distinct episodes of calving several days or weeks apart. The results provide additional detail and confirm a pattern of retreat on both glaciers observed in other studies [*Howat et al.*, 2005; *Luckman et al.*, 2006]. The pattern of retreat and its relation to the bedrock topography suggest links between glacial earthquakes, calving, and tidewater glacier behavior, which we describe below.

4.1. Glacial Earthquakes

[24] Although we can resolve the timing of large calving events to within only about a day, over the intervals when we have data, the strong correspondence between glacial earthquakes and ice-front retreat (Figures 2 and 3) indicates that the earthquakes are associated with large calving episodes. Since 1993, the glacial earthquakes from Kangerdlugssuaq have occurred at a relatively steady rate of about 4 per year, which generally occur over the period from late summer through early winter [*Ekstrom et al.*, 2003; *Tsai and Ekstrom*, 2007]. This pattern is consistent with the seasonal pattern of calving we observe both before and after the major 2004–2005 retreat.

[25] It is important to note that the teleseismic detection threshold for glacial earthquakes is $M_{SW}4.6$ [*Ekstrom et al.*, 2003; *Ekstrom et al.*, 2006]; thus, smaller earthquakes might be associated with the calving episodes during which no glacial earthquakes were detected. Likewise, similar but smaller magnitude events might occur on many other tidewater glaciers in Greenland and elsewhere.

[26] Unlike Kangerdlugssuaq, which retreated over a single season, Helheim calved back progressively over the course of four summers, which coincides with the period of increased glacial earthquakes from this region [*Tsai and Ekstrom*, 2007]. In retreating nearly 7-km, Helheim would have produced about 14 of its typical 0.5-km-long calving events above the steady state number required to maintain a fixed ice-front position. This number is consistent with the increased rate of glacial earthquakes from Helheim [*Tsai and Ekstrom*, 2007] and accounts for nearly half of the post-2001 increase in teleseismically detected events for Greenland [*Ekstrom et al.*, 2006].

[27] Results from Columbia Glacier show significant seismicity during calving (1–3 Hz) and fracturing (10–20 Hz) events [*O'Neel et al.*, 2007]. The teleseismically detected earthquakes from Greenland generate much longer period seismic waves (35–150 s), however, and are best represented by single-force mass-sliding models [*Ekstrom et al.*, 2003; *Tsai and Ekstrom*, 2007]. This suggests that glacial earthquakes may result from either slip of the main glacier trunk or the movement of the newly formed iceberg as it slides toward the ocean. The estimated mass-slip products [*Ekstrom et al.*, 2006] are such that slip of a few decimeters to a few meters along the 10-to-20 km length of the glacier could produce the earthquakes [*Joughin*, 2006]. Alternatively, displacements of 10s to 100s of meters of the either the calving iceberg or displaced water might produce an earthquake in the range of observed magnitudes.

[28] If the earthquakes result from slip along glacier trunks, then they may result from a force imbalance near the front that arises as part of the calving process. We can envision two mechanisms that might produce such an imbalance. The first would occur when basal or lateral resistive stresses are diminished as area in contact with the bed and fjord sidewalls is lost during calving [*Howat et*

al., 2005; *Joughin et al.*, 2004; *Tsai and Rice*, 2006]. For example, the loss of a 100-to-500 m grounded section along the ice front would remove ~1-to-5% of the total resistive force on a 10-km long glacier main trunk, requiring an ~1-to-5 kPa increase in the average resistive stress (~100 kPa) over the main trunk. At longer timescales where Glen's flow law for ice applies [*Paterson*, 1994], similar-scale losses appear to produce speed-ups that increase longitudinal and lateral stress gradients in order to restore force balance [*Howat et al.*, 2005; *Thomas*, 2004]. The second effect that might induce slip on the trunk is the transient force imbalance produced by the movement of ice and water near the front as the glacier calves. For example, the rolling of an iceberg as it calves results in a forward net transfer of ice mass that likely has the energy and moment necessary to produce a teleseismically detectable earthquake. At present, we do not have the necessary data to determine whether there is slip on the trunk, and whether slip results from either of these two processes.

[29] If either effect just discussed does produce a nearly instantaneous imbalance at the glacier front during the calving, then this might yield slip of a few tenths of a meter as an elastic response to the force imbalance, particularly if the effective Young's modulus is at the lower end (~1GPa) of the range of values determined from field and laboratory experiments [*Vaughan*, 1995]. Stress imbalances of similar magnitude yield similar scale elastic responses on Antarctic ice streams [*Anandakrishnan et al.*, 2003; *Bindschadler et al.*, 2003]. These ice streams flow over a weak (2–10 kPa) and possibly near-plastic bed [*Kamb*, 1991; *Tulaczyk et al.*, 2000], which may allow transmission of longitudinal stresses deep inland (20–100 km) if the bed provides little additional resistive stress as the glacier modulates its speed. In contrast, the bedrock beneath Helheim and Kangerdlugssuaq likely can support much higher basal shear stresses (~100 kPa) and that might compensate for a force imbalance near the front and limit inland propagation of slip. Theoretical work, however, suggests that subglacial cavitation at high speeds and low-effective pressure yields sliding with velocity-weakening characteristics (e.g., basal resistance that decreases with increased speed) [*Schoof*, 2005], which might yield more fault-like slip behavior at the ice-bedrock interface [*Scholz*, 2002; *Tsai and Rice*, 2006]. Furthermore, there is tidal modulation of displacement (10–20 cm amplitude) that extends ~25 km inland from the front of Helheim [*Nettles et al.*, 2006]. Together these factors suggest that the trunks of Helheim and other glaciers might slip by a few tenths of a meter as part of an elastic response to force imbalances of the magnitude we anticipate from processes related to calving. While we do not have sufficient data at present to confirm this hypothesis, it is testable with existing field-based methods (e.g., GPS and seismic methods).

4.2. Calving

[30] There are two types of large icebergs that are well resolved in the several ASTER images we have analyzed for each summer. The first and most common type are slab-like icebergs with a dimension of approximately 100-m in the along-flow direction, which yields an aspect ratio that causes them to immediately roll over onto their sides. Numerous smaller icebergs accompany these larger icebergs, choking the fjord with ice. Even in summer, these icebergs are often surrounded by sea ice, which may result from buoyant super-cooled water emerging from beneath the glacier [*Alley et al.*, 1998; *Fleisher et al.*, 1998]. The presence of large, discrete slabs suggests that calving of several ~100-m slabs over a 24-h period may produce one of the 0.5-km scale episodes shown in Figures 2 and 3. Alternatively, the glacier may calve 0.5-km-scale icebergs that rapidly disintegrate once they begin to float.

[31] The second type consists of km-scale tabular icebergs that do not roll and remain intact and upright within the fjord for several weeks. The large width of these tabular icebergs suggests they calved from a floating ice front (or from grounded ice calving into deeper water). We observed the greatest number of these when Helheim was at or near flotation in 2006. A few of these icebergs seem to have grounded on a shoal near the 2001 ice-front position (Figure 5d) and one of these is visible in the August 2006 elevation profile (Figure 4). In earlier years we also observed several tabular icebergs at a location about 20-km down the fjord from the Helheim ice front, where they grounded and remained in place for much of the summer. Although we only have limited temporal sampling, many of the pre-2006 tabular icebergs apparently calved over the winter or in early spring when the trunk was at its maximum seasonal extent and there may have been a short floating section.

[32] Although the ice front retreated nearly 2-km in 2006, extension of earlier teleseismic monitoring [*Ekstrom et al.*, 2006; *Tsai and Ekstrom*, 2007] indicates that there were no glacial earthquakes on Helheim in 2006 [*Nettles et al.*, 2006], making it the first year since 1994 with no detectable teleseismic events on this glacier [*Tsai and Ekstrom*, 2007]. In contrast, there were 10 or more events each year in 2004 and 2005, during which time the grounded ice front retreated substantially. This suggests that glacial earthquakes are more prevalent or occur exclusively during the calving of non-tabular icebergs that roll when they calve.

[33] Many temperate and polar tidewater glaciers exhibit seasonal calving behavior [*Meier and Post*, 1987; *Sohn et al.*, 1998; *Vieli et al.*, 2002]. While we do not have data for roughly half of each year, the results in Figures 2 and 3 indicate some seasonality in the calving rates. Other than in 2002, the first position we measure each spring on Helheim is near the autumn location measured the previous year, indicating a stable or perhaps slightly advancing terminus position over the winter. The calving rate increases in May-September, with most of the retreat occurring during this period. Kangerdlugssuaq exhibits a different pattern with frontal advance at the speed of the ice front and little calving from spring through about mid July. The pattern agrees well with the seasonal distribution of glacial earthquakes for these glaciers, which peaks in the summer for Helheim and early Fall for Kangerdlugssuaq [*Tsai and Ekstrom*, 2007]. Once calving does commence, it continues throughfall with a minimum position some time around January [*Luckman et al.*, 2006].

[34] Several studies have attempted to link the calving rate to a single parameter, such as water depth or height above flotation [*Brown et al.*, 1982; *van der Veen*, 2002]. *Vieli et al.* [2002] used a numerical model to show that dynamic thinning can produce a reverse (with respect to

flow direction) surface slope, as the glacier retreats over a reverse bedrock slope. In their model, they impose a seasonally varying calving rate derived empirically from observations. In addition, they allow calving when the height above flotation drops below some critical threshold. They argue that below this height, basal crevassing can occur because basal water pressure nearly balances the ice overburden, which otherwise limits fracture propagation [*van der Veen*, 1998]. In their results, calving is dominated by the imposed seasonal cycle in most years. Only as the ice front position retreats over the reverse slope (with respect to flow) and into a bathymetric depression does a region of localized thinning to near flotation develop upstream of the terminus, producing buoyancy-driven calving that drives rapid retreat. This is consistent with the suggestion by *Meier and Post* [1987] that during its disintegration, Columbia Glacier calved back to points where the effective pressure neared zero (i.e., near flotation).

[35] The May 2003 and July 2004 profiles from Helheim in Figure 4 show depressions in the surface elevation to near flotation within about 0.5 km upstream from the calving front. In July 2004 an approximately 100-m-wide rift formed near the bottom of one of these depressions (Figure 5c). Three days after this rift was imaged, the ice front calved back to the rift location. We have observed similar rifts on Helheim shortly before two other large calving events in 2003 and 2004. Kangerdlugssuaq also displayed a reverse surface slope near the front in late June 2004. Although not as prominent as the rifts on Helheim, several large crevasses were visible near the Kangerdlugssuaq depression, and a large calving event occurred nine days later. Because we only have a few ASTER images for each summer, it is possible that similar, but unobserved, rifts formed prior to many of the other large calving events.

[36] The observations of rifting and detachment in areas that have thinned to near flotation on Helheim agree well with theoretical and model predictions [*van der Veen*, 1998; *Vieli et al.*, 2002]. Although *Vieli et al.* [2001] noted that the physics behind the calving relation they used is not entirely understood, they argued that bottom crevassing likely plays an important role. The presence of large rifts on Helheim prior to calving supports this conclusion. Since the thinning to near flotation tends to arise as the ice front retreats down a reverse basal slope, this mode of calving may only be important during tidewater retreat, and other factors may control calving when the ice front is in a stable configuration [*Vieli et al.*, 2002]. We note that while instability is expected as the ice front reaches the reverse bedrock slope regardless of calving mechanism [e.g., *Schoof*, 2007], this rift-driven calving may accelerate the rate of retreat.

4.3. Tidewater Behavior

[37] Rapid retreats on Helheim and Kangerdlugssuaq appear to have followed a classic pattern of tidewater glacier retreat. Helheim retreated progressively into deeper water and appears to have stabilized, at least temporarily, only after it retreated past a bathymetric low. While we do not have bed elevation data for Kangerdlugssuaq, its rapid retreat to a new position where it has re-established a similar calving pattern suggests it, too, retreated across a bed depression.

[38] Greenland coastal summer temperatures cooled from the 1940s until the mid 1960s, remained relatively cool through the early 1990s and then began to warm rapidly from about 1995 onwards [*Chylek et al.*, 2006]. This recent warming was similar in magnitude to a warming from 1920-to-1930 [*Chylek et al.*, 2006]. Helheim's 1933 ice front position [*Weidick*, 1995] closely matches the 2006 position, suggesting that rapid retreat was a response to both the present and the 1920s warming periods. The cooler temperatures following the 1920s warming may have allowed a floating ice tongue to exist through at least 1965 (Figure 5). The close correspondence between the position in 1972 and the well-grounded position in 2001 indicates that the floating tongue may have grounded and begun thickening in the late 1960s to early 1970s, which roughly corresponds to the onset of a cool period. By 2001, this region of the glacier was roughly 100-m above the flotation thickness, which implies an average rate of thickening of roughly 3 m/a.

[39] While tidewater retreat can be rapid, many temperate tidewater glaciers advance slowly over a period of centuries as they build a stabilizing moraine shoal [*Meier and Post*, 1987]. If Helheim completed a full cycle by retreating in the 1930s and then re-advancing to a maximum extent in 2001, then this implies a period of 70 to 80 years, which is about an order of magnitude shorter than the classic temperate tidewater glacier cycles [*Meier and Post*, 1987].

[40] There are two factors that may facilitate rapid re-advance on ice sheet outlet glaciers. The first is the ability to form a floating ice tongue. Figure 4 indicates that rather than "bulldozing" a shoal into deeper water as many temperate tidewater glaciers do, Helheim formed an ice tongue that "bridged" the over-deepened area over which it had just retreated. The front of this tongue appears to have re-grounded on the other side of the depression on about 20 August (day 232), 2006, after which the ice front stopped advancing and maintained a stable position for the latter part of 2006. This apparent grounding also slowed the glacier's speed by about 2 m/day and produced a region of compressional flow in the area just above the grounding line in August 2006 [*Howat et al.*, 2007]. We have estimated December 2006 velocities for Helheim that show that the ice front has slowed to near its pre-retreat speed. Upstream speeds still exceed their pre-retreat values, suggesting that the trunk is thickening as it advances.

[41] The presence of a large ice sheet is the second factor that may influence tidewater cycles on Greenland's outlet glaciers. Much of the volume of a temperate tidewater glacier is lost during retreat and by associated thinning, limiting re-advance. In contrast, the volume an outlet glacier loses as it retreats several kilometers represents a small fraction of the overall catchment, leaving a large volume of inland ice that can contribute to re-advance. Despite the large thinning near the front (Figure 4), Helheim lost only about 33 km^3 through increased discharge [*Howat et al.*, 2007]. To restore this volume over three decades requires a positive imbalance on the lower section of $\sim$1.1 km^3/a, or just over 4% of the pre-retreat discharge rate of 26 km^3/a [*Rignot and Kanagaratnam*, 2006]. Thus even factoring in the extra ice volume loss in the fjord that must be replaced during a re-advance, a subtle deceleration gradient near the front could over a few decades replace the ice lost from

2001-to-2006. Therefore while not as rapid as a retreat, a sustained re-advance could occur over a period of years to decades similar to the re-advance that appears to have occurred, when temperatures remained low in the 1970s through early 1990s.

[42] Temperate tidewater dynamics have often been assumed to be relatively independent of direct climate forcing [*Meier and Post*, 1987], although factors such as mass balance can play a role (and may be more important than sometimes assumed [*Calkin et al.*, 2001]). In Greenland, however, a large number of tidewater glaciers accelerated nearly synchronously over a five year (2000–2005) period [*Rignot and Kanagaratnam*, 2006] in which mean summer temperatures at coastal stations increased by nearly a degree relative to the 1992-to-2000 mean. During the warming period, the rate of calving-front retreat increased for many of Greenland's tidewater glaciers (T. Moon, manuscript in preparation). In contrast, there was a trend toward tidewater glacier advance as temperatures decreased from the early 1950s to the mid 1980s [*Warren*, 1991]. These results suggest that while there may not be a simple relation between temperature and outlet glacier advance and retreat, in Greenland the mean-summer temperature has a major impact on tidewater glacier dynamics and calving rates.

[43] Helheim's dynamics seem to respond strongly to temperature; twice it retreated substantially when the summer temperatures were well above average and advanced during a cooler period. Prior to its recent retreat, Helheim's relatively stable front was on a bedrock high and required an annual calving rate of ~8-km/a to match the front speed [*Howat et al.*, 2005]. Retreat and speedup of Helheim between the summers of 2002 and 2003 indicate a substantial increase in calving, leading to retreat into deeper water that likely drove further tidewater retreat. This enhanced calving may have been caused by warmer summer temperatures. The mean summer temperature in 2002 at Angmagssalik (~100 km from Helheim) was the highest in more than 20 years and the 2003 mean summer temperature was the warmest since the record began in 1895 [http://data.giss.nasa.gov]. Thus the relation between calving and changes in temperature may control large changes in ice discharge as temperatures rise or fall. It is not clear yet what drives such a relation. Among the potential causes are increased calving caused by either enhanced hydrological fracturing as a larger flux of meltwater drains into near-front crevasses or by sea ice variability in the fjord that influences the near front stresses [*Sohn et al.*, 1998].

[44] The mean summer temperature for 2006 (6°C) at Angmagssalik was lower than the 2002–2005 summer mean (6.8°C) [http://data.giss.nasa.gov]. This slightly cooler summer may have contributed to the ice tongue's advance, which has helped stabilize the glacier and reduce discharge [*Howat et al.*, 2007]. Because of the apparent sensitivity to temperature, this stabilization may be temporary, and its evolution will depend on the temperature in future summers. The 1933 ice front position and the 1965 Corona imagery suggest that an ice tongue may have existed for more than 30 years and that substantial thickening did not begin until a period of historically low temperatures in the 1970s and 1980s.

5. Summary

[45] Our results capture a series of calving episodes during a period when Helheim and Kangerdlugssuaq sped up dramatically and retreated. These data indicate that dynamic instabilities play a major role as the glaciers retreat back over depressions in the bedrock topography. As these glaciers receded, some of the larger calving events produced large earthquakes that were detected with teleseismic observations [*Ekstrom et al.*, 2003; *Ekstrom et al.*, 2006]. As the glaciers retreated into deeper water, areas behind their ice fronts tended to thin to near flotation, which may have allowed basal crevasses to penetrate the full thickness of the ice and induce calving. It is not clear whether this process contributes to the calving at times when the terminus position remains stable. Numerical models for other polar glaciers predict this thinning should occur when the ice retreats into deeper water [*Vieli et al.*, 2002], and it is at this stage that we observe thinning and rifting. Thus this mode of calving may largely occur during retreat stages.

[46] Historical observations suggest that the recent changes at Helheim are not unique and that a similar phase of retreat occurred in the 1930s when temperatures reached similar highs. Synchronous changes elsewhere in Greenland in response to a recent warming [*Luckman et al.*, 2006; *Rignot and Kanagaratnam*, 2006] suggest that Greenland's tidewater glaciers are sensitive to climate and can retreat and advance rapidly. Sensitivity of calving to temperature may be the key driver, but the processes that yield this sensitivity are not well understood. Despite the uncertainty in our knowledge of the exact mechanism, it is clear that a decadal-scale increase in mean summer temperature of about 1°C coincided with substantially increased ice discharge from Greenland. Because these processes are poorly understood and may be nonlinear, they are not included in recent projections of sea level for the next century [*IPCC*, 2007]. While natural variability may have driven much of the past temperature change, warming of well over the recent 1°C rise is expected for the next century. Thus the apparent sensitivity to temperature likely will trigger additional tidewater glacier instability that will increase Greenland's discharge of ice to the ocean.

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