Title
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Journal
Geophysical Research Letters, 32(22)

ISSN
0094-8276

Authors
Howat, Ian M
Joughin, I
Tulaczyk, S
et al.

Publication Date
2005-11-01

GEOPHYSICAL RESEARCH LETTERS, VOL. 32, L22502, doi:10.1029/2005GL024737, 2005

Rapid retreat and acceleration of Helheim Glacier, east Greenland

I. M. Howat,[1] I. Joughin,[2] S. Tulaczyk,[1] and S. Gogineni[3]

Received 22 September 2005; revised 14 October 2005; accepted 19 October 2005; published 22 November 2005.

[1] A significant amount of the measured coastal thinning of the Greenland ice sheet may be due to recent acceleration of outlet glaciers. Using remote sensing, we measured two major periods of speedup on Helheim Glacier between 2000 and 2005 that increased peak speeds from approximately 8 to 11 km/yr. These speedups coincided with rapid retreats of the calving front, totaling over 7.5 km. The glacier also thinned by over 40 m from 2001 to 2003. Retreat of the ice front appears to decrease resistance to flow and concentrates the gravitational driving force over a smaller area. Farther up-glacier, acceleration may be a delayed response to surface draw-down and steepening of the glacier's main trunk. If the 2005 speedup also produces strong thinning, then much of the glacier's main trunk may un-ground, leading to further retreat. **Citation:** Howat, I. M., I. Joughin, S. Tulaczyk, and S. Gogineni (2005), Rapid retreat and acceleration of Helheim Glacier, east Greenland, *Geophys. Res. Lett.*, *32*, L22502, doi:10.1029/2005GL024737.

1. Introduction

[2] Over the last decade, much of the Greenland Ice Sheet's lower elevations have thinned at rates of up to 10 m yr^{-1} [*Abdalati et al.*, 2001; *Krabill et al.*, 2000, 2004]. While temperatures have also increased, energy balance estimates indicate that only about half of this thinning can be attributed to increased surface melt [*Krabill et al.*, 2004]. The remainder is likely due to dynamic thinning caused by accelerated flux through the narrow outlet glaciers that discharge ice to the surrounding ocean [*Krabill et al.*, 2004]. A reduction in the buttressing resistance provided by ice tongues may accelerate flow [*Joughin et al.*, 2004; *Thomas*, 2004]. Alternatively, such acceleration may be caused by increased surface melt-water penetration to the bed [*Zwally et al.*, 2002]. Direct measurements of accelerated ice flow, either from surface or remote sensing observations, are sparse and neither mechanism has been tested in detail. Understanding such acceleration is important because dynamic thinning may increase an ice sheet's sensitivity to climate warming [*Parizek and Alley*, 2004].

[3] Helheim glacier (66.4°N, 38°W) is the fastest flowing outlet along the Greenland Ice Sheet's eastern margin and has the second largest flux (23 km^{3}yr^{-1} in 1996) [*Rignot et al.*, 2004]. Two main tributaries converge upstream of a main trunk bounded by a 5-to-7-km wide fjord. The glacier terminates at a calving front with no significant floating section [*Rignot et al.*, 2004] and a peak speed of 8 km yr^{-1} in 1996 [*Reeh et al.*, 1999]. Since the mid-1990's, the glacier's lower elevations have thinned at rates of up to a few m yr^{-1}, concurrent with a regional increase in summer air temperatures [*Abdalati et al.*, 2001; *Krabill et al.*, 2004]. Here we compare remotely sensed velocity and elevation data acquired between 2000 and 2005 to determine if there have been recent changes associated with this thinning.

2. Methods

[4] Ice flow velocity at Helheim was measured from satellite image pairs once in 2000 and twice in 2003, 2004, and 2005 (Figure 1). The October 2000 velocities were determined using standard speckle tracking techniques applied to a RADARSAT image pair separated by 24-days [*Joughin*, 2002]. Errors in these estimates are ±3%, which are largely attributable to error in the elevation data used to correct for topographic effects.

[5] Velocities for 2003 through 2005 were obtained from automated surface feature tracking [*Scambos et al.*, 1992], using principle component images of bands 1–3 (visible/near infra-red) of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) sensor. All image pairs were geometrically rectified using the same ground control, so the errors largely arise from uncertainty in the cross-correlation match (<10 m per image pair). To correct for additional errors induced by terrain, which are usually 5–10 m, two-dimensional displacements of known stationary features were triangulated to, and subtracted from, each on-ice measurement

[6] Cloud cover and a lack of trackable features and ground control limited our ASTER-based measurements to within about 35-km of the calving front. Measurements are also sparse in the shear margins because the tracking algorithm cannot resolve strong rotational motion. However, abundant transverse crevasses along the central flow-line (Figure 1) yield good data coverage. Therefore we focus our analysis on the centerline velocity.

3. Results

[7] In 2000 and 2001 the calving front was within 2 km of its positions in the mid-1990's and 1970's [*de Lange et al.*, 2005; *Weidick*, 1995]. Figure 2 shows the subsequent positions of the calving front determined from ASTER images. Between 2001 and 2002 the front retreated 1.8 km along the centerline (Figure 2) and an additional 1 km between 2002 and 2003. After remaining stable from 2003 to 2004, the front retreated by over 4 km between August 2004 and August 2005.

[8] Figure 3 shows the glacier speed along a flow-line (see Figure 1) that extends from the upper end of the northern tributary to the calving front. Comparison of the

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[1] Department of Earth Sciences, University of California, Santa Cruz, California, USA.

[2] Applied Physics Lab, University of Washington, Seattle, Washington, USA.

[3] Center for Remote Sensing of Ice Sheets, University of Kansas, Lawrence, Kansas, USA.

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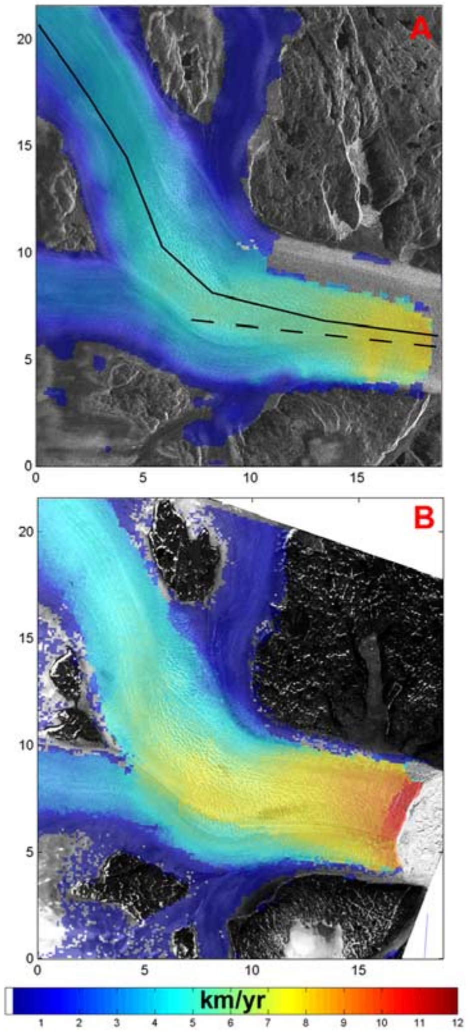

Figure 1. (A) Speckle tracking-derived velocity map from October 2000 overlain on the SAR amplitude image. Solid and hatched black lines denote the profiles used in Figures 3 and 4, respectively. (B) Surface feature tracking-derived velocity for the 7/18–8/03, 2004 image pair overlain the ASTER VNIR-principle component image. Axes in km North and East from 66.3°N, −38.5°E.

2000 and 2003 data reveal a ~2.5 km/yr increase in speed extending over 20 km up-glacier of the front. Between June/July and July/August 2003, speed increased up to 500 m/yr within 10 km of the front, which retreated over 0.8 km during that time. June/July 2004 speeds where similar to July/August 2003 within 10 km of the front, but increased by ~500 m/yr up-glacier. Speed changed little between the two 2004 observations, except for a large variation close to the front as it retreated by over 1 km. The 3-km front retreat between the summers of 2004 and 2005 was accompanied by another large speed increase, reaching over 2 km/yr near the front and extending over 10 km inland. The front retreated over 1.5 km between June/July and July/August 2005 and speed increased between 500 and 1000 m/yr.

[9] Change in Helheim's surface elevation were measured with NASA's Airborne Topographic Mapper (ATM) laser altimeter along two flight lines, one in 1997 and 2001 and another in 1998 and 2003 (Figure 4) [*Krabill et al.*, 2004]. These measurements are accurate to within 10cm. The flight lines are displaced relative to each other by a few hundred meters on the relatively flat glacier trunk, so the small differences between the 1997, 1998 and 2001 elevations can be accounted for by flight line positioning and a thinning of a few m/yr [*Abdalati et al.*, 2001]. The 2003 data, however, show a thinning of over 40m on the lower glacier from 1998. Given the consistency of the 1997 to 2001 data, we infer that most of this change occurred between 2001 and 2003. Other nearby ATM data suggest that most of this thinning occurred from 2002 to 2003 [*Krabill et al.*, 2004].

[10] Bed elevation and ice thickness were surveyed in 2001 by the University of Kansas Coherent Radar Depth Sounder (CoRDS) [*Gogineni et al.*, 2001]. Assuming hydrostatic equilibrium, these data reveal that glacier elevation was greater than the flotation level in 2003, except for very near the front where the glacier may be floating.

4. Analysis

[11] Figures 1–3 indicate that, from 2001 to 2003, the glacier's calving front retreated by nearly 3 km while the glacier's main trunk sped up ~2.5 km/yr and thinned by ~40 m. Speedup during the summer of 2003 was accompanied by another 1 km of retreat, while both speed at the front and front position remained stable from 2003 to 2004. From 2004 to 2005, the calving front retreated another 3 km and the glacier sped up by another ~2 km/yr. Another large speedup and rapid retreat was observed during the summer of 2005. The timing of these events suggests a relation between speedups and the calving front's retreat.

[12] The temporal resolution of our observations prevents a conclusive assessment of the possible contribution of increased seasonal melt-water to the bed in causing speedup. However, observations between 1992 and 1998 show modest variations in Helheim's speed that correlate with ice-front position, suggesting little melt-related variability [*de Lange et al.*, 2005]. Seasonal variations velocity observed at other locations in Greenland are much smaller than the changes we observe at Helheim [*Zwally et al.*, 2002;

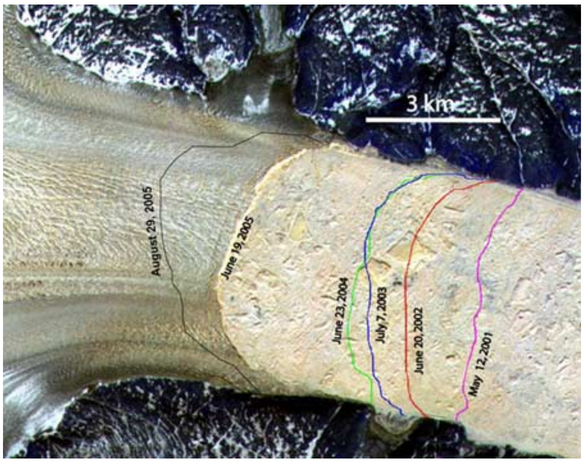

Figure 2. Helheim calving front positions overlain on an ASTER VNIR-band false color image acquired July 19, 2005. Margin positions were mapped from geo-registered ASTER images acquired on the dates shown in black.

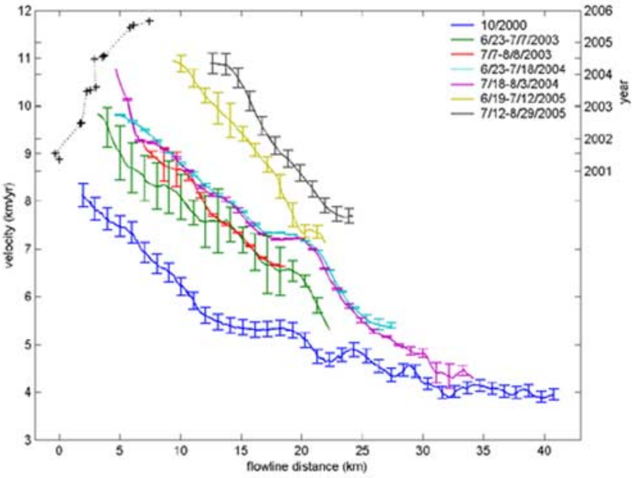

Figure 3. Surface velocity along the flow-line shown in Figure 1a with the origin at the 2000 front position. Crosses mark the observed position of the calving front versus time on the right hand axis. Feature-tracking error varies with time separation and correlation/co-registration uncertainty, which were interpolated from vectors within 100 m of each point on the flow line.

Luckman and Murray, 2005]. Furthermore, the 2004-to-2005 change occurred during the same season, indicating a speedup that is more than inter-seasonal variability. Finally the large thinning between 2001 and 2003 indicates a sustained drawdown of the surface rather than a seasonal fluctuation. Thus, while we cannot completely rule out melt-water penetration as a cause of increased speed, the existing evidence favours the hypothesis that these changes are related to retreat of the ice front.

[13] To examine the effect of calving front retreat on ice velocity, we calculate the gravitational driving force acting on the section of the glacier shown in Figure 4. By considering force over this region as whole, we reduce the impact of errors in point measurements. The main trunk's margins are well confined by the fjord's walls, so we assume a two dimensional geometry and calculate the force per unit width, F_d, inland from the front as:

$$F_d = \int_{x_f}^{x_e} \tau_d dx + F_f = \int_{x_f}^{x_e} \left(g\rho_i H \frac{dh}{dx} \right) dx + \frac{g\rho_i}{2} \left(\left(1 - \frac{\rho_w}{\rho_i} \right) H_f^2 + \frac{\rho_w}{\rho_i} h \left(2H_f - h_f \right) \right) \tag{1}$$

where τ_d is the driving stress and F_f the "pull" at the calving front resulting from the net difference in hydrostatic pressures for water and ice [*Paterson*, 2001]. In this equation g denotes the acceleration due to gravity, H is the ice thickness, h is the height above sea level, and ρ_i and ρ_w are the densities of ice (910 kg/m^2) and sea water (1028 kg/m^2), respectively. The subscripts signify values at the ice front (f) and at the up-glacier end (e) of the region.

[14] Using equation (1), we define a mean effective driving stress as $\overline{\tau}_e = F_d/L$, where $L = x_e - x_f$. With this assumption, $\overline{\tau}_e$ is greater than the mean driving stress, $\overline{\tau}_d$, by an amount that reflects the ice front's "pull", which we assume is entirely distributed over the profile (~15 times the ice thickness) shown in Figure 4. If this pull extends further inland, our results remain qualitatively correct, but we will have overestimated the ice front's contribution to $\overline{\tau}_e$.

[15] Application of equation (1) to the region from 0 to 12.5 km (Figure 4), yields 142 kPa for $\overline{\tau}_e$ in 2001. Since the 2001 and 2003 data were collected along slightly different flight lines, we assume the 2001 elevation approximates the 1998 elevation, which is justified by the small mean difference between the 1998 and 2001 profiles. The 2.1 km retreat between 2001 and 2002 increases $\overline{\tau}_e$ to 168 kPa, largely due to the reduction in L. During the additional 0.9 km retreat in 2003, $\overline{\tau}_e$ remains virtually unchanged. In this case, the ~40 m of thinning largely offsets the effect of additional ice-front retreat on $\overline{\tau}_e$.

[16] In order to balance the increase in $\overline{\tau}_e$, resistive stresses must increase. This can be accomplished by increasing speed. In many cases, glacier speed is proportional to $\overline{\tau}_e^n$ (or some polynomial of $\overline{\tau}_e$), with the dominant resistive stress determining the value of n [*Paterson*, 2001]. The high lateral strain rates observed within Helheim's narrow, deep outlet suggests that marginal shear stresses may provide much of the resistance, in which case $n = 3$. Several sliding laws yield values of n in the range from 2 to 3 [*Paterson*, 2001]. If n is within this range, then increasing $\overline{\tau}_e$ from 140 to 170 kPa should increase speed by ~40 to 65%, which is comparable to the observed speedup (up to 2 km/yr).

[17] If longitudinal pull from the ice front affects only the section shown in Figure 4, then it cannot account for the increased speed that extends an additional 20 km upstream in 2003. Prior to the speedup, the elevation difference over this section of the profile was ~600 m. The 40-m lowering of the main trunk increased this difference to ~640 m, which in turn, increased the mean slope and driving stress by ~7%. If n is in the range from 2 to 3, this would yield a speedup of 14 to 23%, which agrees well with the observed speedup over this section (~1 km/yr).

[18] The speedup appears to be the result of two effects. First there is a direct response over the glacier's main trunk following an ice-front retreat due to increased effective stress. Thinning then propagates up-glacier, causing surface draw-down and steepening and a delayed speedup of the tributaries. Such a transitional response to front retreat may

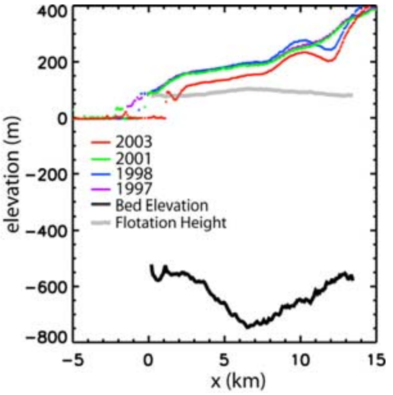

Figure 4. Surface (ATM) and bed elevation (ChORDS) along the profile location shown in Figure 1a. Gray region shows the range in floatation height assuming ρ_i = 910 kg/m^3 and 0 to 14 m equivalent thickness of air in the firn/ice column.

explain the up-glacier migration in acceleration observed between June/July 2003 and June/July 2004.

[19] We have simplified the analysis by assuming the immediate response acts over the main trunk and the delayed response acts over the tributaries. In reality, there is unlikely to be such a clean transition and both responses may make non-negligible contributions over the entire glacier. Nevertheless, the partitioning we chose yields changes in driving stresses that are consistent with the observed speedup. This suggests that we have roughly bracketed the regions over which each response is dominant. It is important to note, however, that this transition will migrate inland as the ice front continues it retreat. This is suggested by the change in velocity during the summer of 2005, where a near uniform speedup is observed at least 13 km up-glacier following the 1.7-km retreat.

[20] A model for the response of Pine Island Glacier (PIG), Antarctica to perturbations at its grounding line produces an immediate speedup and thinning at lower elevations, that in turn steepens the surface as the response diffuses inland. This results in a delayed up-glacier response similar to that described above [*Payne et al.*, 2004]. While the delay is longer (20 years) for PIG, Helheim Glacier is many times shorter, steeper, and nearly four times faster, all of which decrease response time. A rapid response is also indicated by the main trunk's 40-m thinning in less than 2 years. We note that due to the high ice velocity and short length of Helheim glacier's main trunk, the residence time of ice in the trunk is ~1 year.

[21] It is not clear what caused the initial calving front retreat. Calving rates on Jakobshavn Isbrae are higher in summer [*Sohn et al.*, 1998], indicating a sensitivity to temperature/melt. The Greenland melt season has increased in length and intensity over the past decade [*Hanna et al.*, 2005]. Alternatively, the ice front's slow thinning over time may have thinned the ice near the front, causing it to float [*Abdalati et al.*, 2001]. In either case, a small initial perturbation may have been amplified through time by a feedback cycle of retreat and thinning. This instability is evident in the 2005 retreat, which may have been driven by the 40-m thinning. This thinning brought the section that retreated much closer to flotation so that only minor subsequent thinning would yield further un-grounding. We estimate that the 40-m thinning reduced the average height above floatation by about half. Therefore, if the 2005 speedup induces a similarly large thinning, much or all of the glacier's main trunk may un-ground and disintegrate to produce independent calving fronts for the two tributaries.

5. Conclusions

[22] The recent changes at Helheim parallel those observed at Greenland's largest outlet, Jakobshavn Isbrae, which doubled its speed as its ice tongue disintegrated [*Joughin et al.*, 2004]. In both cases, the speedup was accompanied by calving-front retreat. While Jakobshavn had a long floating ice tongue and Helheim did not, in both cases, changes in geometry appear related to loss of resistance and concentration of the total driving force, followed by a delayed response as the inland ice thins. Similar retreat may be driving observed thinning on many other Greenlandic glaciers [*Krabill et al.*, 2004]. The PIG models suggest that a new steady state profile will eventually be reached in response to a fixed perturbation at the grounding line [*Payne et al.*, 2004; *Dupont and Alley*, 2005]. Helheim's boundary conditions are not fixed and are rapidly changing, however, making it difficult to predict how and when the system will stabilize. Given the degree of acceleration and thinning observed at Helheim, these glaciers may make a substantial contribution to sea level before reaching a new equilibrium. If these changes are triggered by warmer temperatures, then we may expect further retreat under climate warming.

[23] **Acknowledgments.** This work was supported by grants from NASA-OIC and NSF-ANS (#0136141) to S.T.. I.J's contribution was supported by NSF grant ARC-0531270. GIS elevation and thickness data were collected as a part of the NASA PARCA initiative.

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S. Gogineni, Center for Remote Sensing of Ice Sheets, University of Kansas, Lawrence, KS 66045, USA.

I. M. Howat and S. Tulaczyk, Department of Earth Sciences, University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA 95060, USA. (ihowat@pmc.ucsc.edu)

I. Joughin, Applied Physics Lab, University of Washington, 1013 NE 40th Street, Seattle, WA 98105, USA.