GEOPHYSICAL RESEARCH LETTERS, VOL. 35, L24503, doi:10.1029/2008GL036127, 2008

Step-wise changes in glacier flow speed coincide with calving and glacial earthquakes at Helheim Glacier, Greenland

M. Nettles,[1] T. B. Larsen,[2] P. Elósegui,[3] G. S. Hamilton,[4] L. A. Stearns,[4] A. P. Ahlstrøm,[2] J. L. Davis,[5] M. L. Andersen,[2] J. de Juan,[3] S. A. Khan,[6] L. Stenseng,[6] G. Ekström,[1] and R. Forsberg[6]

Received 24 September 2008; revised 27 October 2008; accepted 13 November 2008; published 30 December 2008.

[1] Geodetic observations show several large, sudden increases in flow speed at Helheim Glacier, one of Greenland's largest outlet glaciers, during summer, 2007. These step-like accelerations, detected along the length of the glacier, coincide with teleseismically detected glacial earthquakes and major iceberg calving events. No coseismic offset in the position of the glacier surface is observed; instead, modest tsunamis associated with the glacial earthquakes implicate glacier calving in the seismogenic process. Our results link changes in glacier velocity directly to calving-front behavior at Greenland's largest outlet glaciers, on timescales as short as minutes to hours, and clarify the mechanism by which glacial earthquakes occur.

Citation: Nettles, M., et al. (2008), Step-wise changes in glacier flow speed coincide with calving and glacial earthquakes at Helheim Glacier, Greenland, *Geophys. Res. Lett.*, *35*, L24503, doi:10.1029/2008GL036127.

1. Introduction

[2] Understanding the dynamics of the large outlet glaciers that drain the Greenland Ice Sheet is critical for predictions of sea-level rise [*Intergovernmental Panel on Climate Change*, 2007], but recently documented short-time-scale variations in glacier flow speed suggest that our understanding of these dynamics is incomplete. Satellite observations during the last decade have shown dramatic changes in flow speed on interannual timescales at Greenland's outlet glaciers [*Joughin et al.*, 2004; *Howat et al.*, 2005; *Luckman et al.*, 2006; *Rignot and Kanagaratnam*, 2006; *Howat et al.*, 2007; *Stearns*, 2007]. Many of the observed increases in glacier speed have been accompanied by retreats of several km in calving-front location [*Joughin et al.*, 2004; *Howat et al.*, 2005; *Luckman et al.*, 2006; *Howat et al.*, 2007; *Stearns*, 2007] and by increasing numbers of glacial earthquakes [*Ekström et al.*, 2006; *Tsai and Ekström*, 2007; *Joughin et al.*, 2008b].

[3] The processes responsible for acceleration and increased calving rates at Greenland's outlet glaciers remain poorly understood, as does their relation to the glacial earthquakes. Seasonal accelerations believed to be due to the drainage of meltwater to the base of the ice sheet have been documented on the western margin of the Greenland Ice Sheet [*Zwally et al.*, 2002; *Joughin et al.*, 2008a], and subglacial meltwater drainage is clearly associated with glacier acceleration at large mountain glaciers [*Bartholomaus et al.*, 2008]. However, increases in glacier speed of factors of two to eight have also been observed in association with the loss of a buttressing ice shelf [*Rignot et al.*, 2004; *Scambos et al.*, 2004] at Antarctic outlet glaciers where little surface melting occurs, and numerical modeling [*Dupont and Alley*, 2005] suggests that loss of resistance due to large calving events is sufficient to cause the acceleration of ice streams. Glacial earthquakes, which have been interpreted to represent the sudden, short-lived acceleration of glacier ice [*Ekström et al.*, 2003], occur predominantly during the late summer months [*Ekström et al.*, 2006], consistent with a link either to seasonal variations in surface meltwater [*Ekström et al.*, 2006] or calving rates [*Joughin*, 2006].

[4] During the boreal summer of 2007, we conducted a cross-disciplinary experiment at Helheim Glacier, Greenland's third-largest outlet glacier and one of its most prolific generators of glacial earthquakes, to obtain a better understanding of the links between glacier speed, calving-front behavior, and glacial earthquakes.

2. Data and Methods

[5] We operated a network of continuously recording Global Positioning System (GPS) receivers on Helheim Glacier for a period of ~50 days in 2007, from July 4 to August 24. Twelve receivers were installed on the glacier, in a configuration including stations both on and offset from the centerline (Figure 1). The stations spanned an along-flow distance of about 20 km, with the downflow stations located just behind the calving front. Several stations installed within a few km of the calving front were removed and relocated to points slightly farther upglacier during a midcampaign field visit. One GPS receiver was operated at a rock site near the glacier throughout the campaign to help define a stable local reference frame; two additional rock stations operated for shorter durations.

[6] We processed the GPS data using the GIPSY software package [*Lichten and Border*, 1987] with high-precision kinematic data processing methods [*Elósegui et al.*, 1996], and the TRACK software package [*Chen*, 1998], obtaining very similar results. We estimate the positions of the GPS sites on the surface of the glacier at 15-s intervals, relative to

[1]Department of Earth and Environmental Sciences and Lamont-Doherty Earth Observatory, Columbia University, Palisades, New York, USA.
[2]Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark.
[3]Institute for Space Sciences, CSIC, IEEC, Barcelona, Spain.
[4]Climate Change Institute, University of Maine, Orono, Maine, USA.
[5]Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, USA.
[6]Danish National Space Center, Copenhagen, Denmark.

0094-8276/08/2008GL036127$05.00

a static antenna on bedrock, and calculate average daily velocities for each site by fitting a linear model to the position estimates in an East–North–Up coordinate system. The along- and across-flow directions are then defined locally at each station such that the average cross-flow speed during the day vanishes.

[7] We also operated a variety of auxiliary geophysical sensors, including a water-pressure gauge near the end of the glacial fjord and a broadband seismometer in the settlement of Isortoq, approximately 100 km from the glacier. We monitored seismograms from the Global Seismographic Network (GSN) continuously throughout the experiment [*Ekström et al.*, 2003; *Ekström*, 2006] to detect glacial earthquakes located at Helheim Glacier. We also inspected the GSN array stacks [*Ekström*, 2006] in an interactive mode to identify earthquakes too small for detection by our standard algorithm. We used cloud-free visible-band imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) to digitize the position of the calving front at near-daily intervals, estimating a one-pixel (250 m) uncertainty based on comparison with Advanced Land Observing Satellite (ALOS) imagery.

3. Results

[8] Mean horizontal velocities for the GPS sites during the observation interval of each station are shown in Figure 1. The fastest velocities (~25 m/day) are seen closest to the calving front, with slower velocities (~12 m/day) farther upglacier; however, the slowest velocity we observe (~10 m/day) occurs in the middle of the network, near the large bend in the glacier. These summer-season averages are similar to velocity estimates for 2003–2004 obtained in satellite remote-sensing studies, about 15% slower than peak velocities observed in 2005 but ~15% faster than in 2006 and ~30% faster than in 2001 [*Howat et al.*, 2005; *Luckman et al.*, 2006; *Howat et al.*, 2007; *Stearns*, 2007].

[9] Daily estimates of glacier speed in the along-flow direction are shown in Figure 2. Several abrupt, step-like increases in glacier speed, seen at all stations in the network, dominate the timeseries. The amplitude of these velocity increases is largest near the calving front (Figure S1 of the auxiliary material[1]), decreasing with distance upglacier. The sudden changes in velocity thus also represent sudden changes in longitudinal strain rates.

[10] We detected five large glacial earthquakes at Helheim Glacier during the observing period of the GPS network. Modeling three-component seismograms [*Ekström et al.*, 2003; *Tsai and Ekström*, 2007] confirms that the earthquake sources exhibit characteristics like those previously reported [*Ekström et al.*, 2003; *Tsai and Ekström*, 2007], including long source durations and sliding directions consistent with the sense of glacier motion. The earthquakes are closely correlated in time with the step-like increases we observe in glacier speed (Figure 2).

[11] We identified an additional seven earthquakes using our interactive detection procedure (Table S1 and Figure 2c). The times of these smaller earthquakes generally also correlate with increases in glacier velocity, though the increases are of smaller amplitude.

[12] The high sampling rate of our GPS data allows us to examine the character and timing of the glacier acceleration in more detail. The results of a detailed analysis of the GPS data for one station located near the calving front, for a three-day period surrounding the step-like speedup on day of year 225 (August 13), are shown in Figure 3. We estimate the time of the glacier speedup by searching over this range for the time and amplitude of the change in slope of the position estimates that best predict the data in a least-squares sense. The model assumption of an instantaneous velocity change explains the data surprisingly well (Figure 3). Our preferred model allows for two changes in velocity during the three-day estimation period, and includes diurnal and semidiurnal position variations as free parameters. The range of estimates for the time of speedup obtained using a variety of modeling approaches, including curve fitting and Kalman filter analysis, spans ~105 min, or ~140 min with the inclusion of one-sigma formal uncertainties; most of these estimates fall earlier than our preferred speedup time, leading to an asymmetric uncertainty band. Glacier speedup occurs at a time indistinguishable from that of the first, smaller earthquake identified on day 225, and very near, but ~80 min earlier than, the time of the second, larger earthquake.

[13] Analysis of GPS data from the remaining stations (Figures S2 and S3) shows that the speedup occurs coherently along the length of the glacier. Uncertainties in the time of the speedup are greater for stations located farther from the calving front because the amplitudes of the velocity steps are smaller at those stations. The speedup times we estimate are, on average, earlier at the five stations closest to the calving front than at those farther up the glacier, but we cannot distinguish any systematic pattern of propagation of a speedup pulse. Our estimates of the timing of the velocity increase are thus consistent with simultaneous acceleration across the network. GPS timeseries for the glacier speedup events on days 189–190 (July 8–9) and day 207 (July 26) are also similar to those reported here.

[14] Previous workers demonstrated a correlation between the times of glacial earthquakes and large episodes of ice loss at the calving fronts of Helheim and Kangerdlugssuaq Glaciers [*Joughin et al.*, 2008b]. The cumulative change in frontal area of Helheim glacier during summer, 2007, based on MODIS observations is shown in Figure 2b. Large-scale ice loss shows a clear temporal relationship with both glacier acceleration and glacial earthquakes.

[15] The satellite imagery provides temporal resolution of about one day. We obtain better constraints on the timing of calving by examining oscillations in the water-height signal recorded by the pressure gauge deployed during the GPS experiment. Tidal variations dominate the recorded signal, but significant water-level variations occur outside the tidal band. Small tsunamis with amplitudes of several decimeters can be clearly identified immediately following the glacial earthquakes (Figure 2c). The most likely source of these signals is the collapse of large masses of ice into the water of the glacial fjord during the calving process.

[16] Hand-picked tsunami arrival times lie an average of 10 min after the glacial-earthquake origin times. Glacier freeboard at the calving front suggests a fjord depth of

[1]Auxiliary materials are available in the HTML. doi:10.1029/2008GL036127.

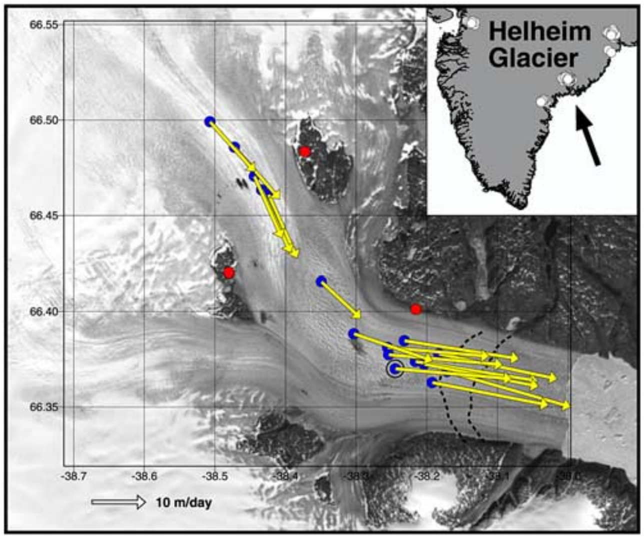

Figure 1. Southern Greenland, with locations of glacial earthquakes; arrow marks Helheim Glacier (inset). Geometry of GPS network at Helheim Glacier during summer, 2007, overlain on a 2001 LANDSAT image. The position of the calving front at two times during the summer of 2007 is shown by the black dotted lines (easternmost line, July 4; westernmost line, August 15). Blue dots, locations of GPS stations on the glacier surface at the time of deployment; black ring shows station IS38 (Figure 3). Red dots, locations of rock-based reference stations. Yellow arrows show average station velocities determined over the duration of station deployment; white arrow shows scale.

~700 m at that location. Assuming an average fjord depth in the range 200 m–1000 m and employing a shallow-water approximation leads to predicted travel times of 6–15 min, consistent with the assumption that the tsunami source is located at or near the calving front of Helheim Glacier, ~35 km away. Cross-correlation analysis provides a high-precision estimate of the time separation between the tsunami arrivals, which we find to be indistinguishable from the time separation between earthquakes. The times of the tsunami-generating calving events are thus strongly constrained to lie within a few minutes of the glacial earthquakes.

4. Discussion

[17] Our results have implications for models of both the glacial-earthquake source process and controls on glacier speed. The model for glacial-earthquake seismogenesis proposed by *Ekström et al.* [2003] and *Tsai and Ekström* [2007] predicts decimeter-to-meter–level coseismic displacement of the glacier surface, as a large volume of the glacier trunk lurches forward abruptly. Displacements of more than half a meter, occurring over ~20 min, have recently been observed in Antarctica in association with weaker seismic signals [*Wiens et al.*, 2008]. We observe no measurable coseismic displacement in association with Helheim's glacial earthquakes. Further, the glacier speedup we observe represents an acceleration, and thus a force, too small to explain the observed seismic radiation, even assuming a total duration of acceleration similar to the source durations of the Greenland glacial earthquakes (30–60 s). The observed acceleration thus cannot itself represent the seismogenic source of the glacial earthquake. Models for seismogenesis involving slip on the calving face and momentum transfer from newly formed icebergs rolling against the calving face [*Joughin et al.*, 2008b; *Tsai et al.*, 2008] are, however, consistent with the timing constraints provided by this study.

[18] The physical processes leading to glacial earthquakes are likely to be complex. Seismograms from the Isortoq station confirm the timing of the two glacial earthquakes detected on day 225, but also show an earlier initiation of low-level seismic activity (Figure 3). Seismic energy begins to arrive approximately one hour in advance of the large earthquake, and at least a quarter hour before the smaller earthquake. The cause of these signals is not yet

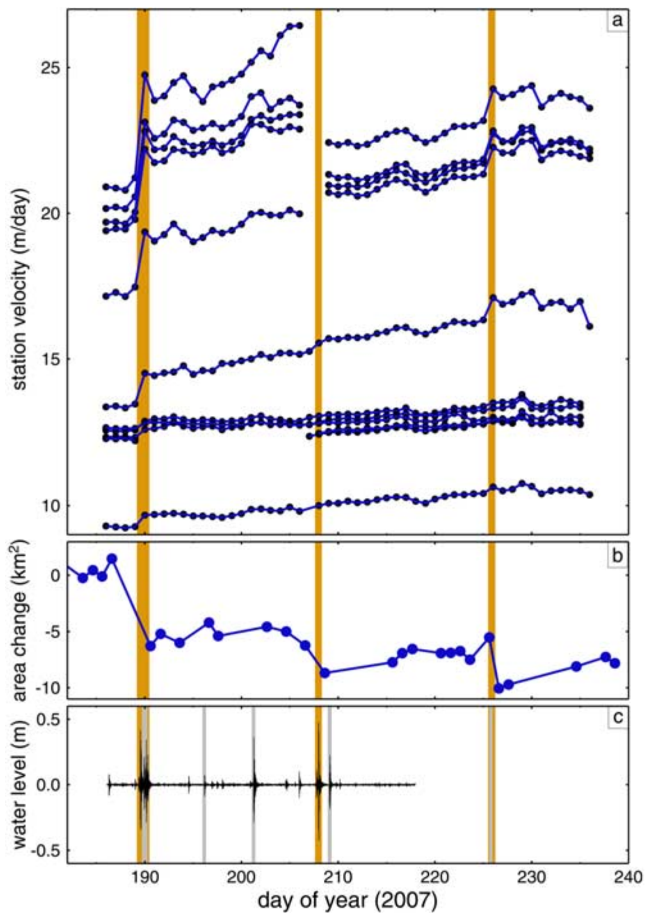

Figure 2. (a) Average daily along-flow speed for GPS stations on the surface of Helheim Glacier. The stations advect with the glacier ice, explaining the gradual upward trend in velocity. (b) Cumulative change in glacier area with respect to total area on day 180. Rapid changes towards more negative values indicate large calving events. (c) Short-period (200–4000 s) variations in water height near the end of the Helheim fjord with respect to the average water level. Times of large glacial earthquakes are indicated by orange bars (three events on days 189–190, one event on day 207, one event on day 225); smaller earthquakes are indicated by gray bars.

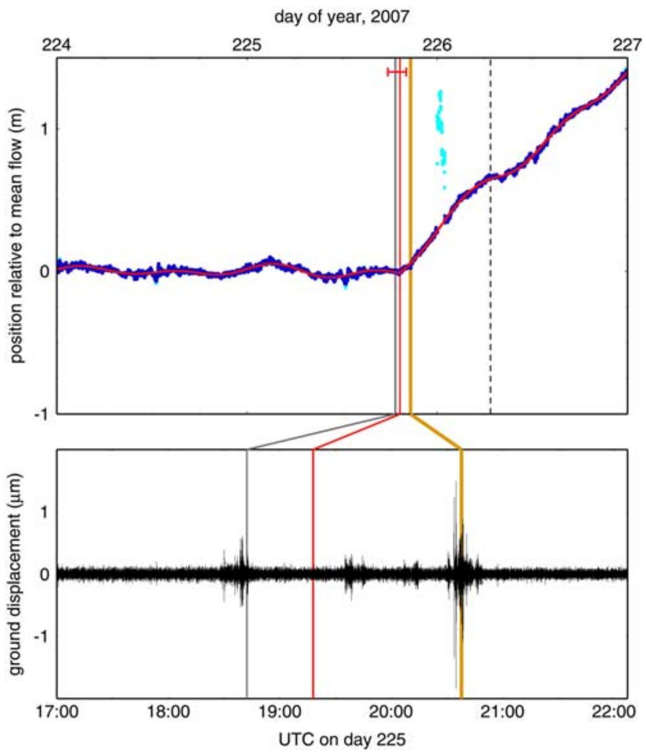

Figure 3. (top) Horizontal displacement of GPS station IS38 (Figure 1) over a period of three days. Blue dots show station position, estimated every 15 s, with respect to position expected for a mean along-flow speed of 21.7 m/day. Cyan dots indicate 4-σ outliers, associated mainly with the day boundary and not believed to represent geophysical signal. The glacier accelerates to 23.0 m/day near the end of day 225 (vertical red bar), and slows to 22.7 m/day $\sim$12 hr later (dashed black line). Horizontal red bar shows estimated uncertainty in acceleration time. Red curve, predicted station position for the model used to estimate time of glacier speedup. Orange and gray bars show times of large and small glacial earthquakes. (bottom) Displacement seismogram (0.5–3 s) recorded 100 km from Helheim Glacier.

known, but they exhibit some characteristics similar to high-frequency 'rumblings' reported in West Greenland [*Rial et al.*, 2007]. They may be related to processes preparatory to glacier calving, such as crevasse opening, to pervasive breakage of sticky spots on the glacier bed and walls, or to subglacial water transport.

[19] Our combined seismological and geodetic observations suggest two plausible scenarios for glacier speedup. In the first, a large calving event leads to the loss of resisting forces at the calving front, resulting in glacier acceleration [e.g., *Howat et al.*, 2005], and produces one or more glacial earthquakes, perhaps through one of the mechanisms of *Tsai et al.* [2008]. The apparent small difference in the timing of acceleration and calving results from the finite duration of the calving process, the uncertainties in our estimate of the time of glacier acceleration, or both. In this scenario, the seismic precursors to the glacial earthquakes are associated with disintegration of the calving front in preparation for a major calving event. In the second scenario, the glacier accelerates as a result of a process other than calving, such as the passage of a meltwater pulse under the glacier, and this process leads to calving and associated glacial earthquakes. The speedup is sustained and perhaps enhanced by a calving-related loss of resisting forces at the calving front. In either scenario, changes in tidewater-glacier speed are closely tied to the behavior of the glacier terminus.

5. Conclusions

[20] Our results demonstrate that large outlet glaciers can accelerate in a near-instantaneous, step-like fashion, and show a clear link between such acceleration and large calving events. In addition, our observations invalidate the lurching-glacier model [*Ekström et al.*, 2003; *Tsai and Ekström*, 2007] for Greenland's glacial earthquakes, and tie the earthquake source closely to processes at the calving front. The glacial earthquakes and the rapid accelerations we document emphasize the importance of short-time-scale processes occurring at Greenland's outlet glaciers, and highlight the need to understand the role such processes play in controlling longer-term, seasonal and interannual, variability in glacier behavior.

[21] **Acknowledgments.** The Helheim 2007 project was supported by the Gary Comer Science and Education Foundation, the U.S. National Science Foundation, the Danish Commission for Scientific Research in Greenland (KVUG), the Spanish Ministry of Education and Science, the Geological Survey of Denmark and Greenland (GEUS), Geocenter Copenhagen, the Danish National Space Center, NASA, the Lamont-Doherty Climate Center, and the Dan and Betty Churchill Exploration Fund. GPS equipment and technical support were provided by UNAVCO, Inc. The GSN data were collected and distributed by IRIS and the USGS. Regional seismic data were archived by GEOFON.

References

Bartholomaus, T. C., R. S. Anderson, and S. P. Anderson (2008), Response of glacier basal motion to transient water storage, *Nature Geosci.*, *1*, 33–36.

Chen, G. (1998), GPS kinematic positioning for the airborne laser altimetry at Long Valley, California, Ph.D. thesis, Mass. Inst. of Technol., Cambridge.

Dupont, T. K., and R. B. Alley (2005), Assessment of the importance of ice-shelf buttressing to ice-sheet flow, *Geophys. Res. Lett.*, *32*, L04503, doi:10.1029/2004GL022024.

Ekström, G. (2006), Global detection and location of seismic sources by using surface waves, *Bull. Seismol. Soc. Am.*, *96*, 1201–1212.

Ekström, G., M. Nettles, and G. A. Abers (2003), Glacial earthquakes, *Science*, *302*, 622–624.

Ekström, G., M. Nettles, and V. C. Tsai (2006), Seasonality and increasing frequency of Greenland glacial earthquakes, *Science*, *311*, 1756–1758.

Elósegui, P., J. L. Davis, J. M. Johansson, and I. I. Shapiro (1996), Detection of transient motions with the Global Positioning System, *J. Geophys. Res.*, *101*, 11,249–11,262.

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.

Howat, I. M., I. Joughin, and T. A. Scambos (2007), Rapid changes in ice discharge from Greenland outlet glaciers, *Science*, *315*, 1559–1561.

Intergovernmental Panel on Climate Change (2007), *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., Cambridge Univ. Press, Cambridge, U. K.

Joughin, I. (2006), Greenland rumbles louder as glaciers accelerate, *Science*, *311*, 1719–1720.

Joughin, I., W. Abdalati, and M. Fahnestock (2004), Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier, *Nature*, *432*, 608–610.

Joughin, I., S. B. Das, M. A. King, B. E. Smith, I. M. Howat, and T. Moon (2008a), Seasonal speedup along the western flank of the Greenland ice sheet, *Science*, *320*, 781–783.

Joughin, I., I. Howat, R. B. Alley, G. Ekstrom, M. Fahnestock, T. Moon, M. Nettles, M. Truffer, and V. C. Tsai (2008b), Ice-front variation and tidewater behavior on Helheim and Kangerdlugssuaq Glaciers, Greenland, *J. Geophys. Res.*, *113*, F01004, doi:10.1029/2007JF000837.

Lichten, S. M., and J. S. Border (1987), Strategies for high-precision Global Positioning System orbit determination, *J. Geophys. Res.*, *92*, 12,751–12,762.

Luckman, A., T. Murray, R. de Lange, and E. Hanna (2006), Rapid and synchronous ice-dynamic changes in east Greenland, *Geophys. Res. Lett.*, *33*, L03503, doi:10.1029/2005GL025428.

Rial, J. A., C. Tang, and K. Steffen (2007), A closer view of glacial earthquakes around Jakobshavn Glacier, Greenland, using a portable seismic array, *Eos Trans. AGU*, *88*(52), Fall Meet. Suppl., Abstract GC13A-0935.

Rignot, E., and P. Kanagaratnam (2006), Changes in the velocity structure of the Greenland ice sheet, *Science*, *311*, 986–990.

Rignot, E., G. Casassa, P. Gogineni, W. Krabill, A. Rivera, and R. Thomas (2004), Accelerated ice discharge from the Antarctic Peninsula following the collapse of Larsen B ice shelf, *Geophys. Res. Lett.*, *31*, L18401, doi:10.1029/2004GL020697.

Scambos, T. A., J. A. Bohlander, C. A. Shuman, and P. Skvarca (2004), Glacier acceleration and thinning after ice shelf collapse in the Larsen B embayment, Antarctica, *Geophys. Res. Lett.*, *31*, L18402, doi:10.1029/2004GL020670.

Stearns, L. A. (2007), Outlet glacier dynamics in east Greenland and East Antarctica, Ph.D. thesis, Univ. of Maine, Orono.

Tsai, V. C., and G. Ekström (2007), Analysis of glacial earthquakes, *J. Geophys. Res.*, *112*, F03S22, doi:10.1029/2006JF000596.

Tsai, V. C., J. R. Rice, and M. Fahnestock (2008), Possible mechanisms for glacial earthquakes, *J. Geophys. Res.*, *113*, F03014, doi:10.1029/2007JF000944.

Wiens, D. A., S. Anandakrishnan, J. P. Winberry, and M. A. King (2008), Simultaneous teleseismic and geodetic observations of the stick-slip motion of an Antarctic ice stream, *Nature*, *453*, 770–774.

Zwally, H. J., W. Abdalati, T. Herring, K. Larson, J. Saba, and K. Steffen (2002), Surface melt-induced acceleration of Greenland ice-sheet flow, *Science*, *297*, 218–222.

A. P. Ahlstrøm, M. L. Andersen, and T. B. Larsen, Geological Survey of Denmark and Greenland, Oester Voldgade 10, DK-1350 Copenhagen, Denmark.

J. L. Davis, Harvard-Smithsonian Center for Astrophysics, MS 42, 60 Garden Street, Cambridge, MA 02138, USA.

J. de Juan and P. Elósegui, Institute for Space Sciences, CSIC, IEEC, Gran Capita 2, 08034 Barcelona, Spain.

G. Ekström and M. Nettles, Lamont-Doherty Earth Observatory, Columbia University, 61 Route 9W, Palisades, NY 10964, USA. (nettles@ldeo.columbia.edu)

R. Forsberg, S. A. Khan, and L. Stenseng, Danish National Space Center, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark.

G. S. Hamilton and L. A. Stearns, Climate Change Institute, University of Maine, Orono, ME 04469, USA.