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Collaborative Research: High-resolution studies of glacier dynamics at two major outlet glaciers in East Greenland

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Final Report for Period: 09/2011 - 08/2012**Submitted on:** 10/26/2012**Principal Investigator:** Hamilton, Gordon S.**Award ID:** 0710891**Organization:** University of Maine**Submitted By:**

Hamilton, Gordon - Principal Investigator

Title:

Collaborative Research: High-resolution studies of glacier dynamics at two major outlet glaciers in East Greenland

Project Participants

Senior Personnel

Name: Hamilton, Gordon**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Dr Hamilton coordinated the UMaine component of the project, including liaison with collaborative PIs, fieldwork planning, and data analysis. He advised a graduate student who worked on the project, and served as a mentor for the project postdoctoral scientist. Dr Hamilton participated in all fieldwork activities in East Greenland and was involved in all aspects of the data analysis.

Post-doc

Name: Stearns, Leigh**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Dr Stearns was engaged as a postdoctoral scientist on this project, prior to taking up a faculty position at the University of Kansas. She participated in summer 2009 fieldwork in East Greenland, and was involved in data analysis and interpretation. She remained involved with this project after moving from Maine to Kansas.

Graduate Student

Name: Schild, Kristin**Worked for more than 160 Hours:** Yes**Contribution to Project:**

Ms Schild was an MS student advised by Dr Hamilton. Her thesis research was based on data acquired during this project. She participated in the field campaigns in 2008 and 2009, and conducted remote sensing analyses of Helheim and Kangerdlugssuaq glaciers. Ms Schild defended her thesis in April 2011, and was engaged as a research assistant from May-September 2011, during which she prepared her thesis material for peer-reviewed publications. She is now a PhD student in glaciology at Dartmouth College.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Organizational Partners

Smithsonian Institution Astrophysical Observatory

Dr James Davis, formerly of SAO's Center for Astrophysics, is a collaborating lead PI. We worked together on the design of a new GPS instrument for challenging environments, as well as on the analysis and interpretation of field data.

Columbia University Lamont Doherty Earth Observatory

Drs Meredith Nettles and Goran Ekstrom are collaborating lead PIs (Dr Davis, formerly of SAO is now also at LDEO). We worked together on field logistics planning and the analysis/interpretation of field data. UMaine and LDEO took the lead in 2008, 2009 and 2010 field activities.

Other Collaborators or Contacts

We collaborated with several groups:

- (1) UNAVCO -- collaborative work on the design and fabrication of a new GPS instrument for remote/challenging environments;
- (2) National Space Institute/Technical University of Denmark -- collaboration on analysis and interpretation of geodetic field data;
- (3) Spanish Institute for Space Studies -- collaborating on the design and fabrication of a new GPS instrument for remote/challenging environments, and the analysis and interpretation of geodetic field data;
- (4) Geological Survey of Denmark and Greenland -- joint field activities, and analysis and interpretation of field data.

Activities and Findings**Research and Education Activities:**

This project involved the following major research and education activities:

- (1) analysis of data collected during field campaigns in East Greenland. We processed and analyzed GPS observations for the presence of transient flow behavior. We also analyzed and interpreted the timing of large calving events seen by time-lapse photography.
- (2) construction of high-temporal resolution records of glacier length. We used MODIS satellite imagery to derive daily (cloud-cover permitting) time series of terminus position for both Helheim and Kangerdlugssuaq glaciers. These data provide a longer-term and a wider-scale perspective in which to place the detailed field observations.
- (3) examined the link between changes in terminus position (calving events) and the generation of teleseismic events. This work has provided unique insights into the glacial earthquake phenomenon.

Findings: (See PDF version submitted by PI at the end of the report)

See attached.

Training and Development:

This project provided opportunities to develop the following skills and experience:

- (1) research management experience for the PI (Hamilton);
- (2) multidisciplinary research experience (field, data analysis) for the graduate student (Schild).

Outreach Activities:

The PI and grad student used project materials to form the basis of a one-day teachers workshop hosted annually by UMaine's Climate Change Institute. They also gave multiple presentations on Greenland research to non-specialist audiences in New England.

The PI has spoken to a wide variety of non-specialist audiences (coastal planning engineers and policymakers, state and federal legislators, etc.) on recent changes in the Greenland Ice Sheet, including many results from the current project.

Journal Publications

Nettles, M.; T. Larsen; P. Elosegui; G.S. Hamilton; L.A. Stearns; A. Ahlstrom; J.L. Davis; M.L. Andersen; J. de Juan; S.A. Khan; L. Stenseng; G. Ekstrom; R. Forsberg., "Step-wise changes in glacier flow speed coincide with calving and glacial earthquakes at Helheim Glacier, Greenland.", *Geophysical Research Letters*, p. L24503, vol. 35, (2008). Published, doi:10.1029/2008GL036127

de Juan, J., P. Elosegui, M. Nettles, T. Larsen, J.L. Davis, G.S. Hamilton, L.A. Stearns, M.L. Andersen, G. Ekstrom, A. Ahlstr???m, L. Stenseng, S.A. Khan & R. Forsberg, "Sudden increase in tidal response linked to calving and acceleration at a large Greenland outlet glacier", *Geophysical Research Letters*, p. , vol. , (2009). Submitted,

Andersen, M. L., T. B. Larsen, M. Nettles, P. Elosegui, D. van As, G. S. Hamilton, L. A. Stearns, J. L. Davis, A. P. Ahlstr???m, J. de Juan, G. Ekstr???m, L. Stenseng, S. A. Khan, R. Forsberg, and D. Dahl-Jensen, "Spatial and temporal melt variability at Helheim Glacier, East Greenland, and its effect on ice dynamics", *Journal of geophysical research*, p. , vol. 115, (2010). Published, 10.1029/2010JF001760

Andersen, M. L., M. Nettles, P. Elosegui, T. B. Larsen, G. S. Hamilton and L. A. Stearns, "Quantitative estimates of velocity sensitivity to surface melt variations at a large Greenland outlet glacier", *Journal of Glaciology*, p. 609, vol. 57, (2011). Published,

Schild, K.M and G.S. Hamilton, "Seasonal and interannual terminus position variability at major outlet glaciers in Greenland", *Journal of Glaciology*, p. , vol. , (2012). Submitted,

Schild, K.M. and G.S. Hamilton, "Glaciological characteristics of glacial earthquakes in Greenland", *Geophysical Research Letter*, p. , vol. , (2012). Submitted,

Books or Other One-time Publications

Hamilton, G.S., K.M. Schild, L.A. Stearns, J. de Juan, P. Elosegui and M. Nettles, "Time-lapse photography yields new insights into Greenland outlet glacier dynamics (Invited)", (2010). Abstract Volume, Published

Bibliography: Eos, Trans. AGU, abstract IN33B-1313 presented at 2010 Fall Meeting, San Francisco, Calif., 13-17 Dec.

Andersen, M.L., M. Nettles, T.B. Larsen, P. Elosegui, G.S. Hamilton and L.A. Stearns, "Quantifying the influence of melt on velocity variations at a large Greenland outlet glacier", (2010). Abstract Volume, Published

Bibliography: Eos, Trans. AGU, abstract C21B-0524 presented at 2010 Fall Meeting, San Francisco, Calif., 13-17 Dec.

de Juan, J., P. Elosegui, J.L. Davis, M. Nettles, T.B. Larsen, G.S. Hamilton and L.A. Stearns, "GPS measurements of flow variations at a large Greenland outlet glacier due to ocean tidal forcing", (2010). Abstract Volume, Published

Bibliography: Eos, Trans. AGU, abstract C21A-0516 presented at 2010 Fall Meeting, San Francisco, Calif., 13-17 Dec.

Schild, K.M., G.S. Hamilton, M. Nettles and G. Ekstrom, "Tidewater glacier terminus changes and glacial earthquakes in Greenland", (2010). Abstract Volume, Published

Bibliography: 60A147, Abstract Volume for the International Glaciological Society Symposium on Ice Sheet-Ocean Interactions, San Diego, CA, June 5-10, 2011

Web/Internet Site

Other Specific Products

Contributions

Contributions within Discipline:

We pioneered the measurement of very rapid glacier flow using in-situ techniques, as well the integrated analysis of glaciological, seismological and hydrographic data.

Contributions to Other Disciplines:

This project was the catalyst for the development of a low-cost, low-powered, telemetry-capable GPS instrument for deployment in rugged and challenging environments. As part of this development, we advanced data telemetry procedures for high-rate data transfer from remote locations. The instrument itself, although designed for glaciological applications, has obvious uses in other disciplines (e.g., earthquake seismology, volcanology).

Contributions to Human Resource Development:

Participation in this project provided international, multidisciplinary research experience for a graduate student, a postdoctoral scientist, and the PI. The student and postdoc are both women scientists.

Contributions to Resources for Research and Education:

As part of this project, we expanded our capabilities to make high-rate in-situ measurements of geophysical processes through the development of our new GPS instrument.

Contributions Beyond Science and Engineering:

The Greenland Ice Sheet has the potential to contribute a very rapid rise in sea level over the coming century. Accurate sea level projections are difficult to make, however, without knowing the detailed physics behind the ice sheet's response to climate change. This project acquired some of the first detailed measurements which will greatly improve our physical understanding of ice sheet dynamics, which should result in more reliable sea level forecasts.

Our GPS instrument has some commercial potential.

Conference Proceedings

Categories for which nothing is reported:

Any Web/Internet Site

Any Product

Any Conference

Major Findings (UMaine) – Award # ANS-0710891

Our major findings come from the analysis of high-rate GPS data collected at a network of sites installed on Helheim Glacier during three summer season (2007, 2008, 2009) (see Figure 1), the analysis of water level records collected by tide gauges installed in Sermilik Fjord, and the analysis of time-lapse photograph acquired by three cameras deployed at sites overlooking the terminus of Helheim Glacier. This work was carried out in collaboration with colleagues from the GEUS (Denmark) and CSIC (Spain).

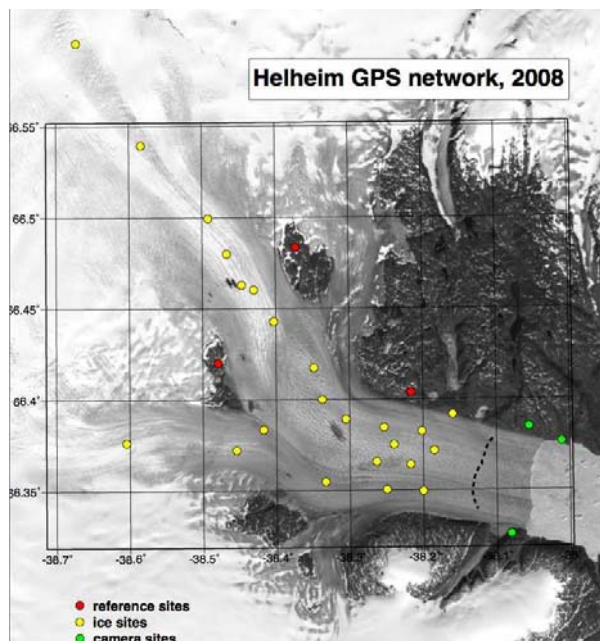


Figure 1. Map of Helheim Glacier, East Greenland showing design of GPS network deployed in the 2008 summer season. Similar networks were deployed in 2007 and 2009. Location of time-lapse cameras is also shown.

Analysis of the GPS data and ancillary measurements allowed us to test two leading hypotheses invoked to explain the recent acceleration of outlet glaciers in Greenland: i) that flow speeds increase as a response to force balance changes at the terminus due to iceberg calving; and ii) that flow speeds increase in response to enhanced surface meltwater generation. In general, we find the first hypothesis to be more compelling.

We examined a time series of glacier speeds derived from GPS observations, paying particular attention to significant speed-up events. These events are always coincident with the calving of immense icebergs from the glacier terminus, as observed in time-lapse photographs or inferred from the occurrence of small tsunamis in our record of fjord water level (Figure 2). Large calving events are accompanied by an instantaneous speed-up of the glacier, insofar as we can detect with the resolution of our observations. The largest changes are observed at sites closest to the terminus, although detectable speed ups occur up to 35 km inland. These speed-ups are on the order of 25% of the background speed and persist for many days after the calving event (Figure 2). Taken together, these results yield insights into the flow coupling on large outlet glaciers and point to the importance of force balance perturbations on overall flow behavior.

We carried out a similar analysis of glacier speeds and daily estimates of surface melting derived from an energy balance model forced by in situ observations collected colleagues from GEUS.

Surface melting is taken as a proxy for enhanced basal sliding. In general, we find that the flow response of the glacier to increased surface melting is lagged by one day, i.e., the speed of the glacier is faster on the day following an increase in melt generation. However, we also find that a doubling in melt rate only leads to a ~4% increase in glacier speed (Figure 3). This result is not consistent with the hypothesis that increased melting caused the widespread acceleration of Greenland outlet glaciers.

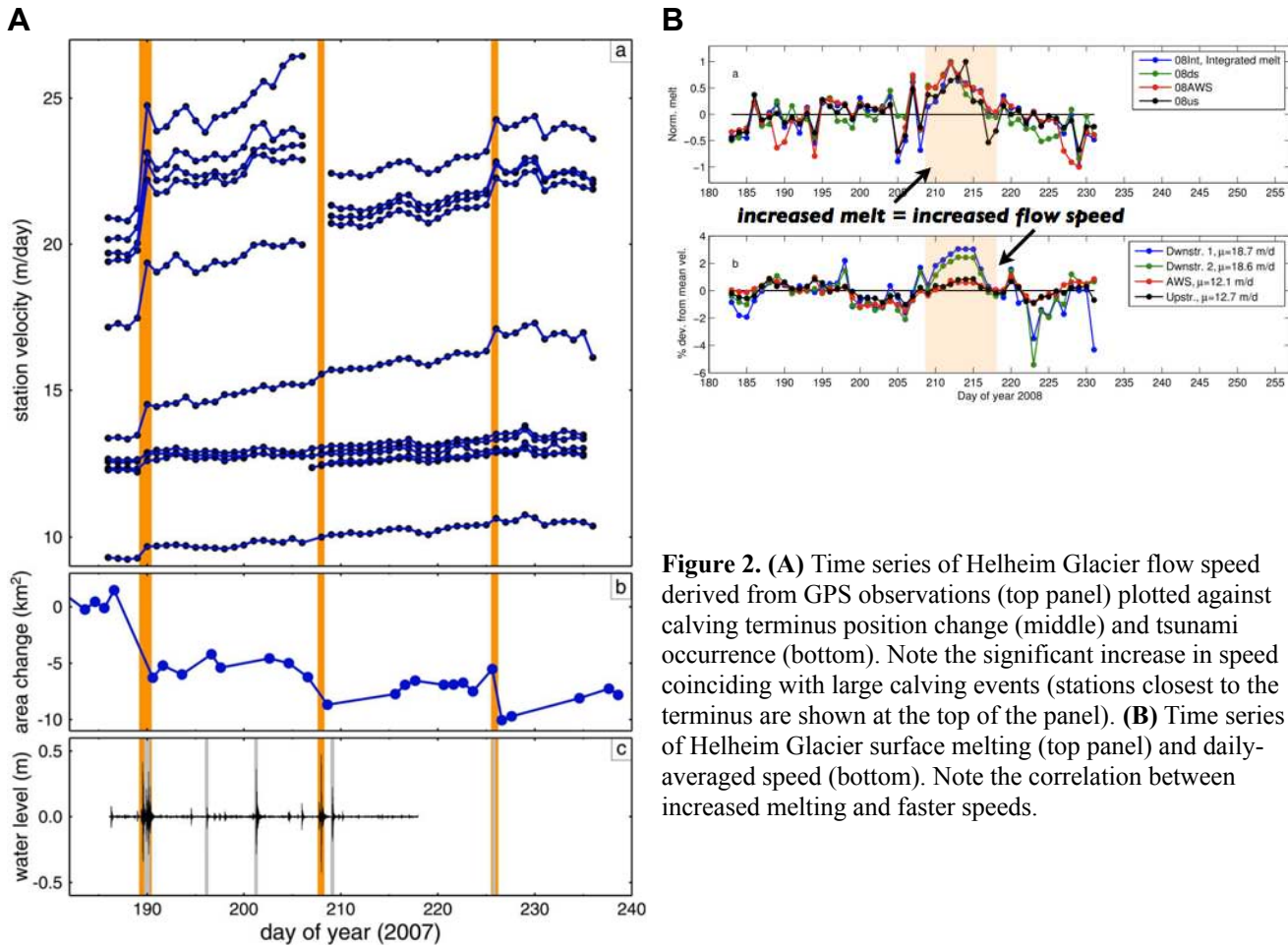


Figure 2. (A) Time series of Helheim Glacier flow speed derived from GPS observations (top panel) plotted against calving terminus position change (middle) and tsunami occurrence (bottom). Note the significant increase in speed coinciding with large calving events (stations closest to the terminus are shown at the top of the panel). (B) Time series of Helheim Glacier surface melting (top panel) and daily-averaged speed (bottom). Note the correlation between increased melting and faster speeds.

Long-duration (>30 s) seismic events equivalent to $M \approx 5$ earthquakes are associated with fjords in Greenland containing fast-flowing outlet glaciers. Of these, Helheim Glacier is one of the most prolific generators of glacial earthquakes. While their genesis is largely understood to be the result of mega-scale calving events, details of this hypothesis still need to be resolved. For example, it is not clear why some glaciers and some calving events generate glacial earthquakes and others do not. We constructed and examined a decade-long record of ~daily resolution MODIS images of terminus position for five major marine-terminating glaciers (Daugaard-Jensen, Kangerdlugssuaq and Helheim glaciers in East Greenland, and Jakobshavn and Rink Glaciers in West Greenland) known to generate large teleseismic events to better understand this phenomenon.

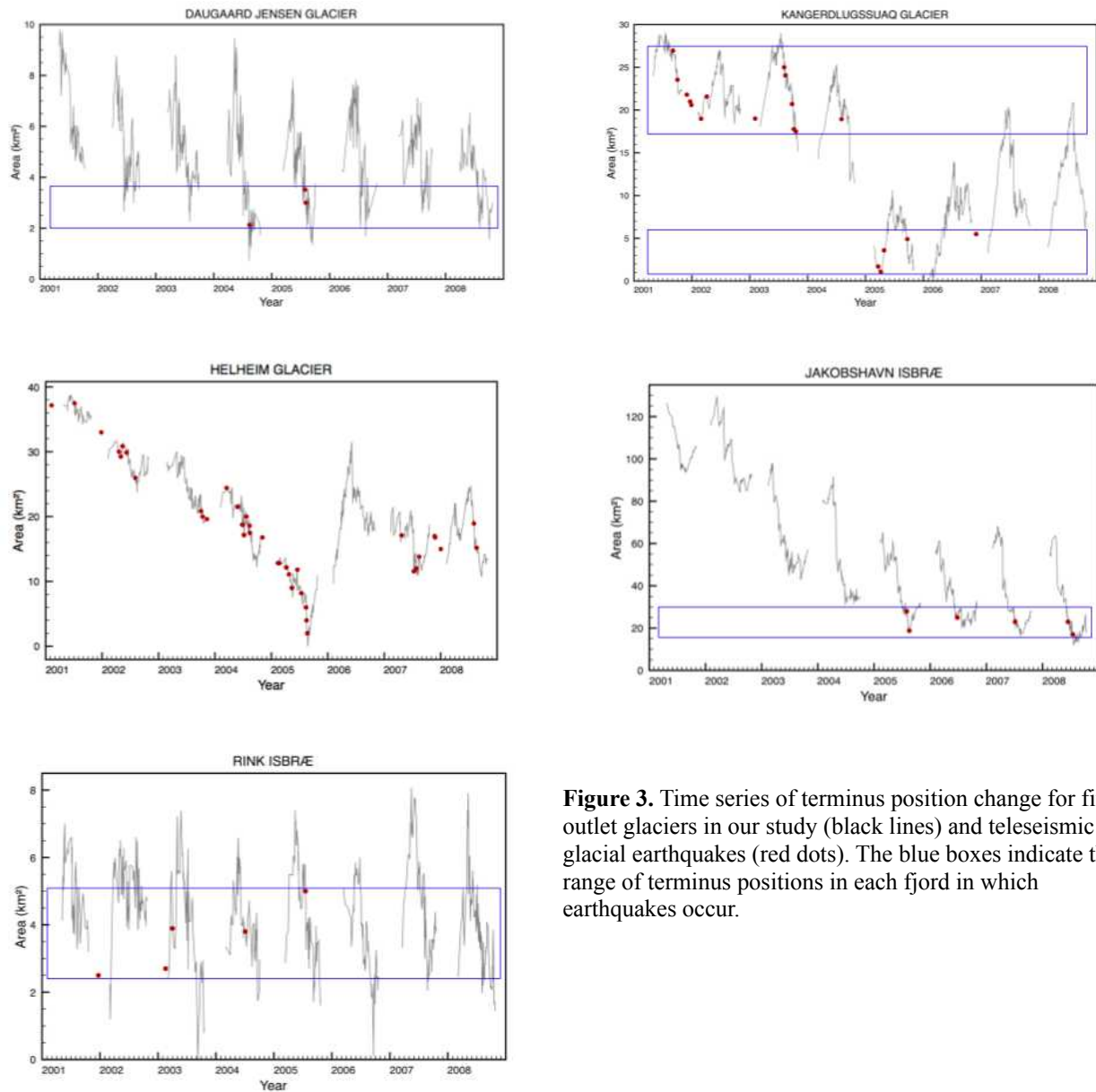


Figure 3. Time series of terminus position change for five outlet glaciers in our study (black lines) and teleseismic glacial earthquakes (red dots). The blue boxes indicate the range of terminus positions in each fjord in which earthquakes occur.

Our observations show that glacial earthquakes *always* occur during periods of retreat (Figure 3). Daugaard-Jensen and Rink Glaciers were the least teleseismically active glaciers in our sample and were also the glaciers exhibiting the smallest amounts of terminus change. Helheim and Kangerdlugssuaq glaciers, which both underwent rapid retreat this decade, generated the largest number of teleseismic events (Figure 1), although the annual frequency of earthquake occurrence is not always correlated with the magnitude of terminus retreat. Jakobshavn Isbrae experienced the largest terminus retreat in our sample but generated relatively few glacial earthquakes and none at all until the glacier retreated to a certain point in its fjord. We find a clear relationship between the occurrence of glacial earthquakes and the position of the each terminus in its fjord (Figure 3), except for Helheim Glacier which generates teleseismic events across the full range of positions.

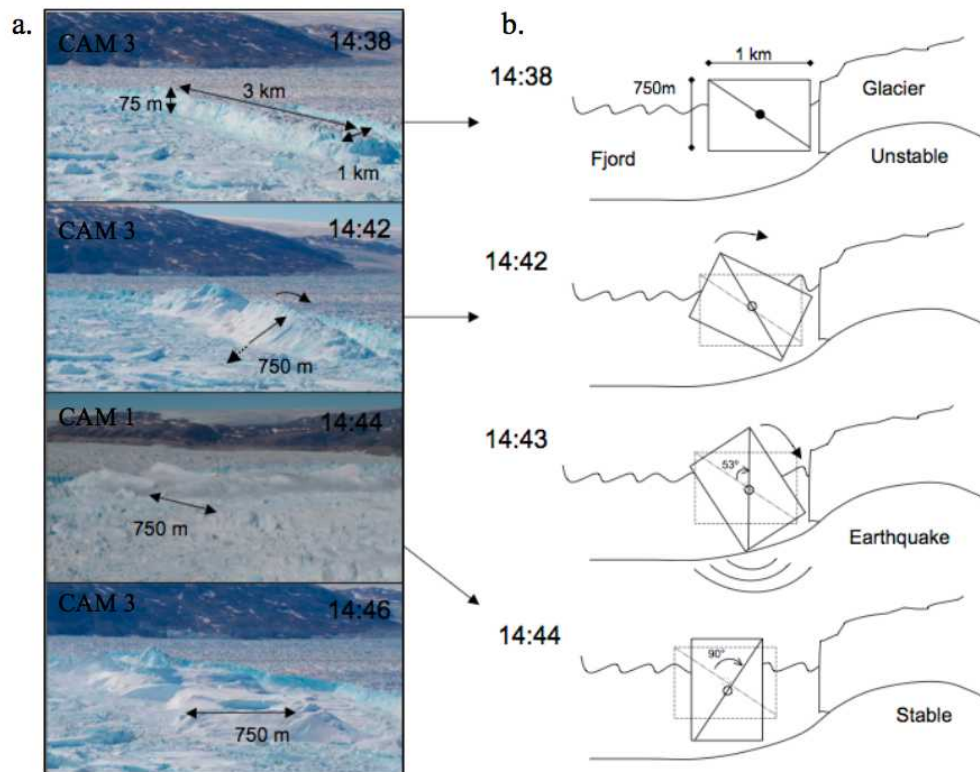


Figure 4. A calving event (a) at Helheim Glacier on 1 August 2008 observed by time-lapse cameras. The iceberg has an estimated mass of ~ 2 Gt and created a 4.8 surface wave magnitude earthquake. Cartoon (b) of the observed calving event with estimates of the iceberg dimensions and fjord bathymetry.

Our observations of the size invariance of calving events on earthquake occurrence as well as the link between earthquake occurrence and terminus position in the fjord lead us to hypothesize four factors are required for a tidewater glacier to generate a teleseismic event:

1. the calving event needs to involve rotation of the iceberg;
2. the rotating iceberg needs to come into contact with the ocean floor in order to couple kinetic energy to the solid earth;
3. the rotating icebergs need to have sufficient dimensional mass; and
4. the rotational speed at the moment of contact needs to be above a certain threshold.

Criteria 1 provides an explanation for why Helheim Glacier did not produce any glacial earthquakes in 2006, despite experiencing terminus retreats of magnitudes similar to other years; that year, observations from satellite images show that none of the icebergs rotated during calving. We further tested criteria 2-4 by analyzing a sequence of time-lapse photographs of calving event at Helheim Glacier in summer 2008. By extracting iceberg dimensions from the photographs and estimating its rotational speed from the image time stamps we are able to compute the kinetic energy released at the moment of contact. For the event shown in Figure 4, the energy estimate is well within the required range for the observed $M \sim 4.8$ glacial earthquake. However, a similar-sized iceberg calving event occurring ~ 10 hours later failed to produce a glacial earthquake because, according to our analysis of time lapse photographs, the rotational speed was too slow.

If any of these four factors are weak or absent, a teleseismic glacial earthquake will not occur. Our analysis shows that the processes leading the generation of glacial earthquakes are complex.