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Dr. Edward Cook, Chairperson
Climate Center Committee
Lamont-Doherty Earth Observatory
61 Route 9W
Palisades, New York 10964

Dear Dr. Cook and Members of the Climate Center Committee:

I am writing to apply for support from the Climate Center for a pilot project to be carried out in Greenland for approximately one year, from the Arctic summer of 2007 through the summer of 2008. The goal of the proposed work is to obtain seismic constraints on processes of glacier dynamics important for understanding the response of glaciers and ice sheets to climate change.

The funding requested in this proposal would cover most of the costs of the installation of a high-quality, broadband seismometer near Helheim glacier, with remaining costs covered by leveraging other funded work.

Thank you in advance for your consideration. Please let me know if I can provide further information or clarification regarding any aspect of this proposal.

Sincerely,

Meredith Nettles
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# Near-field seismic observations of glacial earthquakes and glacier dynamics

This proposal requests support for a pilot project to be carried out in East Greenland beginning in the boreal summer, 2007, and continuing through at least the summer season of 2008. The proposed work has the main goal of obtaining near-field broadband recordings of the seismic signal due to glacial earthquakes and other movements of a major outlet glacier. Glacial earthquakes, which appear to represent the rapid sliding of a large mass of ice over the glacier bed, are one indicator of the importance of dynamic processes for outlet glacier, and thus ice-sheet, behavior. Such processes are of fundamental importance for understanding how the ice sheets respond to climate change, and, in particular, for understanding how quickly ice sheets may respond to climatic forcing. This response, in turn, has important implications for predictions of sea-level rise and the freshwater input to the world's oceans.

Though glacial earthquakes themselves are unlikely to represent any significant fraction of total mass transport in a glacier, they provide a new constraint on the relative importance of the various processes influencing outlet-glacier dynamics. The utility of this constraint would, however, be greatly improved if the physical source process of the earthquakes were known in more detail. The seismological observing campaign proposed here aims to make high-quality seismic recordings of glacial earthquakes that can be used to obtain better location estimates and source models for the earthquakes. It also aims to expand the range of glacial processes that may be monitored seismically, an approach that provides a remote-sensing capability when other, more direct, observations of glacier behavior are not available. In particular, year-round seismic recording will allow for an assessment of the seasonality of large-scale calving events at the major outlet glaciers, which is currently a topic of much interest, many firm opinions, and little data.

## Background

In 2003, the proposer was a member of the team that discovered a new class of earthquakes associated with the motions of large masses of ice at mountain and outlet glaciers (Ekström et al., 2003). More than 200 "glacial earthquakes" have now been detected for the 14-year period 1993–2006, with approximately 95% of these occurring on Greenland, in close spatial association with the major outlet glaciers of the Greenland Ice Sheet (Ekström et al., 2006; Tsai and Ekström, 2007). The seismic radiation from the earthquakes is explained well by a source process in which a glacier suddenly slides downhill, moving perhaps 10 m over 30–60 s. The frequency of glacial-earthquake occurrence in Greenland is strongly seasonal (Ekström et al., 2006), with the largest numbers of earthquakes occurring in the late summer, coincident with peak summer melting (Steffen et al., 2004). In addition, glacial-earthquake frequency doubled between 2002 and 2005 (Ekström et al., 2006), a time period over which the extent of summer melting on Greenland also increased (Steffen et al., 2004; Steffen and Huff, 2005). The rapid change in earthquake frequency, like observations of dramatic changes in glacier flow speeds over time periods of only a few years (e.g., Howat et al., 2005; Stearns and Hamilton, 2007) indicates the capacity of the outlet glaciers to respond dynamically and quickly to external forcing, including changes in climate. The rapid nature of the changes in glacial-earthquake behavior, and the need to understand what physical processes actually operate before, during, and after such an earthquake, led the proposer to request support from the Climate Center for a field experiment at Helheim glacier, East Greenland, in 2006. The Helheim 2006 field experiment resulted in the successful collection of 62 days of high-rate GPS data on the glacier surface.

Our analysis of global seismic data from 2006, however, produced a surprising result: the level of glacial-earthquake activity declined precipitously at Helheim glacier in 2006. Twelve large earthquakes were detected at Helheim during 2005 (Tsai and Ekström, 2007), but no earthquakes large enough for routine detection (Ekström, 2006) occurred during 2006. This sudden shut-off in earthquake activity was not observed elsewhere, with glaciers both to the south and north continuing to generate glacial earthquakes. The explanation for this decrease is not immediately obvious, as other changes in the glacier's behavior, such as a decrease in flow speed, were small in comparison with the dramatic change in earthquake activity. Analysis of a more complete global seismic dataset, along with regionally recorded seismic data, has allowed us to identify and model two small glacial earthquakes that were missed in the routine processing; seismograms from one of these earthquakes are shown in Figure 1. This experience makes it clear that better seismic data, particularly when recorded near the earthquake source, would allow us to detect and analyze more earthquakes, and to analyze them in greater detail.

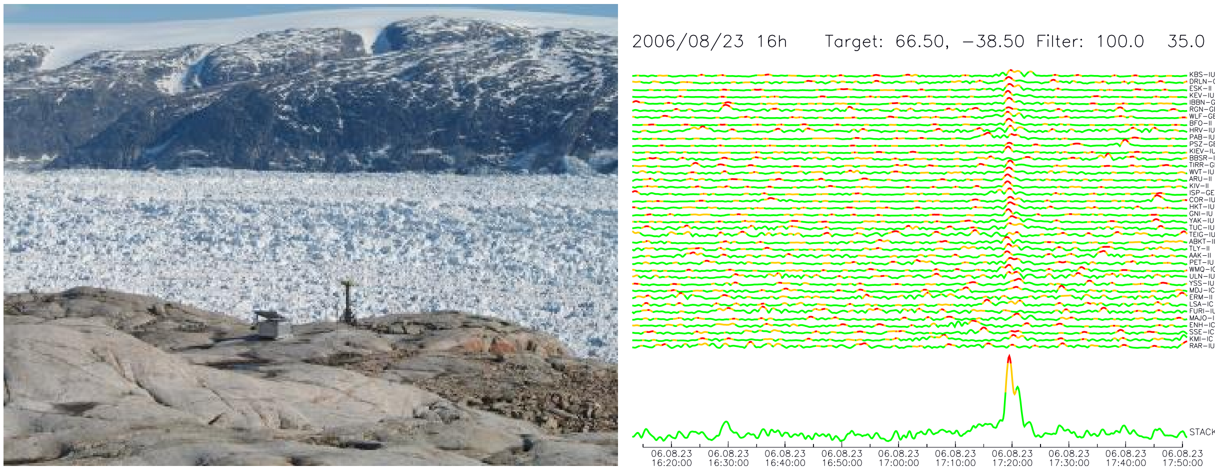


Figure 1: Left: Site of permanent GPS station installed in 2006. The proposed seismic station would be installed in a protected area on the same outcrop. Right: Seismograms from a glacial earthquake at Helheim glacier on August 23, 2006. The closest station used for this detection was located in Norway, 18° (2000 km) away. The seismograms have been back-corrected for propagation effects, and the source pulses (red blips) at each station line up at the earthquake origin time. A stacked trace is shown at the bottom.

## Proposed work: Near-field seismic observations

Most observations of glacial earthquakes have been made at a distance of more than 4000 km from the earthquake source, with a smaller number at distances of a few hundred km. A set of seismograms from a temporary array of seismometers that happened, fortuitously, to be deployed in Alaska at the time of a glacial earthquake in the Alaska Range in 1999 represent the highest-quality recordings of a glacial earthquake available; these were made at a distance of about 200 km. The closest known recording of a glacial earthquake in Greenland was made at a temporary station in Kulusuk, ∼100 km from Helheim glacier, during our 2006 GPS campaign.

Here, I propose to install an observatory-quality broadband seismometer on the exposed rock at the edge of Helheim glacier. The installation of a broadband seismometer adjacent to the glacier would allow us to make the first-ever near-field recording of a glacial earthquake, allowing us to assess in detail both the low and high-frequency components of the seismic radiation. The high-frequency component is very weak, and is nearly completely attenuated at distances of 100-200 km, but will contain important information about the earthquake source. Close-in recordings will also allow for much more accurate location of the earthquakes recorded, and for identification of smaller glacial earthquakes. The size distribution of regular tectonic earthquakes is well characterized, but remains essentially unknown for glacial earthquakes. High-quality seismic recordings at a distance of a few km will allow us to describe the earthquake source in unprecedented detail. To complement the seismic recordings I plan to make at the glacier edge, my Danish colleague Tine B. Larsen at GEUS will operate a seismic station 100 km from the glacier, in Tasiilaq, and we are working together to obtain instrumentation for a third station in the settlement of Isortoq, ∼120 km away.

In addition to the capability for recording glacial earthquakes that the seismometer will provide, it will allow us to assess the extent to which glacier motions produce seismically detectable signals in other frequency ranges. For example, it is known that many calving events produce seismic signals that are detectable locally (O'Neel et al., 2006). Recent reports from Antarctica (Wiens et al., 2006) suggest the presence of seismic transients at periods longer than the glacial earthquakes reported by Ekström et al. (2003), but it is not clear whether such signals are present at outlet glaciers like those in Greenland. One aim of installing a broadband seismic system at Helheim is thus to survey the range of frequencies over which glaciers "speak", for the purpose of gaining a wider range of constraints on glacier dynamics and evaluating the extent to which seismic observations can be used as remote-sensing data for outlet glaciers.

The seismic system I propose to install (an STS-2 seismometer with Quanterra Q-330 datalogger and Baler) runs on very low power (1 W), and can thus be powered over the winter with a reasonably sized battery bank (600 Ah). Seismic recording through all four seasons will allow us to assess in greater detail the seasonality of seismic activity at Helheim glacier. Because rapid calving events are known to produce high-frequency seismic signals, we hope that this will allow us to assess the seasonality of calving activity, as well as that of other glacially induced seismic activity.

## References

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## Support for the proposed project

The 2006 GPS project at Helheim was carried out as an international collaboration involving participants from the United States, Denmark, and Spain. The initial results from that project have allowed us to obtain funding for a second year of GPS observing at Helheim, in 2007. The current proposal would take advantage of the logistics platform provided by the planned GPS campaign to carry out the proposed seismic observing program, which has complementary goals.

**Personnel**
Collaborators on this project include Göran Ekström (LDEO, global seismology) and Tine B. Larsen (GEUS, Denmark, regional seismology). Morten Langer, a Danish Ph.D. student at GEUS, will assist with fieldwork in Greenland. All salary costs will be covered by other sources.

**Equipment and deployment**
The seismometer I propose to deploy is owned by the Global Seismology Group at LDEO, and can remain in the field for at least one year. Shipping costs for this equipment will be obtained from other sources, piggybacking on the GPS deployment. Helicopter transport costs for the seismic equipment will be similarly leveraged.

**Requested support**
Here, I request support for equipment necessary for seismometer installation, sufficient power for continuous operation through four seasons, materials for the construction of a seismic vault, and one person-trip for the proposer to travel to Greenland to install the seismometer.

## Budget

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| *Travel and subsistence for one trip to install/maintain seismometer* | |
| Airfare to Tasiilaq, Greenland: 1 round-trip from New York @ $2363.04 (July) | $2,363 |
| Subsistence in Tasiilaq, Greenland: 7 days @ $100/day | $700 |
| *Equipment for seismometer installation* | |
| Environmentally hardened enclosure for batteries, datalogger, data-storage device (Mil-Spec Hardigg "Mobile Master 36" plus specially cut insulating foam, watertight through-the-box connectors; available from Unavco as "Unavco continuous system enclosure") | $1000 |
| Sealed gel-cell batteries acceptable for air transport by Air Greenland and sufficient to power the seismic system over the winter (600 Ah), including shipping from mfr. to LDEO: 6 PS-121000 @ $242.95 ea | $1,458 |
| Solar panels for battery charging Feb. – Nov.: 4 Solarex MSX-40 @ $270 ea | $1,080 |
| Materials for construction of seismic vault: quick-drying concrete, sewer pipe, insulation, PVC pipes for drainage, sand, armor for cables, etc. | $500 |
| **total** | **$7,101** |
| **Total Requested** | **$6,000** |