2-5-2015

# Collaborative Research: Glacier-Ocean Coupling in a Large East Greenland Fjord

Gordon S. Hamilton
*Principal Investigator; University of Maine, Orono*, gordon.hamilton@maine.edu

# Preview of Award 0909274 - Final Project Report

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## Cover

| | |
|---|---|
| Federal Agency and Organization Element to Which Report is Submitted: | 4900 |
| Federal Grant or Other Identifying Number Assigned by Agency: | 0909274 |
| Project Title: | Collaborative Research: Glacier-Ocean Coupling in a Large East Greenland Fjord |
| PD/PI Name: | Gordon S Hamilton, Principal Investigator |
| Recipient Organization: | University of Maine |
| Project/Grant Period: | 08/15/2009 - 07/31/2014 |
| Reporting Period: | 08/01/2013 - 07/31/2014 |
| Submitting Official (if other than PD\PI): | Gordon S Hamilton<br>Principal Investigator |
| Submission Date: | 02/05/2015 |
| Signature of Submitting Official (signature shall be submitted in accordance with agency specific instructions) | Gordon S Hamilton |

## Accomplishments

*** What are the major goals of the project?**

The overall aim of our proposed work is to improve the understanding of glacier-ocean interactions in Greenland through an in-depth field study of one outlet glacier/fjord system – Helheim Glacier/Sermilik Fjord, in East Greenland. The characteristics of this system are typical of many outlet glacier/fjord systems in Greenland, so we expect our findings to be of broad relevance to understanding the large- scale ocean/ice sheet interaction.

We posed several specific questions to guide us in fulfilling our overall aim:

1. On what time scales does an estuarine circulation model describe the circulation in Sermilik Fjord? Theoretical models of glacial fjords are based on an estuarine circulation, but it is important to test the validity of this approach.
2. What is the seasonal cycle of the coupled fjord/glacier system? We presently do not know if the circulation in the fjord slows substantially in the winter. If it does not, then presumably it will continue to drive submarine melting which, in turn, will continue to draw warm water in to the fjord.
3. What are the dominant scales of variability for the fjord circulation and glacier dynamics and over what time scales are the two coupled? The hypothesis of an ocean trigger for the acceleration of Greenland's glaciers suggests that these two systems are coupled on annual to interannual timescales but direct evidence is lacking, and little is known about their coupling on shorter timescales.
4. What processes drive the short-term fluctuations in the fjord circulation? Short period variability was clearly observed in the two month mooring record but the controlling mechanisms are unknown. Potentially important factors include local winds, offshore changes in the ocean or large-scale episodic discharges from Helheim Glacier (either in the form of iceberg calving or catastrophic drainage of subglacial water).

These questions are being addressed through the simultaneous monitoring of fjord circulation and glacier dynamics over at least two complete years. The project involves a multi-institutional team of oceanographers and glaciologists.

### * What was accomplished under these goals (you must provide information for at least one of the 4 categories below)?

**Major Activities:**

Our major research activities were to (1) conduct collaborative fieldwork to understand the glaciological and oceanographic environment at Helheim Glacier–Sermilik Fjord, Southeast Greenland; (2) carry out remote sensing studies of the Helheim Glacier–Sermilik Fjord system; (3) perform a series of numerical experiments to investigate the behavior of Helheim Glacier, using observational data as model constraints.

Our major educational activities were the advising of a PhD-level graduate student and several undergraduate students studying glacier/ocean interactions in the polar regions.

**Specific Objectives:**

The specific objectives of the UMaine contribution to this project were to;

1. observe and understand variability in the geometry and dynamics of Helheim Glacier
2. observe and understand variability in fjord conditions
3. determine if and how variability in the fjord and glacier systems are coupled
4. use numerical modeling to investigate possible trigger mechanisms for the rapid retreat of Helheim Glacier.

**Significant Results:**

The terminus position of a tidewater outlet glacier is the result of multiple factors including glacier geometry, fjord bathymetry and environmental conditions. To investigate possible links, we continued to build a time series of Helheim Glacier terminus positions started under a previous award (0710891). We use 250 m resolution images collected by the MODerate resolution Imaging Spectroradiometer (MODIS) sensor on the Terra satellite to map the terminus position of Helheim Glacier on a near-daily basis, and constructed a record for the period 2001-2014 (early summer).

We also complemented the remote sensing record using terrestrial time-lapse photography (see Figure 1, attachment). Two cameras were deployed, one overlooking the terminus and another overlooking the melange in the fjord. Each camera was programmed to acquire an image every 6 h (light conditions permitting) and transmit the data via Iridium telemetry in near-realtime. The camera overlooking the terminus ("terminuscam") experienced technical problems with its light sensor, and only functioned on a sporadic basis. Much more successful was the camera overlooking the fjord ("melangecam") operated continuously from September 2011 until present (camera is still deployed).

On seasonal to interannual timescales, the position of Helheim Glacier's terminus shows some dependence on surface air temperatures (SAT) and sea surface temperature (SST) (see Figure 2). The dependence on both is not surprising, because SAT and SST are expected to correlated. In general, Helheim Glacier undergoes net retreat of the terminus during periods of above-average temperatures (SAT and SST) and undergoes net terminus advance when temperatures are below average. However, at shorter timescales (monthly or shorter), temperatures are a poor predictor for the change in terminus position. In particular, we find no link between the onset of terminus retreat and the arrival of warm air or ocean temperatures.

From this analysis alone, it is not possible to decipher the environmental factors that control terminus position change or the mechanisms involved. The lack of an obvious link between terminus position change and air temperature forcing suggests that other factors may modulate the glacier's response. For many of Greenland's outlet glaciers, including Helheim, a dense melange of icebergs and sea ice is a near-ubiquitous feature of the fjord directly in front of the terminus. One hypothesis is that the melange characteristics control the advance/retreat of the terminus (i.e., rigid melange prevents the glacier from calving new icebergs, or a mobile melange enables icebergs to calve and the terminus to retreat). If that idea is valid, the question then becomes what controls the behavior of the melange.

We investigated this hypothesis using our records of melange conditions from time-lapse photography and meteorological conditions from the weather station (AWS) adjacent the glacier. Using the time lapse photographs, we define three-stage melange index: 'Rigid' (0) means that there are no cracks or areas of open water inside the mélange and it does not move; 'Mobile' (0.5) means there can be cracks and the ice mélange can move slightly (motion is observed in sequential photographs); 'Open' (1) means that individual ice pieces are not connected and there is a lot of open water. We compare the ice mélange index with SAT (from the AWS) and SST. To test the hypothesis that strong winds can clear the ice mélange we define a wind event if the maximum daily wind speed exceeds 19 m/s. If this condition is fulfilled on consecutive days, only the first day is counted as a wind event.

The occurrence of these wind events coincides with a change of the ice mélange index, either from 'rigid' to 'mobile', or from 'mobile' to 'open' or even from 'rigid' to 'open' (Figure 3). This indicates that strong winds can indeed give rise to a clearing of the mélange. However, opening of the mélange does not depend solely on the wind speed but also on the rigidity of the mélange prior to the onset of strong winds. The rigidity might be affected by the air or water temperatures, or the preceding calving activity of the glacier and the time span during which the mélange had been rigid. An example of rigid initial conditions is April 2012 when mean daily wind speeds above 17 m/s were not able to open it (Figure 3); conversely, there are numerous instance during other months when the melange opened up during periods of weaker wind speeds.

Having established a possible link between the occurrence of strong winds and a weakening of the melange, we tested for possible linkages with a change in Helheim Glacier terminus position using our MODIS-derived time series (Figure 4). The onset of retreat usually occurs in the spring or early summer, pointing an environmental trigger. One possibility is a seasonal weakening of the melange, perhaps because of seasonality in the wind field. However, Figure 3 shows there is no apparent seasonality in melange characteristics. Furthermore, the seasonal pattern of wind speeds is anti-phase to the seasonality of terminus position change (Figure 3), i.e. wind speeds get weaker in spring which in when the terminus starts to retreat.

Clearly the controls on outlet glacier terminus position are complex and probably involve some amount of delayed response. We are currently examining this issue in more detail.

We carried out high-resolution numerical modeling of the Helheim Glacier terminus in an effort to understand the relative role played by different forcing mechanisms in its rapid retreat earlier this century. Our modeling was based on the University of Maine Ice Sheet Model (UMISM), in which we run a low-resolution model of the entire ice sheet with an embedded high-resolution model of Helheim Glacier. This approach allowed us to model physical processes at a relevant spatial scale of an outlet glacier while retaining realistic boundary conditions provided by the whole ice sheet model. Initial experiments focused on recreating the observed ~30-year stable terminus position prior to the start of this century and simulating the rapid retreat that began in 2003. The model was able to faithfully reproduce observations, giving a solid foundation on which to conduct perturbation experiments.

Having demonstrated that UMISM is able to simulate the ‘background’ conditions of Helheim Glacier, we investigated three different triggering mechanisms hypothesized to have caused the observed dynamic changes:

1. air temperature changes which alter the surface mass balance, leading to thickening/thinning and a change in force balance;
2. an increase in meltwater filling surface crevasses leading to enhanced calving at the terminus;
3. an increase in submarine melt rate at the terminus (from 80 m/yr to 500 m/yr) which destabilizes the glacier front.

We find that, individually, the three different triggering mechanisms are capable of causing the observed changes of Helheim Glacier. However, it is likely that no single mechanism alone but rather the interaction of the different factors destabilized the calving front. This interaction is difficult to determine quantitatively, because it requires knowledge of conditions prior to the onset of retreat such as fjord temperatures at the calving front for the modeled time period, or measurements to determine the amount of meltwater in crevasses and its change with time. We note that the temperature change in fjord water needed for the modeled increase in submarine melting is about 0.15 K. This change is consistent with the range of variability observed in the fjord during this experiment and, moreover, is wholly in line with observed changes in abyssal water temperatures in the sub-polar gyre in the last two decades. Altogether, this work is powerful evidence for an oceanic trigger for the rapid ice dynamic changes observed in Greenland.

Key outcomes or Other achievements: See list of products in the next sections.

*** What opportunities for training and professional development has the project provided?**

This project provided training for a graduate student and professional development opportunities for the PI. The PhD student was involved in all aspects of the research, from developing hypotheses, to designing experiments to conducting data analysis, interpretation and presentation of results. The PI obtained valuable experience in a new discipline for him (oceanography), as well as numerous opportunities to practise project management and communication skills. Results of the work contributed to advancing the PI's teaching skills.

*** How have the results been disseminated to communities of interest?**

There are several relevant communities of interest. First is disciplinary scientists in the field of glaciology. We have communicated the results of our work to this group via presentations at national and international conferences, and via peer-reviewed papers. Second is an interdisciplinary group of glaciologists and oceanographers studying the ice-ocean interactions. This is a new and rapidly-developing field, and we have played a major role in bringing this interdisciplinary community together via a US-CLIVAR working group on Greenland-Ice-Sheet-Ocean Interactions (GRISO) and by convening a major international workshop on the topic (Beverly, MA, June 2013). A third group is policymakers dealing with issues of climate change and sea level rise. We have communicated our findings to this group via a number of policy briefings and presentations (e.g., US Congress, November 2009; Spanish Parliament, October 2010). Finally, we have communicated the science of climate change to lay audiences via numerous invited outreach presentations (e.g., Florida Audubon, local schools, alumni groups).

**Supporting Files**

| Filename | Description | Uploaded By | Uploaded On |
|---|---|---|---|
| ANS-0909274-final-figures.pdf | Figures to accompany "Significant Results". | Gordon Hamilton | 02/05/2015 |

## Products

### Books

### Book Chapters

### Conference Papers and Presentations

Oltmanns, M., F. Straneo, G.K.C. Moore, K.M. Schild, G.S. Hamilton (2012). *Impact of katabatic wind events on the sea-ice and icebergs in a large glacial fjord in southeast Greenland*. American Geophysical Union, 2012 Fall Meeting. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Finnegan, D., G.S. Hamilton, L.A. Stearns, A.L. Lewinter, A. Fowler (2013). *Monitoring Tidewater Glacier Processes Using A Long-Range Terrestrial LiDAR Scanner; Comparative Results From Helheim Glacier Southeast Greenland and Hubbard Glacier Southeast Alaska*. American Geophysical Union, 2013 Fall Meeting. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Roth, G., D.A. Sutherland, G.S. Hamilton, L.A. Stearns (2013). *Monitoring fjord circulation using iceberg-mounted GPS as real-time drifters*. American Geophysical Union, 2013 Fall Meeting. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Sutherland, D.A., L.A. Stearns, G.S. Hamilton, F. Straneo (2010). *Observations of subtidal circulation variability in Sermilik Fjord, Greenland, and its impact on ice-ocean interactions*. American Geophysical Union, 2010 Fall Meeting. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

Weitz, N.A., G.S. Hamilton, J.L. Fastook (2012). *Simulating rapid changes of a Greenland outlet glacier using an embedded numerical model*. American Geophysical Union, 2012 Fall Meeting. San Francisco, CA. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

## Inventions

## Journals

Schild, K.M. and G.S. Hamilton (2013). Seasonal variations in outlet glacier terminus positions in Greenland. *Journal of Glaciology*. 59 (216), 759. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: doi:10.3189/2013/JoG12J238

Straneo, F., D.A. Sutherland, D. Holland, C. Gladish, G.S. Hamilton, H. Johnson, E. Rignot, Y. Xu and M. Koppes (2012). Characteristics of ocean waters reaching Greenland's glaciers. *Annals of Glaciology, 53(60), 202-210.*. 53 (60), 202. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

Straneo, F., G.S. Hamilton, D.A. Sutherland, L.A. Stearns, F. Davidson, M.O. Hammill, G.B. Stenson and A. Rosing-Asvid (2010). Rapid circulation of warm subtropical waters in a major glacial fjord in East Greenland. *Nature Geoscience*. 3 182. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: doi:10.1038/ngeo764.

Straneo, F., P. Heimbach, O. Sergienko, G.S. Hamilton, G. Catania, S. Griffies, R. Hallberg, A. Jenkins, I. Joughin, R. Motyka, W.T. Pfeffer, S.F. Price, E. Rignot, T.A. Scambos, M. Truffer and A. Vieli (2013). Understanding the dynamic response of Greenland's marine terminating glaciers to oceanic and atmospheric forcing. *Bulletin of the American Meteorological Society*. 94 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: doi:10.1175/BAMS-D-12- 00100

Straneo, F., R.G. Curry, D.A. Sutherland, G.S. Hamilton, C. Cenedese, K. Våge and L.A. Stearns (2011). Impact of fjord dynamics and glacial runoff on the circulation near Helheim Glacier. *Nature Geoscience*. 4 182. Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: doi:10.1038/ngeo1109

Sutherland, D.A., G.E. Roth, G.S. Hamilton, S.H. Mernild, L.A. Stearns, and F. Straneo (2014). Quantifying flow regimes in a Greenland glacial fjord using iceberg drifters. *Geophysical Research Letters*. 41 . Status = PUBLISHED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes ; DOI: doi:10.1002/ 2014GL062256

Weitz, N. G.S. Hamilton & J. Fastook (2015). Evaluating trigger mechanisms for the retreat and acceleration of Helheim Glacier using a 2.5D ice flow model. *Earth and Planetary Science Letter*. 0-0. Status = SUBMITTED; Acknowledgment of Federal Support = Yes ; Peer Reviewed = Yes

## Licenses

## Other Products

*Data and Research Materials (e.g. Cell lines, DNA probes, Animal models).*

Data from this project will be archived for open access via the ACADIS portal:

https://www.aoncadis.org/project/collaborative_research_glacier-ocean_coupling_in_a_large_east_greenland_fjord.html

Data will include time series of meteorological observations from a weather station adjacent to Helheim Glacier, and time lapse images collected 4x daily at two locations overlooking the terminus and fjord.

## Other Publications

Heimbach, P., F. Straneo, O. Sergienko, and G. Hamilton (2014). *International workshop on understanding the response of Greenland's marine-terminating glaciers to oceanic and atmospheric forcing: Challenges to improving observations, process understanding and modeling (workshop report)*. US CLIVAR Report 2014-2, US CLIVAR Project Office, Washington, DC 20005, 38 pp.. Status = PUBLISHED; Acknowledgement of Federal Support = Yes

## Patents

## Technologies or Techniques

**Thesis/Dissertations**

Weitz, N.A.. *Modeling glaciers and ice sheets in Greenland and Antarctica with an emphasis on embedded numerical modeling and subglacial hydrology*. (2014). University of Maine. Acknowledgement of Federal Support = Yes

**Websites**

*Glacier Research*
http://glacierresearch.org/

Real time environmental data from glaciers in Greenland and Alaska (including Helheim Glacier). A collaborative, multidisciplinary project using state-of-the-art monitoring technologies.

## Participants/Organizations

### What individuals have worked on the project?

| Name | Most Senior Project Role | Nearest Person Month Worked |
|---|---|---|
| Hamilton, Gordon | PD/PI | 3 |
| Weitz, Nora | Graduate Student (research assistant) | 12 |

### Full details of individuals who have worked on the project:

**Gordon S Hamilton**
**Email:** gordon.hamilton@maine.edu
**Most Senior Project Role:** PD/PI
**Nearest Person Month Worked:** 3

**Contribution to the Project:** Dr Hamilton was responsible for overall project management between the three collaborating institutions (UMaine, WHOI, Univ Kansas). Tasks included fieldwork planning and organizing logistics. He also managed the UMaine contribution to the project, which involved field work, data analysis, reporting of results in papers and scientific meetings, outreach presentations, and advising a PhD student.

**Funding Support:** This award, and academic year salary from the University of Maine

**International Collaboration:** Yes, Denmark, Greenland
**International Travel:** Yes, Greenland - 0 years, 3 months, 0 days

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**Nora Amelie Weitz**
**Email:** nora.weitz@maine.edu
**Most Senior Project Role:** Graduate Student (research assistant)
**Nearest Person Month Worked:** 12

**Contribution to the Project:** Ms Weitz was a PhD candidate under Dr Hamilton's guidance. She was responsible for numerical modeling contributions to this project, including model code development, data set preparation, running model simulations, and interpreting results.

**Funding Support:** None other than this award.

**International Collaboration:** No
**International Travel:** No

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## What other organizations have been involved as partners?

| Name | Type of Partner Organization | Location |
|---|---|---|
| US Army Cold Regions Research and Engineering Laboratory | Other Organizations (foreign or domestic) | Hanover, NH |
| University of Kansas | Academic Institution | Lawrence, KS |
| Woods Hole Oceanographic Institution | Academic Institution | Woods Hole, MA |

## Full details of organizations that have been involved as partners:

**US Army Cold Regions Research and Engineering Laboratory**

**Organization Type:** Other Organizations (foreign or domestic)
**Organization Location:** Hanover, NH

**Partner's Contribution to the Project:**
In-Kind Support
Collaborative Research
Personnel Exchanges

**More Detail on Partner and Contribution:** We are worked closely with David Finnegan on design and operation of autonomous monitoring instruments (weather stations, remote time-lapse cameras), and terrestrial LIDAR scanning.

**University of Kansas**

**Organization Type:** Academic Institution
**Organization Location:** Lawrence, KS

**Partner's Contribution to the Project:**
Collaborative Research

**More Detail on Partner and Contribution:** Dr Stearns is carrying out glaciological work as part of this project, including remote sensing and field observations.

**Woods Hole Oceanographic Institution**

**Organization Type:** Academic Institution
**Organization Location:** Woods Hole, MA

**Partner's Contribution to the Project:**
Collaborative Research

**More Detail on Partner and Contribution:** Dr Straneo and her group are responsible for oceanographic activities related to this project.

## What other collaborators or contacts have been involved?

NO

## Impacts

### What is the impact on the development of the principal discipline(s) of the project?

The main discplinary findings of this project are:

1. the discovery of warm ocean waters adjacent to the margins of the Greenland Ice Sheet
2. a first understanding of the mechanisms which bring this warm water into contact with Greenland's outlet glaciers
3. new insights into the variability in glacier geometry and fjord hydrography.

Prior to the start of this project, very little was known about processes operating at the margin of the Greenland Ice Sheet. Our project delivered the first observations of many of these processes and the results have provided fundamental insights into the behavior of Greenland.

### What is the impact on other disciplines?

The major impact of this project is its contribution to the emerging study of ice-ocean interactions, an interdisciplinary field bringing together glaciologists, oceanographers, atmospheric scientists, instrumentation engineers, etc. The PIs were co-chairs of a working group on Greenland Ice Sheet Ocean interactions under the auspices of US CLIVAR, and convened a major international workshop on the topic (Beverly, MA, June 2013). They also promoted interdisciplinary studies by organizing ice-ocean interaction sessions at major international conferences (AGU San Francisco 2011, 2012; DACA Davos, 2013).

### What is the impact on the development of human resources?

This project provided new opportunities for interdisciplinary research and trained several scientists on the emerging field of ice-ocean interactions. These scientists have in turn encouraged other researchers to become involved in this growing discipline (by way of workshops, working groups, presentations at specialized conferences, by incorporating project materials in pedagogical activities).

The project supported a female PhD student who has since continued into a postdoctoral position, and is now contributing to the growing number of women in STEM-intensive disciplines.

### What is the impact on physical resources that form infrastructure?

The project contributed to our community's ability to make observations in rugged and challenging environments. Among our key achievements are the development of remote autonomous instrumentation with power and telemetry (time-lapse cameras, weather stations), development of techniques and protocols to deploy instrumentation in hazardous environments (e.g., GPS receivers on glaciers, iceberg trackers), and development of logistics infrastructure and knowledge in a remote region of East Greenland.

### What is the impact on institutional resources that form infrastructure?

Nothing to report.

### What is the impact on information resources that form infrastructure?

This project has generated unique time series of observations of glacier terminus position, ice melange conditions and meteorogical conditions in a major glacier-fjord system.

### What is the impact on technology transfer?

This project provided an opportunity to carry out pilot studies to test the utility of using terrestrial lidar scanning (TLS) methods to study glacier processes in very high spatial and temporal resolution. As a result of those studies, we have engaged a company (Riegl USA) to develop a TLS instrument for dedicated glaciological applications (green laser, fully autonomous operation). The new instrument is likely to be a critical component of a proposed Greenland Ice Ocean

Observing System (GrIOOS, see US CLIVAR workshop report).

**What is the impact on society beyond science and technology?**

Results of this study have contributed to our understanding of the coupled ice-ocean-climate system, and will help inform predictions of future sea level rise.

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## Changes/Problems

**Changes in approach and reason for change**
Nothing to report.

**Actual or Anticipated problems or delays and actions or plans to resolve them**
Nothing to report.

**Changes that have a significant impact on expenditures**
Nothing to report.

**Significant changes in use or care of human subjects**
Nothing to report.

**Significant changes in use or care of vertebrate animals**
Nothing to report.

**Significant changes in use or care of biohazards**
Nothing to report.

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## Special Requirements

**Responses to any special reporting requirements specified in the award terms and conditions, as well as any award specific reporting requirements.**
Nothing to report.

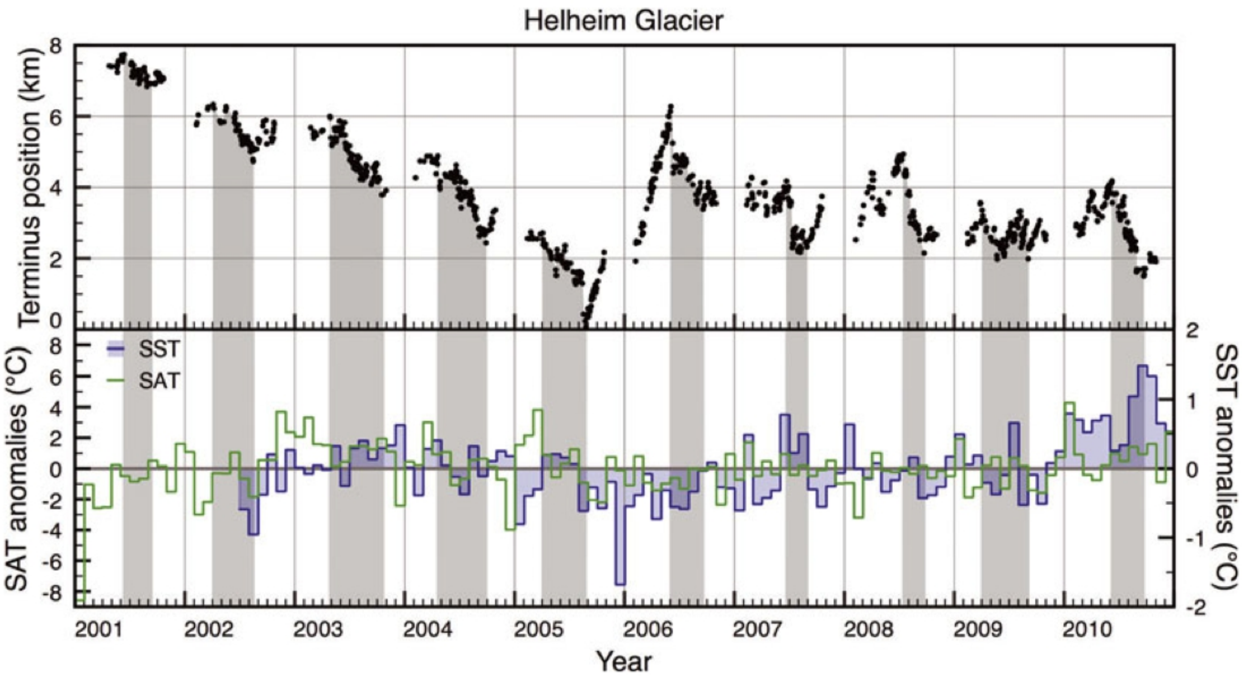


**Figure 1.** Time series of terminus position for Helheim Glacier from MODIS imagery (A), surface temperature anomalies from our weather station (B), and sea-surface temperature anomalies for the region offshore of Sermilik Fjord (C).

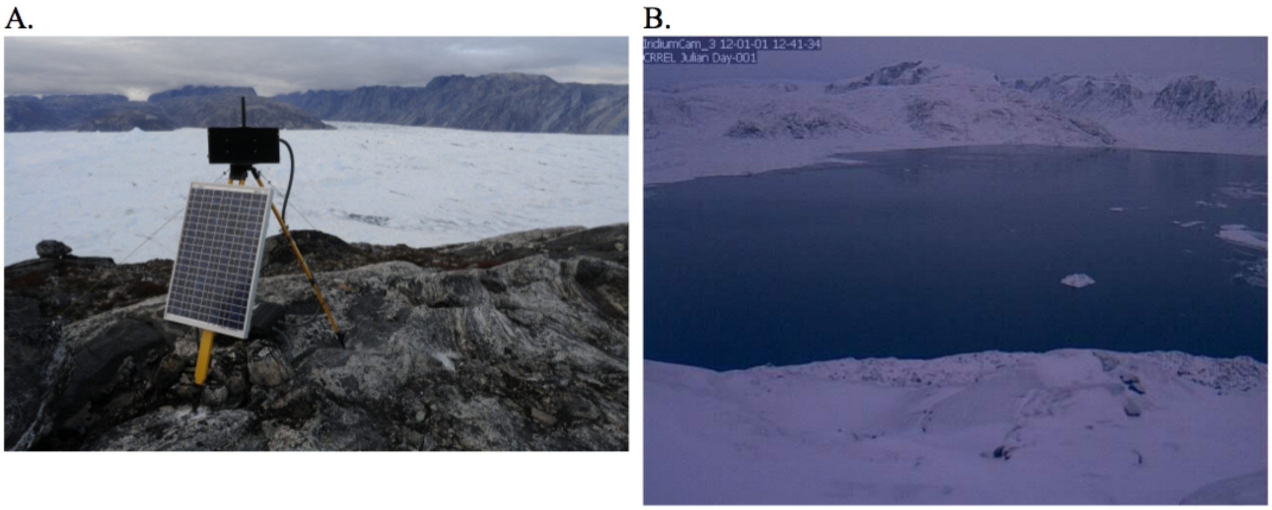


**Figure 2.** Detail of the time-lapse camera system and an example image collected on New Year's Day 2012 from the "melangecam" which monitors the behavior of the sea ice melange in front of Helheim Glacier's terminus.

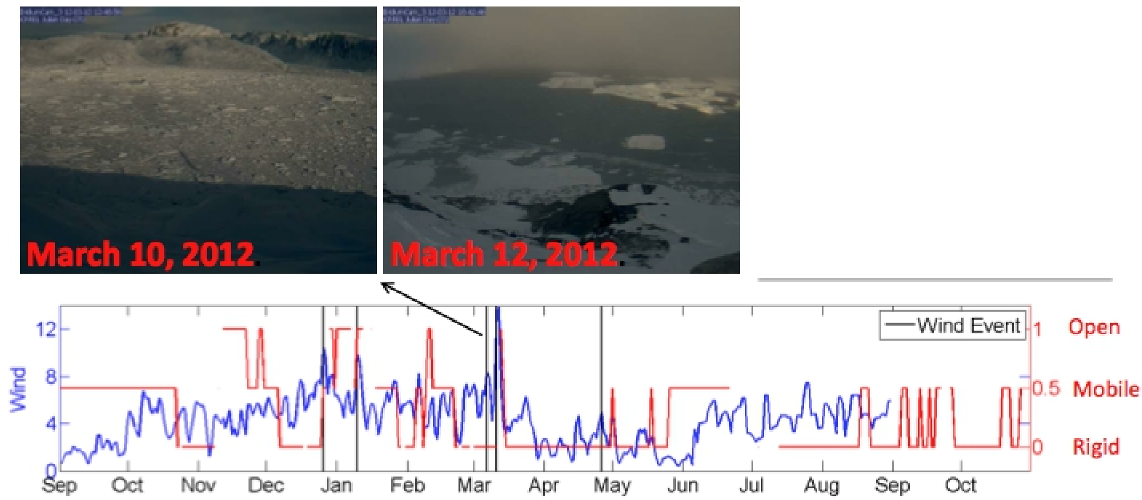


**Figure 3.** Top: Photographs of the ice mélange before and after a wind event. Bottom: Wind speed inside the fjord and ice mélange index in 2011-2012. An index of 1 indicates the mélange is 'open', 0 is 'rigid', and 0.5 is 'mobile'. Only the strongest wind events are shown.

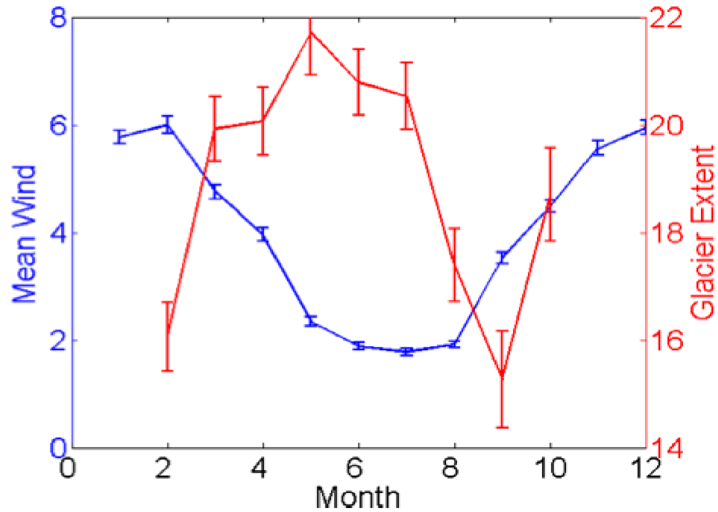


**Figure 4.** Monthly variability of Helheim Glacier terminus position (extent, red) from MODIS and mean daily wind speed (m/s, blue) from our AWS. Note that terminus position change is anti-phase with wind speed (which is a proxy for melange rigidity).