Workshop Report: Greenland Ice Sheet/Ocean Interaction (GROCE)

IASC workshop 8/9 December 2014 hosted by Alfred Wegener Institute in Bremerhaven, Germany

Background

The ongoing mass loss of Greenland ice sheet accounts for a quarter of the present sea level rise, yet considerable uncertainties exist regarding relative importance of the drivers of the mass loss.Two main drivers are discussed to play a role: the changing atmosphere and radiation enhancing surface melting and the potential of the warming ocean in destabilising Greenland's ice streams. Recognizing that addressing the latter requires a high degree of cross-disciplinarity, an international workshop was held on December 8 and 9, 2014, which brought together both observationalists and modelers from the fields of glaciology, oceanography, atmospheric physics, and paleo science.

The aims of the work shop was to identify the key questions of Greenland icesheet - ocean interaction, to increase communication between disciplines and to raise the overall topic high on the agenda of international research efforts in the coming decade.

Remote sensing data reveals that the rate of mass loss has increased rapidly over the last decade. Future projections of ice sheet mass loss based on numerical simulation forced by future Greenhouse gas emission scenarios bear large uncertainties. The increasing mass loss also represents an increasing input of fresh water into the ocean, affection the ocean stratification, upper ocean circulation and deep ocean ventilation. The role of the dynamics of the marine terminating glaciers for the instability of the ice sheet and thus for the ice loss is subject to large uncertainties. These glaciers are exposed to ocean waters that have been warming at different rates almost all around Greenland. The coincidence of widespread glacier retreat and oceanic warming suggests that the observed acceleration of the mass loss from the Greenland ice sheet may have been triggered by an increased ocean-induced melting at the ice front. Research on processes affecting the interaction of these two complex systems, polar ocean and ice sheet, is challenging in terms of both field work and modelling efforts. It thus requires joining forces of different disciplines, research centers and nations.

Workshop goal

The goal of the workshop was to specify research that is mandatory in the coming decade to reach a deeper understanding of the glacial and marine processes destabilizing the Greenland ice sheet. It should provide a guideline for multidisciplinary efforts to conduct the research that shall ultimately lead to better representation of these processes in climate models and, consequently, result in more reliable projections of the contribution of the Greenland ice sheet to sea level rise and freshwater input into the ocean. It should further help to improve communication, coordination, and collaboration between the diverse communities, institutions and nations.

Workshop structure

The workshop brought together 23 scientists, among them 7 early career scientists, from 9 countries (see appendix 2, participants list). The participants consisted of both observationalists and modellers from the fields of glaciology, oceanography, paleo sciences and meteorology, addressing processes on a large range of scales ranging from the small-scale ice-ocean boundary layer, glacier and fjord scales up to hemispheric scales. The variety of skills of the group met our goal of bringing together very different communities with a firm intention to cooperate in the future such that cross-disciplinary questions may be tackled.

In an initial brainstorming based on the presentation of the most pressing research needs by each participant using visual info graphics the communication between the participants was successfully stimulated. Subsequently, three working groups were set up to address (i) the ice stream and glacier dynamics, (ii) fjord processes and glaciers – ocean interface, and (iii) ocean circulation in the near and far field of Greenland glaciers. On the first day the groups had the task to formulate the research questions for the next decade (see attached agenda), while the second day was dedicated to discuss about how to tackle these questions.

Outcome

The **overarching research questions** elaborated by the groups during the first day were: Is global climate change currently driving simultaneous glacial behaviour in a manner not present before the late 20th century? What is the relation between the surface mass balance and the dynamic ice loss? So far, we cannot explain how an ice interface responds to the contact with the ocean and how this response is communicated upstream to affect the dynamics of the entire ice stream. Greenland's ice streams have been observed to behave differently in adjacent fjords despite experiencing similar external forcing. The reason for this is unknown. A basic question outlined also was, to which extent the recent mass loss is still part of the readjustment after the last glacial maximum.

The dynamics of **ice streams** bear several unknown factors. They range from surface mass balance until insufficient formulation of calving and sliding laws in ice flow models. Knowledge is needed about the basal hydrology that is driven by surface melting as well as by melting through geothermal heat flux. This knowledge needs to be combined with better understanding of ice deformation processes. Improvements to this knowledge are needed to project how ice streams and inter-stream areas will evolve in the future. Also, for the development of observational strategies, it would be preferable to know which of the ice stream drainage basins will have the biggest influence on future mass balance change.

At the **marine glacier fronts** the ultimate quantities to be determined are the energy (heat) flux from the ocean across the terminus line towards the glacier and the fluxes of ice and melt water across the terminus line towards the ocean. A number of factors might influence these fluxes. While increasing ocean temperature certainly will lead to more melting this might, on the other hand, evoke changes in the sub-iceshelf melt, and thus ice thickness and the position of the grounding line which then would constitute a negative feedback mechanism. Also, subglacial discharge might play a role. Observations of these features would have to resolve seasonal and shorter time scales because there might be feedbacks to multiyear variations.

In addition to smooth transitions, glacier changes have highly discontinuous components. These range from calving events to long-term processes when stable conditions turn unstable. Which are the thresholds that modulate the response and stability of glaciers to environmental factors? When does a tidewater glacier become instable? Information might be gained from historical records of similar behaviour during e.g. the 1930s.

An important distinction to be found is what are the triggers vs. what are the drivers of glacier change and up to what point is the ocean important in governing glacier stability. The question is: Once the glacier begins to retreat, is the ocean still important?

Is the shape of the calving front important in understanding how subglacial melt takes place? Or can we use the shapes of the terminus to learn about the subglacial melt process?

The **ocean conditions** near the Greenland coast range from warm sub-polar Atlantic waters to cold Arctic waters under the heaviest pack ice of the Arctic. Ultimately it is, however, (modified) **Atlantic Water** that provides the oceanic heat source for the marine glaciers although seasonally warmed polar surface waters have large interannual variability and in some years contain significant heat. It is thus necessary to understand the circulation that carries Atlantic Water towards (and underneath) the glaciers. E.g. northeast of Greenland, the Atlantic water has to cross the wide East Greenland shelf, and little is known about basic circulation features and their driving forces. Both remote and local windstress variations might affect the cross shelf transport. Both the strength and the role of **tides** are unknown due to poor knowledge of shelf bathymetry. Tidal effects (including internal tides) might contribute to the overall transport and be an essential mechanism for mixing warm waters higher into the water column so that it can pass banks and sills in front of the glaciers. **Sea ice** in front of the glaciers might have considerable impact because it modulates air/sea momentum and heat fluxes and thus circulation and temperature of the ocean waters. Buttressing effects of sea ice may also be important for glacial front stability, leading to a potential feedback with surface water temperatures of the preceding summer.

Fjord internal circulation can be dominated by multilayer estuarine type forcing (largely depending on mixing) or through intermittent wind forcing. Again, tides in front of the fjord entrance might play a role in addition to wind driven and topographically steered ocean flows. Estuarine circulation could establish a positive feedback-loop “sucking” warm water towards the glacier front, but for some reason that does not seem to be very efficient. The energetics of the glacier melt zone, in particular the fjord-scale effects of turbulent mixing plumes and their influence as a potential driver of fjordic circulation are largely unknown. Sea ice vs. a mélange vs. pure ice melt can have very distinct effects on the vertical overturning circulation in the fjord. Finally, the depth distribution of melt water at the glacier front will affect mixing and stability in the fjord. To summarize, the processes occurring from a few meters to a few kilometers from the calving front and the glacier melt zone are entirely unconstrained through any observations and thus are unknown.

High resolution topography and its changes through time is a high priority issue for understanding all ice stream, glacier and marine processes. For the water circulation between ocean and fjords, troughs on the shelf are crucial features. Particularly the sill depth is a key parameter since it determines how much warmer (typically deeper lying) Atlantic Water can find its way to the glacier. Similarly, the ice stream and glacier stability depends tremendously on the geometry of the underground. The bedrock geometry under the glacier is also influenced by the lithology and mobility of moraines, which might in turn be very influential on the glacier mobility. Finally, isostatic uplift will change the basin geometry with implications for the termination of glaciers. Seamless mapping of the underground from land across the terminus interface into the ocean is mandatory.

During the second day, the breakout groups developed propositions for methods and strategies **how to tackle the research questions**. Since the time frame is the next decade the propositions should build on new technology and to imply a visionary character.

One of the major preconditions for addressing all processes is an explicit improvement of the knowledge of the **bed topography and ocean bathymetry.** This requires dedicated **mapping surveys** applying classical methodss with airborne radar, seismic, gravimetry and multibeam and sonar. With sufficient resolution, seismics will provide also information on the patchiness and the roughness of the bed, to distinguish bedrock from, e.g., till and to identify the presence of water. High resolution is also needed to capture map-view strain rates and sill depths. Near the ice front, these methods must be replaced by using autonomous operating vehicles (UAV, ROV, drones) with miniaturized sensors and power optimization. A p-band satellite penetrating to the bed would be desirable. Inverse modelling should help to achieve bed construction from surface elevation and velocity data. Cheap pressure sensors on marine mammals could provide additional information. All data should be compiled in a specific project to create a **bathymetry of Greenland**, e.g. in analogy to bedmap 1 and 2 for Antarctica.

Ice cores, providing direct access to the bottom, should be accompanied by a grid of hot water drills to reduce data resolution problems. For this and other applications (in and under ice sensor deployment), rapid access **drill technology** should be developed. New sensors for measuring subglacial hydro pressure, material properties, geothermal heat flux should come into play as well as cryobots and cameras. A very difficult problem remains the determination of the thickness of the subglacial water layer.

To constrain dynamic processes in the icestream, the **properties of ice, fractures and crevasses** need to be better known. Tasks for structural glaciology compile subglacial, subsurface and surface imagery, but also the depth of crevasses must be measured. Helpful instrumentation would be drones, cable car grids along the ice stream, 'floating' cameras (like in a soccer stadium) and a laser scanner. A seismometer network on ice stream should help to locate crack events and to identify crack tips. Also firn cores for determining accumulation rates are needed. Satellite and camera **imaging** should be developed towards feature tracking and classification. Dual polarization satellite technology would be advantageous. Repeat measurements of surface velocities, preferably 3D, should be achieved to detect structural changes and build an early warning framework.

To quantify **energy and water fluxes** and their variability we need oceanographic and glaciological observations as close as possible to the ice face at a representative set of glacier/fjord systems. To measure in the **immediate vicinity of the ice-ocean interface** in narrow, melange-covered fjords, only **remotely-operated or autonomous** underwater (AUV) and airborne vehicles (drones) are appropriate. Acoustic navigation and communication would facilitate the use of AUVs and gliders. This requires hardening of existing technology for long-term deployments near ice fronts and ground-based radar and lidar must be developed for long-term measurement of ice surface motion. The plume and glacier face variability might be observed using seafloor-anchored, glacier-facing ADCPs or sidescan sonars. Observation of subglacial discharge remains a challenge but acoustic or other remote sensing technologies should might be applied for capturing fjord temperature and velocities. Ocean microstructure measurements should provide information on advective/diffusive balances in trough / fjord systems.

To identify **thresholds for terminus stability**, information of historical terminus change can be gained from imagery and landforms and from well-dated sedimentological and other paleo records. However, better dating techniques are required. The role of proglacial sediment in the stability of tide-water glaciers should be tested through process studies in combination with observations of sedimentation rates at glacier fronts using marine seismics, multibeam, and coring. Identification of the properties of favorable terminus locations remains difficult: Are glaciers with greater variability more stable than less variable glaciers? An answer might be obtained from comparing observations with modelled glacier change over decadal and centennial timescales. This approach might also help addressing the problem of triggers vs. drivers of glacier change.

High temporal resolution (hours) multiyear **time series** are needed to capture the statistics of **episodic events** (calving, event-driven fjord inflows). For measuring the ocean parameters, instruments can be moored to the bottom or the ice tongue, and also here acoustic transmission of data can be used to secure valuable data in case of mooring loss. These time series will be interconnected with continuous observations of the cross shelf circulation to follow the flow of Atlantic Water and thus heat supply to Greenland. Long-term observations tracing Atlantic Water pathways from the North Atlantic to Fram Strait should be conducted in concert with existing international efforts (Fram Strait array, Denmark Strait moorings, OSNAP Cape Farewell, ASOF activities, US Arctic observing network).

A number of available instrumentation installed in large numbers will increase the data base considerably: land-based visual and IR photogrammetry (thermal for plumes), automatic weather stations. Technology development is, however, needed to get time series of mélange surface height using e.g. hyper-spectral (inc. IR) and LIDAR.

Challenges for **model improvements** are huge. Small-scale processes such as sliding, calving and firn compaction need a better parametrization. System modelling should be further advanced promoting 3D models with streams in different 'settings' at different scales and using 2d models (cartoon models) to understand processes. Study cases should be developed which include correct bedrock configuration and glaciological, ocean, and atmosphere setting. Palaeorecords from terrestrial and marine sediment archives should be used to reconstruct the history of ice streams. New numerical approaches should be applied like FEM, FD, FV or even Full Stokes including more realistic boundary conditions and softer shear margins. On the long run, we want a model that couples ice sheet, sea-ice/melange covered ocean and atmosphere and that is able to apply the right physics at the right locations. However, the sliding law is a week point and new mathematical approaches might be a huge challenge.

Model intercomparison experiments should be further promoted such as ICEMINT and to grow the modelling community, new courses for modeling need to be developed and the competitions for universities.

It might be suitable to establish observational networks in so-called mega sites that would be maintained over decades and cover a whole basin/catchment. They should be linked to paleo recording. These could be used to improve predictive skills; on the other hand models might be used to identify key target areas.

Final remarks

Research at the interface between the North Atlantic and Arctic Ocean and the Greenland ice sheet is very timely but it is also a great challenge for both the observational as well as the modelling side and it requires developing and fostering the discussion and co-operation between disconnected communities. Scientists from disperse fields need to specify research questions together. To tackle these questions, the logistically demanding field work in a very challenging environment needs to be organised through multi-national efforts. Uniting national and disciplinary studies towards better understanding the interaction between Greenland ice sheet and ocean will therefore be a key challenge of Arctic research in the near future. We therefore propose an **International Greenland Decade (IGD)** to focus full-scale research on 3-4 key regions with systems which behave very differently – looking for contrast in behavior) for focused multi-D, multinational studies of Glacier/Ocean system dynamics.

The workshop has laid the base for compiling a white paper. A document describing a prioritized set of recommendations to advance this problem will be formulated. The outcome of this workshop will be presented in the session B10 during the 3rd International Conference on Arctic Research Planning in Toyama.

Appendix 1 Workshop agenda

Appendix 2 Workshop participants list

Appendix 1 Workshop agenda

Greenland Ice Sheet/Ocean Interaction (GROCE)

IASC workshop 8./9. December 2014

AWI Bremerhaven, Building E, Plenum Room E4025

Breakout groups: E4025, E5100 & E5085 Hafenturm, E2125 (Weser side), coffee tables 1st & 2nd floor, E2470 (only Monday)

Before you arrive:

- ➔ Send a slide with your field of research interest in the GROCE context.
- ➔ Prepare a simple, hand drawn sketch (info graphic) with your burning question

Monday Dec 8:

"Formulate research questions for the next decade"

8:30 Coffee and registration in the foyer

9:00 Plenum E4025: Welcome, Workshop introduction & housekeeping remarks, U. Schauer

9:15 Scientific introduction: "Why GROCE?" A. Humbert & T. Kanzow

9:35 Introduction of 27 participants (everyone sent 1 slide) all & U. Schauer

10:30 – 10:45 Coffee

10:45 Presentation of visual info graphics by the 27 participants (Foyer)

11:45 Grouping of issues and forming ca. 5-6 break-out groups (BOG)

Task of the BOGs: Assemble a list of questions that should be addressed in the coming decade for explaining the interaction between Greenland ice sheet and ocean. (e.g. "Do we think the ocean matters at all?")

Don't feel constrained to today questions – look far into the future.

Each break-out group has 1 discussion host and 1 person who takes minutes

12:00 Break-out groups discuss and compile questions.

13:00 – 14:00 Lunch in Kantine

14:00 – 17:00 continue break-out groups discuss and compile questions.

Individual coffee breaks

17:00 Plenum E4025: Presentation of questions of break-out groups

17:30 Group photo in E Hall of fame (Folke 2007)

19:00 Workshop Dinner in Pier 6

Tuesday Dec 9:

"How to tackle these questions in the next decade"

8:30 Plenum E4025: Recapture questions of break-out groups, discussion.

Forming break-out groups for compilation of measures for tackle the questions?

Task of the BOGs: Come up with list of measures that are necessary to address, or answer these questions. (e.g. "Do we need a new satellite?")

Don't feel constrained by today technology – dream the instruments you require.

9:30 Coffee break optional

9:30 or 10:00 Break-out groups discuss and compile measures.

13:00 Lunch at Kantine

14:00 Plenum E4025: Presentation and discussion of outcome of break-out

15:30 Coffee

16:00 Plenum E4025: Wrap up, tasks for writing workshop report, early career scientists tasks

17:00 END

Appendix 2: Participants list

IASC Supported Participants *(Please indicate early career scientists)* :   *   indicated as ecs

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