Report from the Field Workshop on Studies of Tidewater Glaciers

26-31 August 2012 on board the r/v Horyzont II around Svalbard

TIDEWATER GLACIERS WORKSHOP 2012

Svalbard

r/v Horyzont II

Cryosphere Working Group
International Arctic Science Committee

Sosnowiec 2013

Field Workshop on Studies of Tidewater Glaciers

26 - 31 August 2012, Svalbard

Sponsors and organizers

Cryosphere Working Group, International Arctic Science Committee

Institute of Geophysics, Polish Academy of Sciences

EU - project Ice2sea

Nordic Centre of Excellence SVALI

Committee on Polar Research, Polish Academy of Sciences

University of Silesia, Poland

University of Oslo, Norway

University Centre in Svalbard - UNIS, Longyearbyen

Steering Group

Piotr Głowacki, Institute of Geophysics, Polish Academy of Sciences

Jon Ove Hagen, University of Oslo

Jacek A. Jania, University of Silesia

Tad Pfeffer, University of Colorado

Report prepared by Jenny Baeseman
and Early Career Scientists - participants of the Workshop

Edited by Jacek A. Jania and Joanna Szafraniec

ISBN: 978-3-9813637-5-3

Published by the Polish Polar Consortium
Faculty of Earth Sciences
University of Silesia
ul. Będzińska 60
Sosnowiec, Poland

Table of Contents

Preface

IASC Cryosphere Working Group motivations for the workshop

Tidewater glaciers are important elements of the atmosphere-ocean-cryosphere system When comparing the mass balance of a land-based glacier with that of one ending in the sea, one has to take into account the mass loss associated with icebergs produced by the calving process. How important is this contribution to the loss of mass from land ice? Do tidewater glaciers play an important role in the transfer of ice mass from the land to the sea? Do we understand the process of calving well enough to model this important component of the mass balance of Arctic tidewater glaciers?

Such questions and many more attract people to investigate those “difficult” glaciers that end in the sea. While “normal” glaciers can be readily defined in terms of their extent, the terminus position of tidewater glaciers fluctuates on a seasonal basis. The mechanics and changing rate of calving remain elusive due to the lack of a general calving law, despite numerous attempts to quantify this process over the last three decades.

Bearing in mind the importance of mass transfer from the land to the sea via Arctic tidewater glaciers, a proposal to organize of a workshop on Arctic tidewater glaciers was made during the IASC Cryosphere Working Group Meeting in Utrecht, The Netherlands on 6 - 7 October 2011 and developed further in a special session on tidewater glacier research in the Arctic during the annual Workshop on the Dynamics and Mass Budget of Arctic Glaciers of the IASC Network on Arctic Glaciology that was held on 11 January 2012 in Zieleniec, Poland. Consequently, the “Field Workshop on Studies of Tidewater Glaciers” was held on board the Polish ship r/v *Horyzont II* during its cruise to Svalbard fiords from 26 - 31 August 2012. Scientific sessions were held also at the UNIS in Longyearbyen and at the Marine Laboratory in Ny-Ålesund.

Svalbard is one of the most accessible regions of the High Arctic with tidewater glaciers. The goal of this meeting was to combine scientific sessions with field presentations that took place as close as possible to calving glaciers, that allowed both familiarization with different methods of monitoring of these glaciers and discussions of the methods. The workshop focused on three major issues: field observations of tidewater glaciers, remote sensing methods, and modeling basing upon physical principles and observational data.

These activities were directed at generating a better understanding of calving processes and their importance for mass turnover in Arctic glacierized areas. While a general calving law is still a challenge for glaciologists, the field workshop on studies of tidewater glaciers in Svalbard was an important step forward in initiating interactions across disciplines designed to further our understanding of the behavior of land ice masses emptying into the sea.

The present report was produced thanks to the corporate effort of all the participants under the encouragement and supervision of Jenny Baeseman (WCRP-CliC). It contains a brief overview of the current state of tidewater glacier science and the methods and techniques used by different research groups to study these glaciers, and an attempt to identify major research challenges and knowledge gaps. The report is supplemented by extended abstracts of the papers presented during the workshop. One of most the important results of this workshop is intended to be the development of a comprehensive international program of studies of tidewater glaciers in the Arctic (and potentially also West Antarctica) in which young scientists can play a leading role.

Martin Sharp and Jacek A. Jania

Executive Summary

Twenty-four scientists met onboard the Polish ship *Horyzont II* and onshore at several Svalbard locations for the Field Workshop on Studies of Tidewater Glaciers, held 26 - 31 August, 2012. The group, consisting of 10 senior scientists and 14 early career scientists drawn from 8 countries, met to present and discuss the most recent progress on understanding the characteristics and behavior of tidewater glaciers, with special emphasis on development and application of field and remote sensing techniques. Supported by the IASC Network on Arctic Glaciology, presentations and discussions were held onboard the *Horyzont II* as it cruised along Svalbard's west coast, and field excursions and demonstrations were conducted at four onshore locations. Further presentations were given at the Norwegian Polar Institute Sverdrup Station in Ny Ålesund, and with an audience expanded to 30 at the UNIS campus in Longyearbyen.

With a rapidly growing recognition of the importance of tidewater terminating glaciers to the overall dynamic character of the cryosphere, particularly including sea level rise and high-latitude environmental change, the time was right for a comprehensive review and discussion of the diverse body of knowledge about tidewater glacier dynamics and mass balance, acquired at many locations in the Arctic and elsewhere, and developed over more than three decades, combined with presentations on the newest developments in observation and analysis. To this end, the workshop was proposed during the Cryosphere Working Group Meeting in Utrecht, The Netherlands on 6 - 7 October 2011 and at the Workshop on the Dynamics and Mass Budget of Arctic Glaciers in Zieleniec, Poland held on 11 January 2012, where the organizers proposed to bring senior scientists with broad and long-term experience together with young scientists with specific interests and expertise in tidewater glaciers in a location at the heart of Arctic glacier change. The additional idea of hosting the meeting on board the *Horyzont II* had the added advantages of concentrating the group in a novel environment ideally suited to the subject, comfortable and well-designed facilities, and mobility to visit field locations on a flexible schedule. Mobility turned out to be a crucial advantage since weather and ice conditions required frequent revisions of the schedule of landings, and the shipboard venue permitted constant “polar flexibility”.

Three major goals were pursued during the workshop: (1) recent results from studies of tidewater glaciers in Svalbard and other locations were presented; (2) experience in application of new techniques and results were demonstrated and expertise was shared directly in the field by visiting key tidewater glaciers in Spitsbergen; and (3) preliminary plans for an international program of coordinated field and remote sensing observations of calving glaciers in the Arctic were discussed. The first goal helped bring the group to a shared state of common knowledge about tidewater glacier characteristics and behavior, combining long-standing knowledge (not all of which has been carried forward in the glaciological mainstream); the second goal provided all participants with valuable experience of seeing and using the latest observational techniques in context, while the third goal is a critical first step toward a comprehensive field, observational, and analysis program to make full use of the broad, deep, but generally under-utilized potential of Arctic tidewater glaciers for major improvements in our understanding of global cryospheric change. In common with the Greenland and Antarctic ice sheets, glacier-covered regions elsewhere often have major tidewater outlets that largely control their dynamics and response to climate change, while in contrast to the ice sheets, these regions often have histories of observation that go back decades and because of their smaller size are vastly more efficient and inexpensive research locations. The discussions of an international, coordinated program started at this workshop

are continuing with a subgroup of Workshop attendees, and plans for funding and implementation are ongoing.

During four field sessions the following areas with tidewater glaciers were visited: Brepollen - the inner part of Hornsund Fiord (S Spitsbergen) with landing near the Storbreen, Hansbreen near the Polish Polar Station in Hornsund, Kronebreen and Kongsvegen in Kongsfjorden (NW Spitsbergen) and Tunabreen in Tempelfjorden (Central Spitsbergen). Severe weather and sea conditions (waves and ice brash fields) caused changes of the workshop's program almost every day. Nevertheless, all components of it were completed. The workshop was finished by a panel discussion on the most crucial directions of further studies of tidewater glaciers in the Arctic and suggested rudiments of collaborative international programs. The workshop was co-sponsored and organized by IASC Cryosphere Working Group & IASC Network on Arctic Glaciology, Institute of Geophysics Polish Academy of Sciences, Committee on Polar Research, Polish Academy of Sciences, EU 7FP project “Ice2sea”, SVALI - Nordic Center of Excellence in Glaciology, University of Silesia, Poland, University of Oslo, Norway and University Centre in Svalbard - UNIS, Longyearbyen, Norway.

Tad Pfeffer and Jacek A. Jania

Group of participants of the workshop - Hansbreen at the background. (Photo by D. Ignatiuk)

1. Relevance of tidewater glaciers and a review of the current state of knowledge

By definition, tidewater glaciers are moving bodies of ice (glaciers) that terminate at vertical cliff faces in the ocean and are, therefore, tidally influenced. Grounded termini are characteristic of both temperate and polythermal tidewater glaciers, which may only unground and form a floating ice tongue over relatively small areas such as observed during the retreat of Columbia Glacier, Alaska (Walter *et al*. 2010). Grounded termini are found throughout the Arctic. However, floating ice tongues with lengths exceeding several kilometers are confined to polythermal and cold tidewater glaciers in polar regions, such as the Canadian Arctic, Greenland, and Antarctica.

The initial triggering mechanism for dynamic change can be from a reduction in resistive stress, generally associated with the loss of sea ice or ice mélange (Amundson *et al*. 2010, Howat *et al*. 2010, Christoffersen *et al*. 2011), thinning of the ice tongue or ice shelf from increased submarine melting (Holland *et al*. 2008, Pritchard *et al*. 2009, Motyka *et al*. 2011), thinning near the terminus from increased surface melting (Pritchard *et al*. 2007), and/or grounding line retreat (Joughin *et al*. 2011). Although an increase in surface melt water reaching the glacier bed has also been shown to cause short-term ice acceleration (Zwally *et al*. 2002), the response to the associated increase in basal lubrication varies spatially and temporally (Joughin *et al*. 2008, Sundal *et al*. 2011). Thus, it is likely that observed changes in dynamics are triggered by changes in resistive stress at the terminus as opposed to increased surface meltwater penetration to the glacier bed.

Mass loss by way of a glacier's terminus can comprise a large proportion of the glacier mass budget through a combination of two highly variable processes: iceberg calving and submarine melting. Changes in the rate of mass loss from the terminus can substantially influence tidewater glacier behavior by altering the glacier stress balance. If increased calving or submarine melting reduces the resistive stress component at the glacier terminus (i.e. loss of buttressing or backstress), acceleration will initiate near the terminus, resulting in increased longitudinal stretching (i.e. dynamic thinning) and a transfer of resistive stresses towards the glacier interior. For glaciers close to flotation, dynamic thinning will reduce the gravitational driving stress and basal resistive stress, causing additional acceleration, thinning and ungrounding of the terminus (Pfeffer 2007). If a glacier is well grounded, thinning concentrated near the terminus will increase the surface slope, thus the gravitational driving stress will increase and the glacier will stabilize.

For glaciers grounded across basal depressions, which is a common configuration for tidewater glaciers, dynamic thinning could lead to the flotation of ice above the depression, resulting in an unstable retreat of the grounding line (Schoof 2007, Pfeffer 2007). Thus, these glaciers have the potential to rapidly increase their discharge over a short time period as has been observed for several Greenland tidewater outlet glaciers (Howat *et al*. 2007, Nick *et al*. 2009, and others). Constrictions within outlet troughs should act as stabilizing points due to higher friction and increased ice convergence (O'Neel *et al*. 2005), suggesting that glacier geometry may strongly influence changes in tidewater glacier dynamics.

Changes in tidewater glacier dynamics have the potential to strongly influence global sea level rise, but an incomplete understanding of the processes acting on the ice-ocean interface greatly limits the ability of numerical models to predict future changes in tidewater glacier dynamics. Over the past decade, melt from glaciers and ice caps have contributed more to global sea level rise (~60%) than the Greenland and Antarctic Ice Sheets combined (Meier *et al*. 2007). Recent large-scale studies around Greenland have revealed, however, that tidewater outlet glaciers draining the ice sheet have accelerated (Luckman *et al*. 2006, Howat *et al*. 2008, Moon *et al*. 2012), thinned (Howat *et al*. 2008, McFadden *et al*. 2011) and retreated (Howat *et al*. 2008, Moon and Joughin 2008, McFadden *et al*. 2011) noticeably within the past decade. If mass loss trends from changes in tidewater outlet glacier dynamics continue at a similar rate, the ice sheets will become the dominant contributor to global sea level rise within the next several decades (Rignot *et al*. 2011).

The observed rapid changes in dynamics bring the future contribution of tidewater glaciers to sea level rise into question. Van de Broeke *et al*. (2009), shown that changes in glacier dynamics contributed to half of the Greenland Ice Sheet's total mass loss between 2000 - 2008. Previous estimates of glacier and ice-sheet contributions to global sea-level change did not, however, take the mass contribution from changes in dynamics into account (Rignot and Kanagaratnam 2006, IPCC 2007), leading to inaccuracies in model-derived predictions of sea level rise. In order to incorporate changes in glacier dynamics into projections for sea level rise, a better understanding of the climate forcing mechanisms and the controls of tidewater glacier response must be obtained through collaborative efforts within the broader scientific community that combine *in situ* and remotely-sensed data coupled with numerical models.

Ellyn Enderlin and Yoann Drocourt

Ice cliff of Hansbreen (Photo by T. Budzik)

2. Challenges and gaps in studies of tidewater glaciers

Linking tidewater glacier dynamics to atmospheric and oceanic climate forcing and projecting the contribution of tidewater glaciers to global sea level rise (SLR) is currently limited by gaps in our understanding of the mechanisms involved. Technical, logistical, and organizational challenges have limited our ability to properly address these issues. Advancing the state of knowledge of these problems must be addressed by innovative application of emerging technology and coordinated, multi-disciplinary research efforts involving a synthesis of fieldwork, remote sensing, and modeling at targeted monitoring sites. Open communication, collaboration and data sharing among the scientific community are key to making the rapid progress that these issues require in order to properly inform policy makers on a short timeline.

The main gaps and challenges in tidewater glacier knowledge are summarized as follows:

- **Large range of temporal and spatial variability**: Glacier fluxes and calving rates vary at many temporal and spatial scales. Temporal scales include diurnal, seasonal, annual, decadal, and millennial timescales as well as episodic events influenced by weather and related processes, including surge events. Spatial scales range from millimeters within boundary layers, to 10s of meters across a terminus, to kilometers along flowlines, to 10s of kilometers between tributaries and basins, to regional scales over 1000s of kilometers. Putting observed changes into context requires characterizing the variability using collaborative studies that span all scales.

- **Gaps in regional ice fluxes and calving rates**: A paucity of baseline data from som geographic areas has been identified as increasing the uncertainty of the contribution of tidewater glaciers to SLR. Specifically, the Canadian Arctic Archipelago (CAA), including Devon Island, Axel Heiberg Island and Ellesmere Island have very limited data of glacier velocity, terminus width and ice thickness that are necessary to constrain ice fluxes and calving rates. The first comprehensive survey of CAA ice fluxes is currently underway using expanded coverage of high-resolution remote sensing data, and plans are to repeat the survey annually. However, the comprehensive dataset only begins in 2010, is limited to one month of the year, and ice thickness measurements are still sparse in the region. Similar data limitations are prevalent throughout the Arctic.

- **Impact of seasonality on glacier dynamics**: Annual timeseries have shown strong seasonality of glacier velocities indicating that 'snapshot' datasets, particularly remotely sensed velocity estimates based on a short time window, require ground-truthing and should be used with caution when deriving annual averages.

- **Basal conditions and basal motion:** Fast glacier flow is achieved by basal motion, rather than ice deformation. A large part of the temporal variability in glacier flow is attributed to changes in basal conditions. Basal water pressure and the nature of the basal hydraulic drainage system affect glacier flow on short time scales (diurnally to seasonally). Changes in basal thermal regime are acting on larger time scales of decades to centuries and may trigger surges. The subglacial environment is largely inaccessible, and direct observations are generally limited to measurements within a few boreholes. More field observations combining borehole measurements of water pressure, temperature and ice deformation with geophysical methods such as radar and seismic measurements are requisite for improving the understanding of the key processes involved.

- **Impact of summer melt on glacier hydrology and dynamics**: The mechanisms of how glacier hydrology, in particular summer melt and rain events, are linked to glacier velocity, crevasse formation and calving are not well constrained. These processes need to be addressed with targeted field studies and further development of hydrological models.

- **Sea ice and ice mélange terminus buttressing**: The effect of sea ice and ice mélange stresses on the glacier terminus and its role in influencing glacier velocity and calving rates and timing has not been well studied. Fjords with an ice mélange are particularly difficult for field studies due to the logistical challenges of accessing study sites and installing monitoring instruments. In these environments there is a pressing need for improved remote sensing methodologies that can quantitatively assess the influence of sea ice and mélange using timelapse photography and satellite imagery.

- **The contribution of surging glaciers to annual ice fluxes**: Identification of surging glaciers and the role of their time-variable ice flux should be further constrained to properly quantify regional contributions to SLR. The mechanisms that trigger surges are not well understood and tightly linked to basal motion. Surge behaviour of glaciers partly grounded below sea level may be highly significant, as it has been associated with the rapid disintegration of former ice sheets.

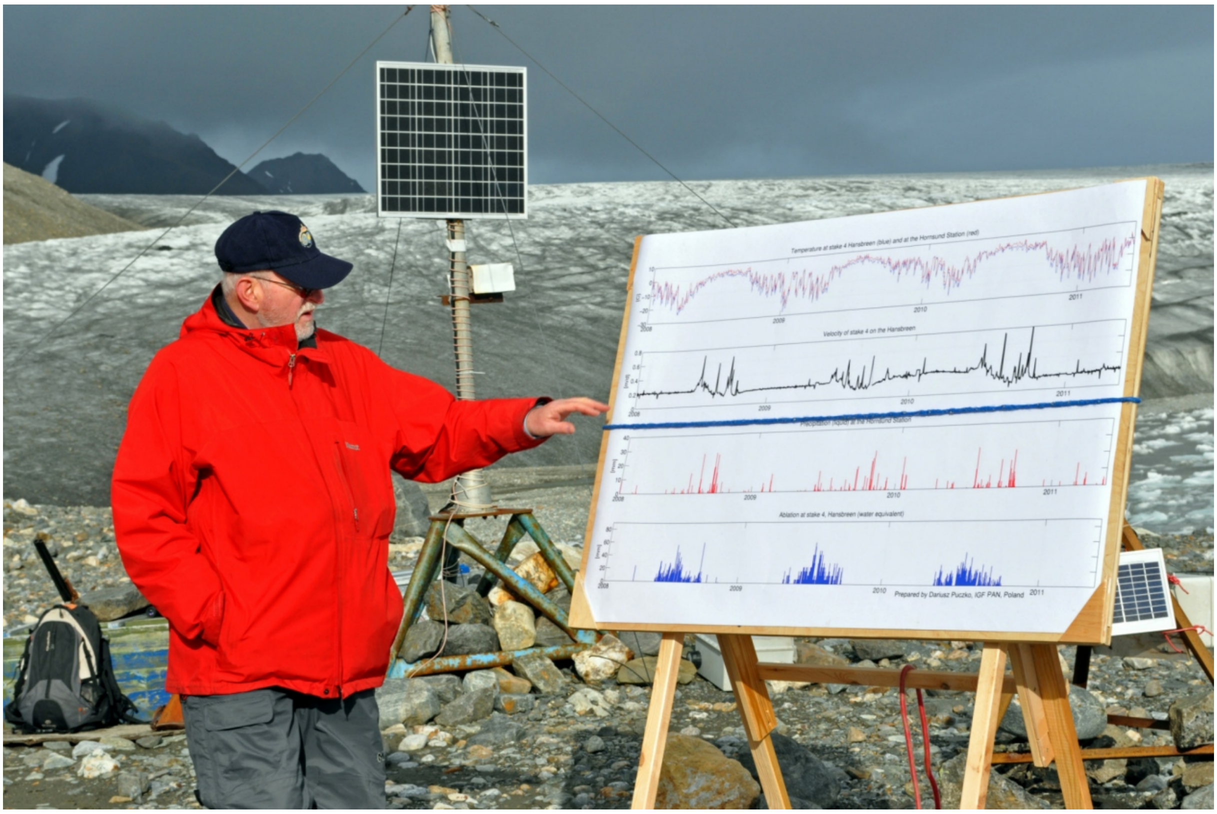
- **Ocean properties, fjord circulation and basal melt**: Ocean dynamics are thought to play a fundamental role in tidewater glacier dynamics yet it is only recently that more studies are addressing oceanographic processes. Logistical difficulties in monitoring ocean properties at calving glacier termini in ice-choked fjords present major challenges for data collection. However, targeted oceanographic field efforts have revealed profound insight, so a well thought out expansion of these efforts will improve the state of knowledge in this topic. Broader geographical coverage from a variety of ocean basins is required, investment in long-term monitoring sites is needed, and process-oriented studies focusing on ice-ocean interaction is critical for large scale global circulation model (GCM) parameterizations.

- **Subglacial discharge and plume dynamics**: Freshwater discharge into the fjord environment and plume dynamics, as well as the influence of water-ice feedback mechanisms on glacier dynamics and calving, are poorly constrained. Linking atmospheric forcing and glacier hydrology to responses at the marine glacier terminus requires a combination of freshwater flux estimates from catchment area snow / ice melt models and *in situ* observations of drainage channels, plume characteristics, basal melting, and calving events. Submarine mapping efforts of glacier termini (including both ice face and bathymetry) are also needed to understand the geometry of the problem which will influence plume trajectory, turbulence, ocean water entrainment and ice-ocean boundary layer mechanics.

- **Calving dynamics**: Continued efforts are required to establish a comprehensive description of the physical mechanics involved in calving, which currently remains incomplete. Further field, theoretical, and experimental research efforts will improve the development of a 'calving law' applicable to all scales of calving events.

- **Regional and long-term context**: Observations from individual glaciers should be put into context with other glaciers from the same region that are subject to similar atmospheric and oceanic forcing to understand the variation in response. Recent observations must also be viewed within a long-term context, from ice core isotopic analysis for example, to understand the natural variability of the system.

- **Data visualization**: As datasets have become larger, classic visualization tools have reached their limits. Novel data visualization techniques are under development that can avoid problems such as cluttering and loss of geographic information from regionally dense and multilayered datasets.



At the Hansbreen front - Jacek A. Jania during the field session (Photo by D. Ignatiuk)

To address the above data gaps and research challenges we suggest the following approaches:

- **Technological developments**: Innovation in instrument design, as well as innovative application of emerging technologies, will enhance the ability to monitor the challenging environments surrounding tidewater glaciers. The logistical difficulties of accessing and deploying instruments in these environments will remain, so an improvement in the ability of instruments to collect high-quality data, year-round, in harsh and changing conditions is key. Technical improvements would include the design of inexpensive, telemetered instrumentation for both glaciological and oceanographic work, low-cost GPS receivers, development of robust moorings for deployment in iceberg-filled fjords, novel exploitation of remote sensing datasets, and utilization of 'intelligent' high-tech ocean instruments for ice-covered waters (e.g. gliders and autonomous underwater vehicles).
- **Standardized methodology and data sharing**: The problems the tidewater glacier community needs to address will require data synthesis from variety of sources so standardized sampling methods and coherent databases are needed to drive integrated studies and cross-comparisons. Standard methodologies and data archives for basic data (similar to those developed by the oceanographic community for example) would be beneficial. Early career scientists would also benefit from an archive of methods developed by senior scientists so that there is a 'passing on' of knowledge gained from their years of experience (ranging from field sampling techniques and instrument

utilization advice to innovative remote sensing analysis methods). As well, open access to certain datasets, for example the high-resolution (in time and space) remote sensing imagery only available to select parties, would be extremely beneficial to increasing pan-Arctic monitoring.

- **Targeted efforts at keys sites**: Given the logistical and funding constraints of Arctic research, for optimal return on research investment we recommend a number of representative field sites be targeted for intense study through a combination of file and remotely-sensed data collection and numerical modeling. Ideal target glaciers would have an ongoing research network, existing field infrastructure, a history of long-term monitoring, relatively easy access, and span the various types of glacier systems so that the dataset can be considered representative of all glaciated regions in the Arctic.

- **Integrated multi-disciplinary and international approach**: Integration of multi-disciplinary field studies (e.g. glaciological, hydrological, atmospheric, oceanographic), remote sensing, theoretical analysis, and modeling efforts at key sites is required to properly address unanswered research questions. A collaborative effort is necessary so that each scientific community can inform the others of their data requirements and obtain a systems view of the problem. International collaboration is imperative to coordinate large-scale science studies, direct funding efforts, initiate regional surveys, direct instrumentation development, and to synthesize findings into a pan-Arctic description of tidewater glacier dynamics.

Andrew Hamilton, Wesley Van Wychen and Yoann Drocourt

Participants of the Tidewater Glacier Workshop on Hansbreen with georadar (Photo by M. Błaszczyk)

3. Modeling needs: key boundary conditions, validation data sets and requests to data collectors

The modeling session in the workshop ("Requests of modelers to field observers of tidewater glaciers") included talks on modeling calving glaciers, inferring basal drag using field and remote sensing data, linking calving to damage using an inverse method and remote sensing data, estimating sea level rise attributable to changes to glacier basins on the Antarctic Peninsula, exploring sensitivity of a tidewater glacier model to variations in numerous physical parameters and forcing, and highlighting challenges and data requirements for modeling tidewater glaciers. The modeling studies covered a wide range of spatial and temporal scales and demonstrated advances in computation complexity, process representation, and assimilation of observational data. As the presenters noted, however, all models are dependent on a variety of parameterizations that are used to simplify the complex processes that occur within the glacier system. For tidewater glaciers, one process that received particular attention is a "calving law" used to describe the calving process at the marine boundary, a process that is still not adequately represented in models.

Many of the glacier models presented in this session utilized a crevasse-penetration calving relationship, which determines the location of the calving front by the depth of crevasses generated by longitudinal stretching. This calving relationship allows the model glacier to maintain a floating terminus, which is not possible for some calving relationships (e.g. height or fraction above flotation). Furthermore it allows linking of atmospheric and oceanic climate forcing into calving, but currently the involved parameters are poorly constrained and the process of ocean melting and related input forcing data (e.g. plume entrainment, ocean / fjord temperature) remain uncertain.

A new calving model based on damage mechanics was presented, which led to a discussion of what measuring "damage" in the field would look like, especially in the context of a planned study of crevasse mechanics and calving in a tidewater glacier that was later visited in the workshop. Despite the variety of representations of calving, it was agreed that detailed field studies of calving on tidewater glaciers are necessary to further develop, calibrate and objectively validate the available calving models.

The strong dependency of calving and ice flow on trough geometry has been demonstrated in several presentations and highlights the critical importance of precise basal topography measurements for accurately modeling the behavior of tidewater glaciers. Bed topography can be obtained using ground- or aircraft-based radar, yet measurements of basal topography are limited to a few isolated glaciers and are seldom available for the entire model domain due to either field logistic challenges or difficulties in signal processing due to low quality radar signals. It was therefore agreed that limited data on basal topography continues to be a major challenge in predicting tidewater glacier behavior.

Another parameterization that was discussed is basal motion. The related basal boundary conditions and bed roughness are difficult to reasonably parameterize because they cannot be directly measured nor are they expected to remain spatially uniform or temporally constant. The application of inverse methods was discussed as a means of constraining and understanding the basal boundary condition, however, inverse methods cannot account for temporal variability of basal motion related to basal hydrology (see others sessions).

A vigorous discussion period at the end of the session was evidence of the synergy produced by the inclusion of modelers in a field-based workshop. It was agreed that collaboration between modelers and field experts should start at the definition of the research problem so that the needs of all parties are addressed before data collection begins. Important topics to be agreed upon from the outset include the definition of the glacier or study boundary, the spatial and temporal resolution of data needed for modeling the glacier, the magnitude and spatial distribution of uncertainties in the data, and sharing the data in a format (e.g. ascii, netcdf) that can be read without the use of special licensed software. Critical data obtained in the field or through airborne- or satellite-based remote sensing include bed and surface elevations for the entire glacier or study boundary, if possible, and point measurements of speed and ice temperature for model validation. Measurements of surface mass balance, terminus position, glacier thickness evolution, and temperature profiles were not discussed in detail during this session but may also be crucial input depending on the chosen model type and purpose.

Numerical modeling efforts would also benefit from the creation of validation datasets compiled from a variety of well-studied tidewater glaciers that are representative of glaciated regions in the Arctic. Similar to the benchmark studies performed for ice sheet models in general, these validation datasets would enable direct comparison and calibration of specific tidewater glacier models. The following glaciers were proposed as possible candidates: Hansbreen (Svalbard), Belcher Glacier (Canada), Columbia Glacier (Alaska, USA), and several tidewater outlet glaciers in Greenland (see Enclosure). In order to create such a validation dataset, however, data would have to be voluntarily compiled from all studies conducted on the selected glaciers. Data compilation may prove to be a difficult task, and there was some concern about whether such an effort would duplicate existing data clearinghouses and thus diminish user buy-in. However, such datasets would greatly improve the scientific community's ability to assess the numerical models of tidewater glacier behavior.

Ellyn Enderlin, Martina Schäfer and Chris Borstad

Ice cliff of Hornbreen, Brepolen (Photo by M. Szymocha)

4. Recommendations for field and remote sensing methods for tidewater glaciers

Studies of tidewater glaciers usually have two types of objectives:

(1) A reliable quantification of ice mass loss due to calving as a component of the glacier mass budget and its contribution to global sea level rise.

(2) Understanding of the physical processes that control calving and identification of key factors that influence calving intensity in different environmental conditions.

While the first objective often analyzes the entire glacier system as a source of icebergs without examining the specific calving processes in detail, the second objective requires a combination of high precision, long-term calving measurements and a robust record of glaciological and environmental parameters. The most common studies implement both approaches for a limited number of key glaciers.

The use of remote sensing methods is necessary for calculation of ice volume lost by calving on an annual basis and for larger number of tidewater glaciers in a region. These methods require data on ice thickness and ice flow velocity at the glacier terminus, and records of changes in the glacier terminus position. Thickness data are acquired from radar sounding or differencing of ice cliff elevations with bed depths from ocean surveys. High resolution optical satellite images are appropriate for the mapping of glacier retreat or advance and the survey of glacier flow velocity by feature tracking. Data from high resolution optical satellite images such as ASTER, Iconos, and GeoEye do not provide high-temporal resolution sampling at the Arctic latitudes, however, due to orbit limitations, frequent cloud cover and lack of sunshine light during polar winter, limiting the number of images available for study. Similar remote sensing tools are also used for studies of calving processes. Unfortunately, the restricted availability of remote sensing data greatly limits our ability to monitor small-scale calving processes over a large spatial extent and with long temporal coverage. Future studies will require higher temporal and spatial resolution sensors with both optical and radar imaging capabilities.

Presently, moderate resolution imagery from MODIS (Moderate Resolution Imaging Spectroradiometer - 250 m-resolution) is our best resource for high-temporal optical samplingat the Arctic latitudes. MODIS images are freely available and collected several times per day; however, optical sensors are limited to cloud-free days with solar illumination eliminating the ability to monitor during the polar night. The Envisat satellite carried a synthetic aperture radar (SAR) sensor that freely provided regular sampling of the polar regions at night and through clouds until its failure in April 2012. Unfortunately, with the failure of Envisat and the ERS 2 mission ending in 2011, a large gap in the data record is now present as there are no other satellites collecting regular SAR images that are freely available. The first of two Sentinel satellites is scheduled to be launched in late 2013. Due to a planned ramp-up phase, the sensor is expected to reach full capacity not before late 2014. The high resolution TerraSAR-X Radar Satellite imagery system is a recent tool that is neither light nor cloud depend which meets the data requirements for precise studies of tidewater glaciers. Nevertheless, the price and wider availability of these data are not yet promising. The additional of a second, tandem-orbiting TerraSAR-X satellite in 2010 (i.e. TanDEM-X) enabled the acquisition of regional digital elevation models (DEMs) that are necessary for glacier mass budget calculations, however, the price of TanDEM-X data remains very high.

Analysis of the glaciological processes controlling calving and the environmental conditions that are likely to influence calving mechanisms requires more data than studies that focus on the annual calving flux. First, glacier geometry and behavior near the frontal zone of the glacier tongue should be monitored as accurately as possible throughout the year. Second meteorological conditions that influence glacier melting, and thus, the water supply into the subglacial drainage system need to be measured on short (daily or less) time scales. Moreover, ocean characteristics and ice-ocean interations at the glacier frontal cliff must also be measured during the same time period. Taken together, these data required a large number of tools deployed at and around the glacier terminus, as described below:

- Glacier geometry features and temporal changes in these feature (i.e. ice thickness, surface topography of the glacier, cliff elevation and its freeboard, short term ice cliff fluctuations): airborne photogrammetric or laser scanning flights to obtain DEMs and terrestrial and airborne terrestrial photogrammetry from multiple photos by non-metric cameras (as recently developed by T. Pfeffer and E.Z. Welty);
- Velocity measurements and strain rate distribution: precise dual and single frequency global positioning system (GPS), time lapse cameras, repeated terrestrial laser scanning;
- Detection of calving: seismic and acoustic measurement stations, pressure sensors to record calving “tsunami” waves, fast time lapse cameras;
- Weather parameters: automatic weather stations (AWSs) with at least temperature, wind speed and direction, total irradiation sensors, ablatometer, and automatic precipitation gauge;
- Subglacial water pressure and meltwater discharge from the glacier system: subglacial water pressure sensors with loggers, stream gauge station on a lateral land based outflow stream or from a nearby glacier;
- Ocean parameters in fiord: marine gauge station with frequent record interval, conductivity temperature and depth (CTD) mooring near the glacier front, current meter for surface and deep waters, etc.;
- Detailed ice-ocean interface changes: autonomous submarine vehicle (ASV);
- Fjord bed properties at front of the ice cliff: echo and active seismic sounding from a boat.

Below is a list of the minimum set of measurements and employed instruments for terrestrial monitoring of dynamics and environmental factors for a medium size tidewater glacier. These data must be accompanied by a surface topography map, subglacial topography measurements, bathymetry of the fiord, and information on ice thermal structure in order to thoroughly analyze changes in glacier behavior.

- Recurring survey (~every other year) of geometry of the glacier terminus, ocean depth along the ice cliff, and glacier mass balance components (accumulation and ablation stakes);
- Time lapse camera(s) operating year-long period with frequent release (1-3 h) and long exposure time for night photos;
- GPS station(s) close to terminus and upstream (at least low cost single frequency) as reference for extraction of velocity field from remote sensing data or terrestrial time lapse photos;
- Subglacial water pressure sensor and stream gauge station on a nearby land-terminating glacier;
- Marine gauge station with continuous monitoring of sea level and near surface ocean water temperature;
- Meteorological station (AWS) on the glacier or on a neighboring glacier (longer set of climate data desired).

Every developed tidewater glacier monitoring system has to be tailored to the glacier size and topography near its terminus. Maintenance of the equipment, the ability to maintain a constant power supply and logistic costs to keep system in operation are also extremely important. Costs of safe field campaigns are also important to consider when designing or developing monitoring systems. Special efforts must also be made to ensure that the deployed data collection equipment can withstand extreme weather events (e.g. strong winds).

Kristin M. Schild et al.

5. Perspectives for further coordinated research

The synergy produced by the interaction between modelers and observational scientists at the workshop points to the need for continued collaboration between these two communities. However, the difficulty in securing funding to establish field programs on tidewater glaciers was highlighted by some participants, especially when competing for funds to study in areas other than Greenland.

For future collaborative research on tidewater glaciers in Svalbard specifically, the Svalbard Science Forum (SSF) was identified as a promising funding agency. The SSF is a program of the Research Council of Norway that coordinates research conducted in Svalbard and provides funding for students working in Svalbard and for international collaborators wishing to work with Norwegian scientists in Svalbard. Several participants of the workshop are already in the process of applying for funds from SSF to establish a collaboration involving fieldwork and modeling of a tidewater glacier in Svalbard.

A cooperative Circum-Arctic program focused on the analysis of selected key tidewater glaciers using recommended uniform methods and instruments for *in situ* data collection, coupled with data acquired from remote sensing techniques, is highly recommended. Such a collaborative international program should have two objectives: (1) to monitor the mass loss due to calving in relation to the total glacier mass budget for multiple years on the key study glaciers (listed in Enclosure) and (2) to collect high temporal resolution data on changes in glacier dynamics and calving processes under different environmental conditions.

The first objective requires a relatively simple set of data, including the geometry of the glacier near its terminus, the ocean bathymetry near the terminus, the ice flow velocity, and the rate of front position change on sub-annual time scales. Estimation of regional calving fluxes throughout the Arctic would be extremely valuable for evaluation of the contribution of Arctic tidewater glaciers to the global ocean level rise. Research efforts aimed at accomplishing the second objective would also provide data for physical models of calving, which is imperative for predicting future tidewater glacier behavior.

We further suggest that field studies focus on the collection of a standard minimum set using similar methods in order to directly compare glacier behavior and ensure that numerical models are well constrained with observational data. The IASC Cryospere Working Group in co-operation with the IASC Network on Arctic Glaciology could provide a platform for coordination of these studies. Funding of field work and remote sensing studies in particular key areas should be obtained from national and international sources in order to support such a large, well-planned collaborative international program.

Chris Borstad and Jacek A. Jania

6. Field trips and additional educational experiences

Hornsund Fjord - Brepollen

A field trip introductory presentation was given to give background information. This included Multibeam echo sounding of the sea bed and oceanographic equipment demonstrations. Recognition of surges evidenced in bathymetry of the Brepollen region and the history of Hornsund deglaciation together with remote sensing methods gave the introduction to observation of geomorphic evidences of surges during the field trip. Results of oceanographic research such as sea water temperature and salinity conducted during summer expeditions in Hornsund were also presented. An 11-year time series of physical properties of water along the fjord axis showed significant summer to summer variability. Atlantic water entering the fjord is strongly modified due to mixing with cold Arctic water on the shelf. Moreover, the sill in the entrance to Brepollen limits the inflow of warm and saline water into this region and allows for the deposition of cold and dense water forming during winter in the depression. The highest values of temperature and salinity occurred in 2006, which was correlated with the warming and strengthening of the West Spitsbergen Current (Walczowski and Piechura 2007).

Hornsund Fjord - field and training session on Hansbreen

Field training on Hansbreen presented different activities on the glacier and in the vicinity preformed since 1982 (Grabiec *et al*. 2012). The main objective of long term studies is to survey flow dynamics and contributions of calving flux to the overall mass balance.

New tools and methods applied for glacier front monitoring (the Riegl FG21-LR laser distance ranger, Garmin GMR 18HD panoramic radar and time lapse camera Canon 1000D) placed close to the glacier front were presented. Tracing of seasonal glacier front fluctuation, velocity and calving by these methods are giving a more detailed picture of spatial and temporal variability of Hansbreen front dynamics than has previously been documented. A precise periodic GPS survey of mass balance stakes on the glacier show good correlation of the air temperature, precipitation with velocity and ablation of the glacier.

GPR equipment was demonstrated and GPR data on the internal structure of Hansbren was discussed. Bedrock topography of the glacier has been also obtained from ground based radio-echo-sounding giving the volume of the glacier.

In 2011 CTD surveys in Hansbukta were carried out in order to observe short-term variability of water properties including the influence of the vicinity glacier. The spring - summer measurements started on 14 May and lasted until late August. Data of water temperature and salinity were collected using the SBE 19plus CTD probe. Results from measurements along section H (from the head of the glacier to the fjord) were presented. Data showed that until June there were practically no changes in water salinity with small fluctuations of water temperature, especially in the upper 25 m, due to insolation. During this time a larger part of Hansbukta was filled with Winter-cooled water forming during winter. In July a rapid decrease of water parameters has been observed due to significant input of freshwater into the fjord. In late August, the region was characterized by a fully mixed water column filled with warm, saline water from the fjord.

One of the activities during the field session was using terrestrial laser scanning of the ice cliff of Hansbreen. Measurements were done with Optech ILRIS-LR scanner, deployed ca. 500 meters from the cliff on Baranowskiodden peninsula. Repeated scans allow for calculating the volume and size of individual calving events, this combined with time-lapse photogrammetry and continuous survey with a laser range finder provide complete monitoring of the calving activity of Hansbreen.

Polish Polar Station tour

The Polish Polar Station, Hornsund belongs to the Institute of Geophysics of the Polish Academy of Sciences. The station is situated on the northern shore of the Hornsund Fjord in the centre of the South Spitsbergen National Park (8504 km^2), Svalbard Archipelago. In 2002, the Polish station, together with the Hornsund Fjord was recognized as one of six the European Marine Biodiversity Flagship Sites (*http://www.iopan.gda.pl/projects/biodaff/*).

The Polish Polar Station was established in 1957, as a winter base during the 3rd International Geophysical Year 1957/1958. Today, the station is a modern research platform with access to well-equipped laboratories, satellite communication, and internet. Accommodation, washing, and cooking facilities for 20 visitors (in addition to the permanent staff of 10 persons) are in the same building. There is also a well-equipped workshop, a boat house, and storage for instruments and field equipment. The station lounge has a multimedia projector and is used for scientific seminars and conferences for up to 20 - 30 participants.

The research at the Polish Polar Station focuses on meteorology, glaciology, monitoring of geophysical fields (i.e. seismology, geomagnetism and atmospheric electricity), permafrost, and geomorphic processes. The main study objectives are related to the evolution of the high Arctic environment with respect to Climate Change. Projects include the research on mass and energy balance of glaciers, fluctuations and changes of their hydrothermal state, and dynamics of tidewater glaciers and their interaction with the ocean. Changes in marine and terrestrial ecosystems are systematically studied, including a strong ornithological component. Existing databases include meteorological and glaciological records (*http://www.glacio-topoclim.org*), geophysical data (collected in several world data centers), as well as marine and terrestrial biological parameters.

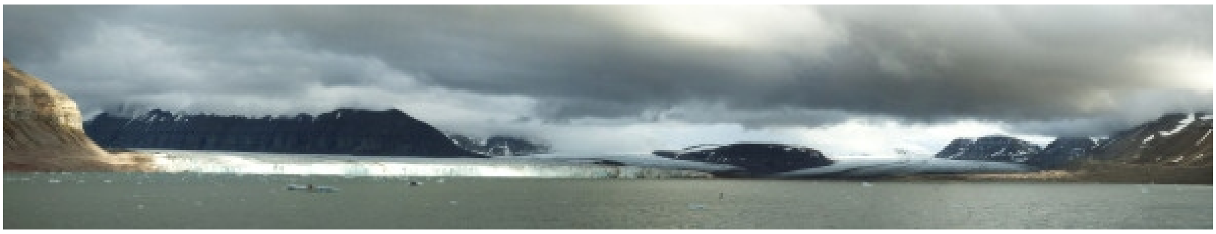
Polish Polar Station, Hornsund, S Spitsbergen (Photo by D. Ignatiuk)

An introduction to Nordenskiöldbreen / Lomonosovfonna

This presentation was intended to give an introduction to the ice field trip. The background of the present activities on Nordenskiöldbreen and Lomonosovfonna is activities performed since 1997, primarily in accordance to ice core expeditions. Since 2006 a mass-balance and ice speed monitoring project was initiated, and 2009 an AWS was installed. An introduction to use GPS at glaciological field work was done by V. Pohjola.

This lecture is an introduction in GPS theory and instrumentation with the aim to make different issues of GPS instrumentation more clear, and to give guidelines of how to maximize the performance of this technical platform. Results from use of the low-cost single frequency GPS receivers system deployed on Nordenskiöldbreen were presented (den Ouden *et al*. 2010).

Tunabreen in Tempelfjorden was visited by the workshop participants under guidance of D. Benn. Mechanisms of calving processes were discussed directly in the field.



Tunabreen and Van Postbreen in Tempelfjorden (Photo by T. Schellenberger)

Workshop venue onboard the *Horyzont II*

HORYZONT II is Gdynia Maritime University (GMU) oceanographic training and research vessel of 56.34 m length and 11.36 m breadth. Vessel is designed to allow for conducting internal GMU scientific programs, as well as various sea research projects during its regular voyages. *HORYZONT II* has obtained the ice class, which allows it to perform its regular cruises to West Spitsbergen in the Arctic Ocean. The purpose of these voyages is to supply the provisions and equipment to Polish research polar stations and at the same time to train on-board the students of Gdynia Maritime University. Thanks to the multiplied training stands on the bridge, spacious engine control room and on-board lecture class-room the vessel allows for conducting on-board all types of marine training for both GMU and external students. The vessel is capable of transporting two 20' feet containers; the containers may be used also as portable research laboratories. Thanks to high standard of accommodation spaces, spacious mess room and club on-board *HORYZONT II* may be used for tourist escapades, depending on the availability of free accommodation. The max. number of crew is 57 persons, including 16 of permanent crew (*http://www.navimor.pl/horyz/*).

Jenny Baeseman

r/v Horyzont II near the front of Hans Glacier (Photo from the Archive of Instytute of Geophysics, PAS)

References

AMUNDSON J.M. *et al*. 2010: Ice mélange dynamics and implications for terminus stability, Jakobshavn Isbrae, Greenland. *J. Geophys. Res.*, *115*, F01005, doi:10.1029/2009JF001405.

CHRISTOFFERSEN P. *et al*. 2011: Warming of waters in an East Greenland fjord prior to glacier retreat: mechanisms and connection to large-scale atmospheric conditions. *The Cryosphere*, *5*, 701 - 714.

GRABIEC M. *et al*. 2012: Surface and bed morphology of Hansbreen, a tidewater glacier in Spitsbergen. *Polish Polar Research*, *33*, 2, 111 - 138.

HOLLAND D.M. *et al*. 2008: Acceleration of Jakobshavn Isbræ triggered by warm subsurface ocean waters. *Nature Geosci.*, *1*, 10, 659 - 664.

HOWAT I.M. *et al*. 2007: Rapid changes in ice discharge from Greenland outlet glaciers. *Science*, *315*, 5818, 1559 - 1561, doi: 1510.1126/science.1138478.

HOWAT I.M., Joughin I., Fahnestock M., Smith B.E. and Scambos T.A. 2008: Synchronous retreat and acceleration of southeast Greenland outlet glaciers 2000 - 2006: ice dynamics and coupling to climate. *J. Glaciol.*, *54*, 646 - 660.

HOWAT I.M. *et al*. 2010: Seasonal variability in the dynamics of marine-terminating outlet glaciers in Greenland. *J. Glaciol.*, *56*, 198, 601 - 613.

IPCC 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 [Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M. and Miller H.L. (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

JOUGHIN I. and Alley R.B. 2011: Stability of the West Antarctic ice sheet in a warming world. *Nature Geosci.*, *4*, 506 - 513.

JOUGHIN I. *et al*. 2008: Seasonal speedup along the western flank of the Greenland ice sheet. *Science*, *320*, 781 - 783, doi:10.1126/science.1153288.

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

McFADDEN E.M., Howat I.M., Joughin I., Smith B.E. and Ahn Y. 2011: Changes in the dynamics of marine terminating outlet glaciers in west Greenland (2000 - 2009). *J. Geophys. Res.*, *116*, F02022, doi:10.1029/2010JF001757.

MEIER M.F. *et al*. 2007: Glaciers dominate eustatic sea-level rise in the 21st century. *Science*, *317*, 5841, 1064 - 1067, doi:10.1126/science.1143906.

MOON T. and Joughin I. 2008: Changes in ice front position on Greenland's outlet glaciers from 1992 to 2007. *J. Geophys. Res.*, *113*, F02022, doi:10.1029/2007JF000927.

MOON T. *et al*. 2012: 21st-century evolution of Greenland outlet glacier velocities. *Science*, *336*, 576 - 578.

MOTYKA R.J. *et al*. 2011: Submarine melting of the 1985 Jakobshavn Isbrae floating tongue and the triggering of the current retreat. *J. Geophys. Res.*, *116*, F01007, doi:10.1029/2009JF001632.

NICK F.M. *et al*. 2009: Large-scale changes in Greenland outlet glacier dynamics triggered at the terminus. *Nature Geosci.*, *2*, 110 - 114.

O'NEEL S. *et al*. 2005: Evolving force balance at Columbia Glacier, Alaska, during its rapid retreat. J. Geophys. Res., 110, F03012, doi:10.1029/2005JF000292.

den OUDEN M.A.G., Reijmer C.H., Pohjola V., van de Wal R.S.W., Oerlemans J. and Boot W. 2010: Stand-alone single-frequency GPS ice velocity observations on Nordenskiöldbreen, Svalbard. *The Cryosphere*, doi:10.5194/tc-4-593-2010.

PFEFFER T. 2007: A simple mechanism for irreversible tidewater glacier retreat. *J. Geophys. Res.*, *112*, F03S25, doi:10.1029/2006JF000590.

PRITCHARD H.D. and Vaughan D.G. 2007: Widespread acceleration of tidewater glaciers on the Antarctic Peninsula. *J. Geophys. Res.*, *112*, F03S29, doi:10.1029/2006JF000597.

PRITCHARD H.M., Arthern R.J., Vaughan D.G. and Edwards L.A. 2009: Extensive dynamic thinning of the margins of the Greenland and Antarctic ice sheets. *Nature*, *461*, 971 - 975.

RIGNOT E. and Kanagaratnam P. 2006: Changes in the velocity structure of the Greenland ice sheet. *Science*, *311*, 986 - 990, doi:10.1126/science.1121381.

RIGNOT E. *et al*. 2011: Acceleration of the contribution of the Greenland and Antarctic ice sheets to sea level rise. *Geophys. Res. Lett.*, *38*, L05503, doi:10.1029/2011GL046583.

SCHOOF C. 2007: Ice sheet grounding line dynamics: Steady states, stability, and hysteresis. *J. Geophys. Res.*, *112*, F03S28, doi:10.1029/2006JF000664.

SUNDAL A.V. *et al*. 2011: Melt-induced speed-up of Greenland ice sheet offset by efficient subglacial drainage. *Nature*, *469*, 521 - 524, doi:10.1038/nature09740.

van den Broeke M. *et al*. 2009: Partitioning Recent Greenland Mass Loss. *Science*, *326*, 5955, 984 - 986.

WALCZOWSKI W. and Piechura J. 2007: *Pathways of the Greenland Sea warming. Geophys. Res. Lett.*, *34*, L10608, doi:10.1029/2007GL029974.

WALTER F. *et al*. 2010: Iceberg calving during transition from grounded to floating ice: Columbia Glacier, Alaska. *Geophys. Res. Lett.*, *37*, L15501,doi:10.1029/2010GL043201.

ZWALLY H.J. *et al*. 2002: Surface melt-induced acceleration of Greenland ice-sheet flow. *Science*, *297*, 218 - 222.

Acknowledgements

Organizers wish to acknowledge with gratitude financial support by the IASC Cryosphere Working Group for participation of early career scientists. The same thanks are directed to the Institute of Geophysics, Polish Academy of Sciences for covering a part of the ship's charter cost. Contributions of University of Silesia, University of Oslo and UNIS - The University Centre in Svalbard, Polish Polar Station, Hornsund are greatly appreciated. Special thanks are directed to Captain and crew of r/v *Horyzont II* and staff of the Polish station for logistic support and hospitality. Similar thanks are going to Jenny Baeseman for assistance in documentation of the workshop and providing outreach site on the CliC platform (*http://www.climate-cryosphere.org/index.php/albums/twg-2012?limitstart=0&display=list*).

Enclosure

Examples of brief description of key glaciers that could be Special Study Sites

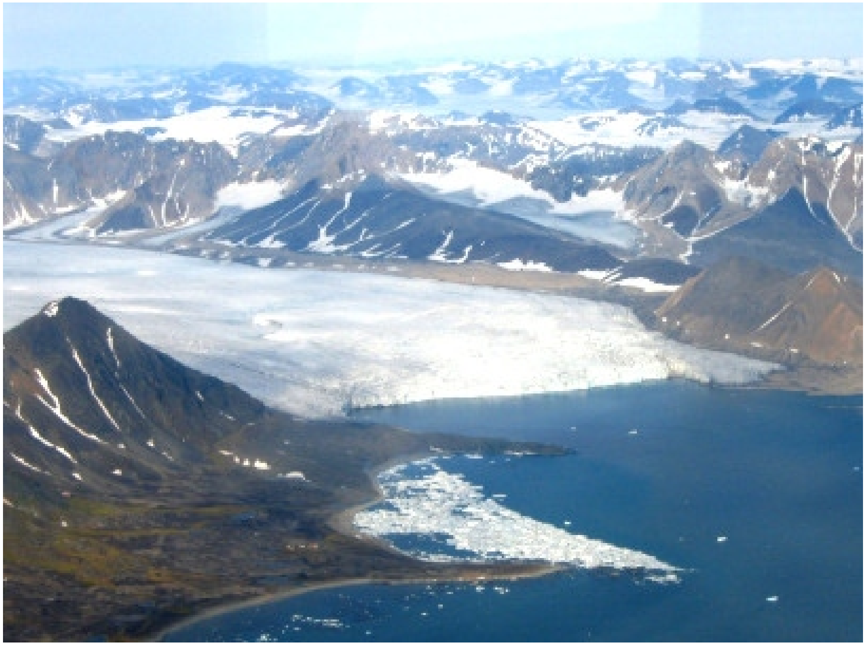
The variety in the size and type of tidewater glaciers in the Circum-Arctic area is large. Glaciers differ by morphology, thermal structure, dynamics and climatic / environmental setting. The majority of the glaciers are inaccessible for direct field studies because of safety or logistic difficulties. Only approximately two dozen tidewater glaciers have long (multi-year to decadal) data sets or are currently monitored. For a more precise estimation of the calving glacier contribution to sea level rise and a better understanding of the processes governing iceberg production, a set of key glaciers in different geographic regions with robust datasets must be compiled. One can designate these glaciers as Special Study Sites (SSS). Several criteria for selection are:

1) Existence of monitoring systems with multi-year records;
2) Relatively easy access and/or not expensive logistics for continued study;
3) Location in different climatic regions and environmental settings.

SVALBARD

Hansbreen

Glacier Name: Hansbreen
Location: Svalbard, Southern Spitsbergen (77°05'N 15°38'E)
Adjacent water body: Greenland Sea, Hornsund Fiord
Glacier area: Approximately 15 km in length, 2 - 4 km wide
Glacier type: Medium sized grounded polythermal glacier with ca. 4 km-wide tongue and 1.5 km-wide active calving front.



Hansbreen - frontal part. Buildings of the Polish Polar Station are visible.
Photo by courtesy of SLICES Project (Swansea Glaciology Group, Swansea University, 2004)

Brief description of environmental setting: Polar climate (Polish Polar Station) with annual average temperature -4.1ºC and 430 mm average annual precipitation. The mean annual surface mass balance measured on 11 stakes is -0,28 m w.e. for the 23 year period (from 1989 to 2011). Calculations of calving flux for the period 2000 - 2008 show a volume of ca. 25.5 x 10^{6} m^{3} of lost icebergs annually, making ca. -0.41 m yr^{-1} (w.e.) contribution to the overall mass loss (Grabiec *et al.* 2012).

Logistic conditions for field studies: Hans Glacier is located ca. 2 km from the S. Siedlecki Polish Polar Station. The Polish Polar Station has been in operation year-round since 1978. The station is a modern research platform with access to well-equipped laboratories, satellite communication and internet. During the summer season, the station can be reached by ships or yachts. Flights by helicopter may be used all year-round. The trip by ship from Longyearbyen (the capital of Svalbard) to Hornsund takes 12 - 24 hours and by helicopter ca. 1 hour. In winter and spring, Hornsund can be reached by snow scooters (ca. 180 km), if two fjords between Longyearbyen and the station have stable and thick enough sea ice cover.

Ongoing field research / monitoring or available data sets:

The ground-based radar soundings (GPR) have been conducted in 1989, 1997 - 1998, and from 2008 until now. The elevation of the glacier surface, in a badly crevassed region near the terminus of the glacier, was surveyed by terrestrial laser scanning in 2009 and 2012. Mass balance and dynamics are measured on 11 stakes since 1988. Permanent station for flow velocity measurements with Leica 1230 GPS receiver (located about 4 km upstream of the terminus) has been maintained since 2005. Measurements of meteorological components and glacier ablation (SR 50) are collected by three AWS in ablation zone, accumulation zone and near ELA. Permanent WMO standard meteorological station is in operation close to the Polish Polar Station. Two time laps cameras were used to permanent observations of frontal part of glacier in years 2007 - 2010. Since 2010, one camera has been recording frontal part of glacier and second camera the calving front horizontally. Automatic station for monitoring of the glacier cliff equipped with long range scanner Riegl LPM-321 and a Garmin GMR 18HD panoramic radar has been worked from the end of summer 2009. Marine gauge station for monitoring of sea level changes due to tides and storm waves has been installed in summer 2011 and 2012. Oceanographic mooring has been deployed in the fiord in 2010 - 2012. Multibeam echo sounding of the seabed in front of Hans Glacier has been done.

Dariusz Ignatiuk

Hansbreen at the begining of the springtime (Photo by T. Budzik)

CANADIAN ARCTIC

Devon Island - Belcher Glacier

Glacier Name: Belcher Glacier
Location: Northeast Devon Ice Cap, Devon Island, Nunavut, Canada; 75°40'50" N, 81°21'20" W
Adjacent Water Body: Jones Sound, Baffin Bay
Glacier Area: ~ 188 km^2 (valley glacier), 40 km long (valley glacier) - 47 km from ice divide, 2.8 km to 4.7 km wide (valley glacier), drains an area of ~718 km^2
Glacier Type: 40 km long outlet glacier fed from Devon ice cap at its head and by nine lateral tributaries; 4.25 km wide terminus formed by 2 flow units - the more northerly is nearly stagnant, but the more southerly (2.5 km wide) is flowing at ca 300 m/yr. Terminus is mostly grounded below sea level, but local flotation likely as mean terminus thickness = 217 m (maximum = ~300 m), but average terminus water depth is 220 m. Bed is continuously below sea level for 10 km upglacier from terminus, and intermittently below sea level for a further 10 - 14 km.

Terminus of Belcher Glacier in May 2011, showing the region of active calving and mélange development, and folded and faulted sea ice in front of the glacier (Photo by M. Sharp)

Brief Description of Environmental Setting:
Devon Island is a cold, high-latitude desert; annual precipitation is <200 mm and annual mean air temperature is well below 0°C. The Devon Ice Cap covers 14,400 km^2 of the eastern side of island. The central ice cap summit reaches >1900 m a.s.l.; much of the western margin terminates on a rocky plateau at ~600 m a.s.l., while along the fjord-incised north, east, and southern margins, outlet glaciers reach sea level. The Belcher Glacier flows towards the Northeast margin of the ice cap, facing Baffin Bay and the North Open Water polynya, which contributes to frequent foggy conditions in this region. Accumulation on the Devon Ice Cap is negatively correlated with distance from the polynya; the southeast margin of the icecap may receive up to ~50 cm w.e., but the northern area around the Belcher Glacier receives considerably less. Between 2008 and 2010, mean annual accumulation in the part of the glacier below 1000 m a.s.l. was ~10 cm w.e. Mean annual ablation across the same zone in the same time period was ~100 cm w.e., which demonstrates the strong control of warm summer air temperatures on this glacier's surface mass balance.
Logistic Conditions for Field Studies: Accessible by snowmobile from University of Alberta / GSC

base camp on summit of Devon Ice Cap; base camp is reached from Resolute Bay by Twin Otter on skis, making spring (pre-melt) fieldwork most feasible; has been accessed from the sea by boat (Amundsen and a small sailing vessel), and a zodiac has been operated in the fjord in summer. Helicopter access required to work on terminus region of glacier, and to access viewpoints on cliffs on south side of terminus. Most cliff tops along west side of the glacier, and some on east side, are accessible by snowmobile. Fly camps are possible on main glacier to within ca 5 km of terminus, and a camp has been maintained on moraine within 1 km of terminus, but Polar Bears are an issue there in late summer. It is possible to walk around on the glacier near the terminus, albeit slowly.

Ongoing field research / monitoring; available datasets

- Work on glacier began during IPY as part of GlacioDyn project;
- Sea floor topography (2006) in front of glacier has been mapped using swath bathymetry (conducted by the CCGS Amundsen);
- CTD profiles have been measured in fjord in front of the glacier in 3 different years (2006, 2008, 2011) - always late in the melt season;
- Tide-gauge validated model simulations (Webtide) of tidal variations at terminus;
- Some ground-based radio echo sounding measurements in upper part of basin and some tributaries;
- 3 sets of centerline ice thickness profiles from airborne radar (SPRI April 2000, UKansas 7 May 2005, NASA MCORDS 4 May 2012), and 2 cross profiles in terminus region (May 2005 and 2012);
- 3 sets of airborne laser altimeter surface profiles (NASA ATM May 2005 and 4 May 2012, DTU 3 May 2012);
- Annual surface elevation change measured from 4 sets of repeat ground based kinematic GPS surface elevation profiles (2009 - 2012) along glacier centerline from 5 to 34 km upglacier from terminus. Relative contribution of dynamic thinning / thickening and surface mass balance to observed thinning assessed;
- Aerial photography from 1960; SPOT SPIRIT DEM (August 2007); high resolution summer imagery from Digital Globe since 2011;
- Annual LandSat7 imagery from 1999 - 2012;
- 2 full mappings of surface velocity field using radar interferometry and/or speckle tracking (February 1992 via ERS1/2 InSAR, October - December 2000 via RadarSat1 speckle tracking (terminus region only, March 2009 via RadarSat2 speckle tracking);
- Full annual surface velocity field measurements for 1999 - 2011 from gradient correlation methods applied to LS7 imagery - used (along with annual measurements of terminus position change from Ls7 imagery) to estimate annual calving fluxes from glacier;
- Annual ice displacement measurements via repeat DGPS survey at 16 points along the glacier centerline, 15 points at 3 cross-glacier transects, and 11 points at mergers with tributaries (2008 - 2010);
- Continuous GPS measurements of centerline ice velocity for the complete May - August period (2008 - 2010) at positions 1 km, 20 km, and 30 km up-glacier of the terminus. Additional GPS units added at 8 km and 13 km along the centerline in 2009 and 2010. Incomplete and lower temporal resolution data for early spring (March - April) and fall (September - November) also available from these sites;
- Time-lapse camera observations of supraglacial lake filling / drainage events at 3 - 5 sites (May - August 2007 - 2009). Additional 1 - 2 Time lapse cameras used at glacier marine terminus to observe iceberg calving, meltwater plume, and sea ice interaction (2007 - 2009). Currently operating 5 - 6 time-lapse cameras at glacier terminus (2012 - present);
- Continuously recoding geophone / seismic / audio instruments (2009 and 2012/13):
  - local hydro-fracturing events identified by 3 sets of continuously recording 2 two-component geophones installed 5 m into the ice at distances of 0.4 km, 2 km, and 6.6 km from terminus (2009) and 0.5, 2.25, 3.0 km from terminus (2012 - present);
  - 1 year of data (2012/13) from two continuously recording seismic stations installed 5 m into the ice; 1 located 600 m from terminus along the centerline (fast moving ice) and 1 located 400 m from

the terminus adjacent to cliff / sidewall centerline (slow moving ice);
- 2 years of data (2009 and 2012/13) from a continuously recording audio device located 400 m from the terminus;
- Inventory of supraglacial lakes in catchment, setting of formation, mode of drainage; year-to-year changes in lake extent and timing of drainage;
- Mapping of supraglacial meltwater drainage system, sub-catchment structure, and distribution of crevasses;
- Meteorological data from 2 automatic weather stations (2008 - 2010) and 7 Hobo air temperature monitoring stations (2008 to present);
- Monte-Carlo temperature Index model simulations of annual surface mass balance 1960 - 2012;
- Energy Balance model simulations of annual surface mass balance for 2007 - 2008;
- GPR measurements of snow water equivalent distribution in accumulation area, spring 2008;
- Point measurements of spring snow depth and density, and summer ablation at 8 -10 sites along glacier centerline in ablation area, 2008 - 2010.

Researchers
Martin Sharp, Bradley Danielson, James Davis, Angus Duncan, Gabrielle Gascon, Jeff Kavanaugh, Hannah Milne, Colleen Mortimer, Ian Scriver, Faye Wyatt, University of Alberta
Sarah Boon, University of Lethbridge
Alex Gardner, Clark University
David Burgess, Wesley van Wychen, Natural Resources Canada
Luke Copland, Tyler Sylvestre, University of Ottawa
Lev Tarasov, Memorial University of Newfoundland

Milne Glacier

Glacier Name: Milne Glacier
Location: Canadian Arctic, Canadian Arctic Archipelago, Ellesmere Island, British Empire Range, Milne Fiord (82°44'N 81°45'W)
Adjacent water body: Arctic Ocean
Glacier area: Approximately 55 km in length, 4 - 5 km wide
Glacier type: Surge-type glacier with ~8 km long floating glacier tongue and the separate Milne Ice Shelf at mouth of the fiord. Perennially ice covered fiord with minimal calving activity at present.

Milne Glacier, Ellesmere Island seen upstream from the calving front (Photo by D. Mueller, 2012)

Brief description of environmental setting: Polar climate with annual average temperature -18ºC and between 75 -150 cm annual precipitation. The Milne Ice Shelf thinned on average 0.26 ± 0.09 m w.e. yr^{-1} from 1981 to 2009 (Mortimer *et al*. 2012). Regional mass balance estimates suggest a negative mass balance for Milne Glacier as well but this has not been validated with *in situ* measurements.
Logistic conditions for field studies: Remote field camp setting with minimal camp infrastructure, requires self-supported field logistics. Access by Twin Otter or helicopter from Resolute Bay via Eureka (~300 km south).

Ongoing field research / monitoring or available data sets: Extensive GPR thickness surveys of the Milne Ice Shelf have been conducted since 2008 and a met station and ablation stake network installed. Milne Glacier has a minimal surface mass balance network at present. A through-ice oceanographic mooring has been deployed in the fiord since 2011 with twice yearly CTD profile surveys along the fiord. The ongoing research program includes GPR surveys, ablation stakes, a network of automated surface mass balance and temperature recorders, automated weather station, oceanographic mooring (conductivity / temperature), and CTD profiles.
Additional comments: Milne Fiord is the site of the last intact ice shelf and epishelf lake (ice dammed lake) and glacier tongue on northern Ellesmere Island. Although access is logistically intensive, Milne Fiord has not undergone the dramatic calving events of adjacent ice shelves or glacier tongues, and so provides an opportunity to study the evolution of the system from an undisturbed state to predicted widespread breakup and calving in the near future.

Andrew Hamilton

Other SSS candidate glaciers

Svalbard: Kronebreen, Nordenskiöldbreen

Greenland: Jakobshavn Isbræ (Sermeq Kujalleq), Helheim Glacier

Canadian Arctic: Ward Hunt Ice Shelf

Alaska: Columbia Glacier

Iceland: Breiðamerkurjökull

RUSSIAN ARCTIC, Novaya Zemlya

Inostrantseva Glacier

Glacier Name: Inostrantseva Glacier
Location: Russian Arctic, Novaya Zemlya lat: 76.4800 lon: 66.4500
Glacier area: 186.9 km^2
Glacier type: type 4 WGMS, outlet glacier, grounded or semi-grounded (?)
Brief description of environmental setting: major outlet glacier draining the Northern Ice Cap on Novaya Zemlya. Annual precipitation - ca 400 mm, T sea level +2 °C (July) -18 °C (January) No data on mass balance, ELA = ca. 300 m
Logistic conditions for field studies: polar station at Cape Zhelaniya might be re-opened.

An oblique aerial photo of the frontal part of Inostrantseva Glacier, Novaya Zemlya (Photo by A.F. Glazovsky)

Pavlova Glacier

Glacier Name: Pavlova Glacier
Location: Russian Arctic, Novaya Zemlya + lat: 76.5800 lon: 66.2000
Glacier area: 84.3 km^2
Glacier type: type 4 WGMS, outlet glacier, grounded
Brief description of environmental setting: outlet glacier with visible changes of calving front position (sussspected as slow surging or better say kind of unstable behavior). Annual precipitation - ca. 400 mm, T sea level +2 °C (July) -18 °C (January). No data on mass balance, ELA = ca. 300 m
Logistic conditions for field studies: polar station at Cape Zhelaniya might be re-opened.

Andrey F. Glazovsky

An oblique aerial photo of the frontal part of Pavlova Glacier, Novaya Zemlya (Photo by A.F. Glazovsky)

Appendix 1. Tidewater Glacier Workshop Agenda
(as originally planned)

26 August 2012 - Sunday

15:00 Lunch in the University Centre in Svalbard (UNIS), Longyearbyen

15:30 - 18:00 Welcome and introductory session (UNIS)

“*Recent advances in studies of tidewater glaciers”.* Co-Chairs: Doug Benn, Jon Ove Hagen

Welcome

J.O. Hagen - *Calving and tidewater glaciers - an introduction*

T. Pfeffer - *The Role of Tidewater Glacier in Sea Level Rise: Accounting for Ice Dynamics in the IPCC's 5th Assessment*

D. Benn - *Glacier calving models: progress and prospects*

J. Baseman - *Education and outreach issues*

P. Głowacki - *Practical and security information*

18:00 Transfer to the r/v *Horyzont II*

19:00 Dinner

27 August - Monday

8:00 Breakfast

9:00 Transfer to Hans Glacier by Zodiacs [Changed to Brepollen and Storbreen field trip]

9:30 - 12:30* 1st field and training session on Hansbreen: “*Time lapse cameras and terrestrial photogrammetry, laser distance meter, terrestrial laser scanner, GPR-tentative”*

(J.A. Jania, M. Pętlicki, D. Ignatiuk, M. Błaszczyk, A. Promińska, M. Moskalik and others)

12:30 - 13:15 Walk to the Polish Polar Station

13:15 Lunch in the Station

15:00 - 18:30* Scientific session: “*Methods and techniques in monitoring of tidewater glaciers”*. Co-Chairs: Tad Pfeffer, Piotr Głowacki (at the Polish Polar Station, Hornsund)

Welcome to the Polish Station

J.A. Jania and P. Głowacki - *Monitoring system of Hans Glacier. Main results and prospect*

T. Pfeffer - *Special Methods for Observing of Tidewater Glacier Dynamics*

C. Nuth - *Observing the Kronebreen glacier system from the ground, by air and space, and through seismic waves*

A. Hamilton - *Diving under thick ice: investigations of glacier ice-ocean interactions using an autonomous underwater vehicle (AUV)*

C. Mortimer - *Investigating calving dynamics from field and remote sensing data: a field-based program for the Belcher Glacier, Devon Island, Canada, 2011 and beyond*

V. Pohjola - *GPS theory and some hints on the practical use in glaciated areas*

P. Sharma - *Comparative study of mass budget: a case study of Chhota Shigri and Patsio glacier, Chandra and Bhaga basin, Himachal Pradesh, India*

18:30 Trip back to the ship by Zodiacs

19:00 Dinner

28 August - Tuesday

8:00 Breakfast

9:00 - 13:00* 2nd field and training session Hornsund, Brepollen onboard with potential landing: “*Remote sensing methods vs. real glaciers, geomorphic evidence of surge, multibeam echo sounding of the sea bed, oceanographic equipment”*

(M. Błaszczyk, J.A. Jania and others; P. Głowacki, M. Moskalik, A. Promińska and others)

[Changed to Hansbreen field session and visit to the Polish Polar Station]

13:00 Lunch

15:00 - 18:00* Scientific session: *"Application of remote sensing to studies of tidewater glaciers"* (on board). Co-Chairs: Gordon Hamilton, Luke Copland

M. Błaszczyk - *Estimation of calving from Svalbard tidewater glaciers based upon satellite remote sensing*

T. Shellenberger - *Calving flux of Svalbards tidewater glaciers estimated from remote sensing based surface velocities and terminus position changes*

G. Hamilton - *Designing an ideal glacier-ocean observing system: some consideration of the in-situ, near-situ and remote sensing components*

K. Schild - *The timing between rapid supra-glacial lake drainages on Greenland Ice Sheet and the appearance of a meltwater sediment plume at the glacier terminus - the Rink Isbrae case*

L. Copland - *The Causes and Patterns of Calving Events from Arctic Ice Shelves and Tidewater Glaciers*

19:00 Dinner

29 August - Wednesday

8:00 Breakfast

9:00 - 12:30* 3nd field and training session with cruise to the inner part of the Kongsfjorden and landing *(tentative)* (D. Benn, C. Nuth and others)

13:00 Lunch on board / Lunch in the dining hall (Messa) of the Kings Bay Service Center

14:30 Walk to the Norwegian Station in Ny Aalesund

15:00 - 18:00* Scientific session: *"Requests of modellers to field observers of tidewater glaciers".* Co-Chairs: Faezeh Nick, Andreas Vieli

Welcome to Ny Aalesund

F.M. Nick - *A simple calving model*

M. Schäfer - *Remote sensing data used on Svalbard glaciers to infer basal drag pattern from surface velocities with a Full-Stokes ice-sheet model*

C. Borstad - *Constrains provided by remote sensing data for a new calving law based on continuum damage mechanics*

E. Enderlin - *Do variations in outlet width influence dynamic sensitivity?*

N. Barrand - *Volume projections on the Antarctic Peninsula ice sheet and outlet glaciers for the next 100 years*

A. Vieli - *Modelling tidewater glaciers: challenges, issues and data requirements*

19:00 Dinner

30 August - Thursday

8:00 Breakfast

9:00 - 12.00* 4th field and training session Nordenskioldbreen, Billefjorden on board with potential landing: "*Time lapse GPS single and dual frequency*, automatic weather stations" (V. Pohjola and others) [Changed to field trip to Tunabreen in Tempelfiorden]

13:00 Lunch

15:00 - 18:30* Scientific session (on board): "*Challenges and gaps in studies of Arctic tidewater glaciers"*. Co-Chairs: Veijo Pohjola, Jacek A. Jania

T. Dunse - *Surge initiation or meltwater induced acceleration? Observations of a marine-terminating outlet glacier and its implication on the mass balance of Austfonna, Svalbard*

V. Pohjola - *Glaciological work on Nordenskiöldbreen/Lomonosovfonna since 1997*

A. Hamilton - *Fjord dynamics and glacio-marine interactions on Northern Ellesmere Island, Canada*

W. VanWychen - *Dynamics of Ice Caps and Tidewater Glaciers in the Canadian Arctic*

Y. Drocourt - *Calving front dynamic changes, data visualization and controls*

D. Benn - *Towards modeling the hydrology of tidewater glaciers*

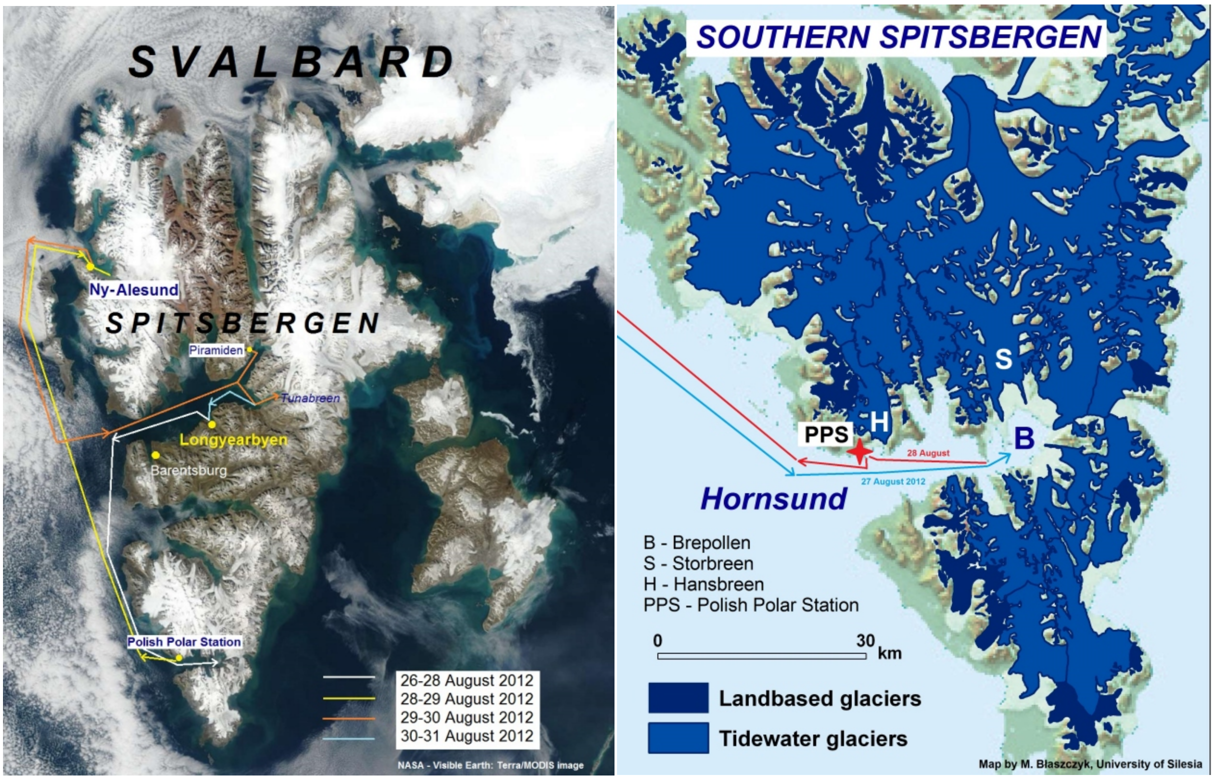
General discussion

19:00 Dinner

31 August - Friday
8:00 Breakfast
9:00 Disembarkation in Longyearbyen and transfer by bus to UNIS
10:00 - 12:00 AM "*Summary session*". Moderators: Jenny Baeseman, Jon Ove Hagen
Panel discussion
12:00 Lunch in the UNIS Cafeteria
12:45 Bus transfer to the airport
---
*Due to variable sea / ice / weather conditions time of particular sessions might be changed

Note: The majority of workshop presentations and photo gallery is available at the CliC project web site *http://www.climate-cryosphere.org/index.php/albums/twg-2012* thanks to kind hosting by Jenny Baeseman.

Workshop cruise itinerary



Appendix 2. Participant List

Early Career Scientists

Nicholas Berrand, British Antarctic Survey, UK (*nirr1@bas.ac.uk*)
Christopher Borstad, Jet Propulsion Laboratory, US (*christopher.p.borstad@jpl.nasa.gov*)
Yoann Drocourt, Svansea University, France / UK (*ydrocourt@gmail.com*)
Thorben Dunse, University of Oslo, Norway (*thorben.dunse@geo.uio.no*)
Ellyn Enderlin, Ohio State University, US (*ellyn.enderlin@gmail.com*)
Andrew Hamilton, University of British Columbia, Canada (*andrew@madzu.com*)
Colleen Mortimer, University of Alberta, Canada (*colleen.mortimer@ualberta.ca*)
Christopher Nuth, University of Oslo, Norway (*christopher.nuth@geo.uio.no*)
Martina Schäfer, University of Lapland, Germany / Finland (*martina.schafer@ulapland.fi*)
Kristin Schild, Dartmouth College, US (*kristin.m.schild.gr@dartmouth.edu*)
Parmanand Sharma, National Centre for Antarctic and Ocean Research, India (*pnsjnu@gmail.com*)
Thomas Shellenberger, University of Oslo, Germany / Norway (*thomas.schellenberger@geo.uio.no*)
Wesley VanWychen, University of Ottawa, Canada (*wesley.vanwychen@gmail.com*)

Senior Researchers

Doug Benn, University Centre in Svalbard, UK / Norway (*doug.benn@unis.no*)
Luke Copland, University of Ottawa, Canada (*luke.copland@uottawa.ca*)
Piotr Głowacki, Institute of Geophysics, Polish Academy of Sciences, Poland (*glowacki@igf.edu.pl*)
Jon Ove Hagen, University of Oslo, Norway (*j.o.m.hagen@geo.uio.no*)
Gordon Hamilton, University of Maine, US (*gordon.hamilton@maine.edu*)
Jacek A. Jania, University of Silesia, Poland (*jacek.jania@us.edu.pl*)
Faezeh Nick, Université Libre de Bruxelles, Belgium (*faezeh.nick@gmail.com*)
Tad Pfeffer, University of Colorado, US (*wtpfeffer@gmail.com*)
Veijo Pohjola, University of Uppsala, Sweden (*veijo.pohjola@geo.uu.se*)
Andreas Vieli, Durham University, Switzerland (*andreas.vieli@durham.ac.uk*)

Assistants and Field Hands

Jenny Baeseman, Climate and Cryosphere (CliC), US / Norway (*jbaeseman@gmail.com*)
Dariusz Ignatiuk, Institute of Geophysics, Polish Academy of Sciences / University of Silesia, Poland (*dignatiuk@gmail.com*)
Małgorzata Błaszczyk, University of Silesia, Poland (*mbl4@wp.pl*)
Mateusz Moskalik, Institute of Geophysics, Polish Academy of Sciences, Poland (*mmosk@igf.edu.pl*)
Michał Pętlicki, Centre for Advanced Studies in Arid Zones, Chile, Poland / Chile (*michal.petlicki@ceaza.cl*)
Agnieszka Promińska, Institute of Oceanology, Polish Academy of Sciences, Poland (*agnieszka.promyk@gmail.com*)

Participants and Field Assistants near front of Hansbreen, Hornsund (Photo by B. Laskowska)

Attendees of the Workshop head out for a glacier field excursion in Svalbard by Zodiac
(Photo by A. Hamilton)

ISBN: 978-3-9813637-5-3