IASC Workshop on the dynamics and mass budget of Arctic glaciers

Abstracts and Programme

IASC Workshop, 25-27 January 2016
Benasque (Spain)

IASC Network on Arctic Glaciology

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IASC Workshop &
Network on Arctic Glaciology annual meeting,
25-27 January 2016, Benasque (Spain)

Organised by C.H. Tijm-Reijmer, F. Navarro and M. Sharp

Local organizing committee:
F. Navarro (Chair), E. de Andrés (Secretary), C. Recio-Blitz, J. Lapazaran, J. Otero

IASC Network on Arctic Glaciology

Cover photo: Nordenskiöldbreen 2011. Photo by A. Waxegard.

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Preface

The 2016 annual workshop and open forum meeting of the IASC Network on Arctic Glaciology took place in the charming Pyrenean village of Benasque, Spain. The meeting attracted 45 participants from all over the world. The IASC Cryosphere Working Group generously supported eleven young scientists to attend the meeting. The participants presented cutting edge science in 30 talks and 8 posters. The open forum meeting provided many ideas to initiate as a community. An overview of the meeting, especially abstracts of the presented work, can be found in this book.

The activities were, as always, not limited to the conference room, but extended to the skiing slopes of Cerler, a ski resort a few km from the conference facility in Benasque. On the slopes and afterwards, the discussions related to, amongst others, science and fieldwork continued resulting in once again a succesful and informal event.

I would like to thank the local organising committee; Francisco Navaro, Eva de Andrés, Cayetana Recio-Blitz, Javier Lapazaran and Jaime Otero for the excellent organisation. Furthermore, since this is the last time I write this preface as the chair of this Network, I would also like to thank Martin Sharp. Martin, I really enjoyed working with you. And finally I wish Thorben Dunse succes as my successor as chair of the IASC Network on Arctic Glaciology.

Next year the meeting will take place in Maine, USA, and I hope to meet you all there.

Carleen Tijm-Reijmer
July 2016

Program

The meeting took place in Gran Hotel Benasque, Benasque, Spain.

Sunday 24 January

ARRIVAL

20:30 - 22:30	**Dinner**

Monday 25 January

08:30 - 09:00	**Registration**
Convener:	*Ward van Pelt*
09:00 - 09:10	Welcome *C.H. Reijmer*
09:10 - 09:40	**Keynote lecture:** Global-scale glacier modeling - Challenges and recent progress ***Regine Hock***
09:40 - 10:00	Dramatic mass loss of Svalbard land-terminating glaciers by the end of the 21st century under an RCP 8.5 scenario *M. Möller, **Francisco Navarro**, A. Martín-Español*
10:00 - 10:20	Investigating Svalbard's climate using a regional climate model ***Stan Jakobs**, W.J. van de Berg, M.R. van den Broeke, E. van Meijgaard, B. van Ulft*
10:20 - 10:40	Mass balance measurements on the Austfonna Ice Cap, Svalbard 2004-2013 ***Jon Ove Hagen**, T. Dunse, T. Eiken, J. Kohler, G. Moholdt, T.V. Schuler, T. Østby, C. Reijmer*
10:40 - 11:10	**Coffee break**
Convener:	*Regine Hock*
11:10 - 11:30	Observed changes in the runoff regime of the West Greenland ice sheet from a 40-year discharge time series ***Andreas Ahlstrøm**, D. Petersen*
11:30 - 11:50	Area, elevation and mass changes of the two southernmost ice caps of the Canadian Arctic Archipelago between 1952 and 2014 ***Etienne Berthier**, A. Royer, C. Zdanowicz, A. Langlois*
11:50 - 12:10	Recent Changes in Thickness and Mass of the Meighen Ice Cap, Canada ***David Burgess**, L. Gray*
12:10 - 12:30	Supraglacial and Ice-Marginal Lakes on the Devon Ice Cap and their Response to Recent Climate Warming ***Martin Sharp**, F. Wyatt*

12:30 - 16:30	**Very Long Lunch**
Convener:	*Carleen Reijmer*
16:30 - 16:50	Dynamics and climate sensitivity of Hans Tausen Iskappe (Greenland) ***Harry Zekollari***, *P. Huybrechts, B. Noël, W.J. van de Berg, M.R. van den Broeke*
16:50 - 17:10	Iceberg identification and characteristics in Yelverton Bay, Ellesmere Island, Canada ***Luke Copland***, *A. Dalton, A. White*
17:10 - 17:30	Drifting across the Arctic Ocean 50 years ago ***Michael Kuhn***
17:30 - 17:45	**Poster presentations by authors**
17:45 -	**Coffee and Poster session**
20:30 - 22:00	**Dinner**

Tuesday 26 January

Convener:	*Luke Copland*
	Special session on glacier-ocean interactions
08:30 - 09:00	**Keynote lecture:** Glacier-Ocean Interactions in the Arctic: Past Work and Future Directions ***Gordon Hamilton***
09:00 - 09:20	Evolution of tidewater glacier calving front morphology in a high resolution ocean model ***Donald Slater***, *P. Nienow, T. Cowton, D. Goldberg, A. Sole*
09:20 - 09:40	Assessing controls on oceanic heat delivery to Greenland's marine-terminating outlet glaciers ***Tom Cowton***, *A. Sole, P. Nienow, D. Slater*
09:40 - 10:00	Ocean and glaciers interactions in Svalbard area ***Waldemar Walczowski***, *M. Błaszczyk, T. Wawrzyniak, A. Beszczyńska-Möller*
10:00 - 10:20	Observations of oceanic waters reaching tidewater glaciers in Hornsund, Svalbard ***Agnieszka Promi nska***, *W. Walczowski*
10:20 - 10:50	**Coffee break**
Convener:	*Thorben Dunse*
10:50 - 11:10	Understanding the control mechanisms of the front position changes of tidewater glaciers ***Jaime Otero***, *F. Navarro, J. Lapazaran, E. de Andrés*
11:10 - 11:30	On seasonal changes of calving flux from Hansbreen, S Spitsbergen ***Jacek Jania***, *M. Błaszczyk, D. Ignatiuk, M. Ciepły, W. Walczowski*
11:30 - 11:50	Flow velocity abnormal and altitude variation of Austre Lovénbreen in Svalbard: a comparison of observation and simulation ***Songtao Ai***, *Z. Wang, M. Yan*

11:50 - 12:10 Characterizing the recent speed-up (1999-2015) of the Trinity and Wykeham Glaciers, Prince of Wales Icefield, Nunavut, Canada ***Wesley van Wychen***, *J. Davis, L. Copland, D. Burgess, M. Sharp, L. Gray, C. Mortimer*

12:10 - 17:00 **Very Long Lunch**

Convener: *Wessley van Wychen*

17:00 - 17:20 An attempt to distinguish glacier facies on Vestfonna (Nordaustlandet), Svalbard based on SAR and GPR data ***Barbara Barzycka***, *M. Blaszczyk, M. Grabiec, J.A. Jania*

17:20 - 17:40 Potential of Pléiades stereo images for measurement of snow accumulation in Drangajökull Ice Cap (NW Iceland) ***Joaquín M.C Belart***, *E. Berthier, E. Magnússon, L. Anderson, A.H. Jarosch, T. Thorsteinsson, F. Pálsson*

17:40 - 18:00 A study of the errors in the estimate of glacier ice volume from GPR data ***Javier Lapazaran***, *J. Otero, F. Navarro, A. Martín-Español, F. Machío, D. Mensah, P. Sánchez-Gámez*

18:00 - 19:30 IASC Network on Arctic Glaciology Open Forum meeting *C.H. Reijmer / M. Sharp*

20:30 - 22:00 **Dinner**

Wednesday 27 January

Convener: *Gordon Hamilton*

09:00 - 09:20 Decadal slowdown of a land-terminating sector of the Greenland Ice Sheet during sustained climate warming - implications for wider ice sheet hydrology-dynamics coupling ***Pete Nienow***, *A. Tedstone, N. Gourmelen, A. Dehecq, D. Goldberg, E. Hanna*

09:20 - 09:40 Comparison of the supraglacial drainage system on different timescale from remote sensing data on Werenskioldbreen, land-terminating Svalbard glacier ***Leo Decaux***, *D. Ignatuik, M. Grabiec, J. Jania*

09:40 - 10:00 Subglacial topography and geometry changes of glaciers forming Sørkapp Land and Torell Land junction (S Spitsbergen) ***Mariusz Grabiec***, *D. Ignatiuk, T. Budzik, J.A. Jania, M. Moskalik, P. Głowacki*

10:00 - 10:20 Subglacial drainage of Werenskioldbreen (SW Spitsbergen) based on numerical modelling ***Darek Ignatiuk***, *A.M. Piechota, S.S. Sitek*

10:20 - 10:50 **Coffee break**

Convener: *Jacek Jania*

10:50 - 11:10	Snow cover as a freshwater input to the glacier surface. Hansbreen as an example. ***Aleksander Uszczyk****, M. Grabiec, J. Jania, T. Budzik, M. Laska, D. Ignatiuk, B. Luks*
11:10 - 11:30	Simulating the present and future state of firn conditions in Svalbard ***Ward van Pelt****, V. Pohjola*
11:30 - 11:50	Heat sources within the Greenland Ice Sheet: dissipation, temperate paleo-firn and cryo-hydrologic warming ***Martin Lüthi***
11:50 - 12:00	Final words *C.H. Reijmer / M. Sharp*
12:00 -	**Lunch / Departure / Skiing**
20:30 - 22:00	**(Dinner)**

Posters

- Greenlands outlet-glacier sensitivity to submarine melting ***Johanna Beckmann***
- Svalbard glacier-mass balance: Freshwater discharge and possible implications for the marine ecosystem ***Thorben Dunse****, K.S. Aas, J.O. Hagen, T.V. Schuler, T. Schellenberger and L.C. Stige*
- Use of GPR and Photogrammetry to study glacier change for Baby Glacier, Axel Heiberg Island, Canada, 1959-2015 ***Michael Hackett****, L. Thomson and L. Copland*
- The relationship between ice velocity and synoptic weather patterns for Vatnajökull outlet glaciers, Iceland ***Christine Jones****, J. Hart, G. Roberts*
- Subglacial topography of the marginal zone of Múlajökull surge-type glacier, central Iceland ***Kristaps Lamsters****, J. Karušs, D. Bērziņš, A. Rečs*
- Ice thickness distribution and hydrothermal structure of Elfenbeinbreen and Sveigbreen, Eastern Spitsbergen, Svalbard. ***Francisco Navarro****, R. Möller, E. Vasilenko, A. Martín-Español, R. Finkelnburg, M. Möller, C. Recio-Blitz*
- Integrated firn elevation change model for glaciers and ice caps. ***Björn Saß***
- A century of geometry and velocity evolution at Eqip Sermia. ***Martin Lüthi****, A. Vieli, L. Moreau, D. Small, I. Joughin, M. Stober*

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44. Harry Zekallori* (hzekolla@vub.ac.be)

(Young scientists receiving support are marked *).

Minutes of the Open Forum meeting

Chair: Carleen Tijm-Reijmer
Vice Chair: Martin Sharp
Minutes: Wesley Van Wychen
Invited to attend: all participants of the workshop.

Agenda

1. Items to add to the agenda
2. Background and information on IASC and NAG
3. Review of meeting minutes from 2015
4. Ongoing and New Network activities
5. Discussion of the structure of the network
6. Discussion of location of next meeting
7. Extended Abstracts
8. Anything remaining topics for discussion

Ad. 1

No additional items for the agenda.

Ad. 2

Short Introduction to International Arctic Science Committee (IASC):
- Background to IASC (not IACS)
- IASC has 5 working groups
- NAG can cross cut the IASC working groups
- Need to demonstrate Network activity to ensure funding and support

Ad. 3

A review of the 2015 open forum meeting minutes was provided.

Ad. 4

Ongoing network activities:
Firn-Processes:
- Jason Box has organized a workshop on the modeling of firn processes, which could include participation from the group. This workshop is scheduled for the first week of June 2016.
Updated analysis of in situ mass balance records from Arctic Glaciers:
- Record of corrected mass balance data is available for download and a paper should be forthcoming (Martin Sharp).
- Records are updated to 2014, except for data from Sweden which has been collected but not submitted to WGMS.
- There are also new datasets available that are not included in WGMS yet.
- Martin Sharp → working on regular updates (to 2015) with Bert Wouters to include GRACE data, and there is the possibility of putting this data on the internet.

New network activities:
Possible field workshop in 2016:
- Jacek Jania raises the possibility that there could be a field workshop in 2016 from the research vessel Horizont.
- There is a limited number of participants (25-28 maximum capacity).
- This could be held in conjunction with UNIS.

Frontal ablation and dynamic discharge:
- Wesley Van Wychen and Luke Copland suggest a new network initiative to pull together all the pan-Arctic frontal ablation/dynamic discharge data together into one location, so that it is accessible to all of those interested.
- A big unknown is the Russian Arctic - however it is suggested that Mike Willis may have this data, otherwise the older Dowdeswell data is available.
- It is suggested to include Greenland into this dataset and that Ellyn Enderlin may be the best contact point for this data.

Ad. 5

Structure of the Network - National points of contact
- A discussion of the role of national contacts was held, as there are many national contacts that are not active in the group.
- There has been no previous tradition of electing or appointing people to be national contacts, and a short discussion of whether there should be was held, with the consensus opinion being that there should not be a formal process.
- However, there is a consensuses that national contacts are a necessary part of the network, and it is suggested that national contacts should provide brief reports each year to provide proof to IASC of each country's activities/involvement within the network.
- A second issue is raise, as to whether there should also be "early-career" national contacts for each region or whether national contacts should only hold their positions for a fixed (2-3 year) period.
- Songtao Ali volunteers to be the Chinese national contact, which is currently vacant.
- It is decided that the current process of appointing national contacts should remain more or less as currently constituted, however it is decided that if national contacts are not present at the workshop in at least two or the last three years, then they are automatically removed and replaced with an active contact representing that region.

Structure of the Network - Appointment of new chairperson
- Thorben Dunse (University of Oslo) is nominated and appointed to be the new chairperson of the Network of Arctic Glaciology.

Ad. 6

- The location of the next IASC NAG meeting was discussed.
- Competition for the facilities in Obergurgl, Austria is high, and as a consequence there is a need to book this location more than a year in advance of the proposed meeting.
- Preference for the NAG workshops to be held at the end of January each year is stated to ensure that it does not conflict with possible field excursions.

- Preference for the 2017 workshop to be held in North America as the previous two meeting have been held in Europe.
- Northeastern United States (Maine) is proposed as a possible location for the 2017 meeting. Gordon Hamilton volunteers to look into possible venues and locations.
- Michael Kuhn volunteers to organize the 2018 workshop in Obergurgl.
- Possibility of a NAG meeting in Hokkaido, Japan in the future is raised.

Ad. 7

Extended abstracts:
- Submission deadline for extended abstracts is set for March 30th, 2016.
- Intention to publish all abstracts as a PDF before August 1, 2016.
- Extended abstracts should be 1-2 pages, and can include 1-2 figures.
- Abstracts book will include an ISBN number.
- No funding is available for printing costs, so copies will be available as a PDF download from the NAG webpage.

Ad. 8

No additional topics discussed and meeting adjourned.

Abstracts

Observed changes in the runoff regime of the West Greenland ice sheet from a 40-year discharge time series

A.P. Ahlstrøm, D. Petersen

GEUS - Geological Survey of Denmark and Greenland, Copenhagen, Denmark

The impact of Greenland ice sheet mass loss on the ongoing global sea level rise has raised concern and a better understanding of the reaction of the ice sheet to a future warmer climate is needed. Yet, observational records of surface melting have so far only been in the form of stake readings or short-term discharge measurements. Here we present continuous, long-term observations of discharge from the pro-glacial lake Tasersiaq in West Greenland (66.3°N, 50.4°W) which has a drainage basin that extends over approx. 8500 km^2 of which around 80% is ice-covered. The discharge time series covers the period from 1975 to 2014 and gives insight into the hydrological system's reaction to climatic forcing, e.g. a clear impact from major volcanic eruptions is observed. Over the entire data period a significant positive trend of 0.06 km^3/yr in annual discharge is seen, where the median annual discharge is 2.50 km^3. In addition to the trend in annual discharge a large and increasing year-to-year variability is observed. We examine both discharge trend and variability in the context of atmospheric circulation patterns and indicators of climate variability.

Flow velocity abnormal and altitude variation of Austre Lovénbreen in Svalbard: a comparison of observation and simulation

S. Ai[1], Z. Wang[1], M. Yan[2]

[1] Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan, China
[2] Polar Research Institute of China, Shanghai, China

In 2005 the Chinese National Arctic Research Expedition started field research on a typical valley glacier: Austre Lovénbreen, Svalbard. This paper describes the GPS tracking station and high-precision GPS surveys measured less than 10 km from the Chinese Arctic Yellow River Station each summer from 2005 to 2010. Both horizontal and vertical annual glacier surface velocities were calculated. Data analysis shows that the range of surface horizontal velocity was 0.360 - 3.986 $m\,a^{-1}$ and the rate of surface altitude variation ranged from +9.6 to -140.5 $cm\,a^{-1}$. A terminal method was used to calculate the altitude variations, while the results from both cumulative and terminal methods indicate that the mass balance of this

glacier is negative and that the glacier has been melting over the 5 year measurement period. Specifically, the east tributary of the glacier has a rather small flow velocity, which is not coinciding with the simulation on the whole glacier. Probably the englacier water channel takes away the mass and releases the sub-ice water pressure, hence slow down the ice flow in this tributary.

An attempt to distinguish glacier facies on Vestfonna (Nordaustlandet), Svalbard based on SAR and GPR data

B. Barzycka, M. Blaszczyk, M. Grabiec, J.A. Jania

University of Silesia, Faculty of Earth Sciences, Centre for Polar Studies, Sosnowiec, Poland

Spatial distribution of glacier zones and their evolution due to climatic warming are very important for mass budget calculations and conditions of glacier drainage system development. SAR data provide information not only about spatial location of the object but also about its surface characteristic. Because of that, SAR data are very useful sources of information in cryosphere's researches, especially in distinguishing glacier facies which extents are one of the indicators of climate changes. Moreover, SAR as a remote sensing technique gives us a possibility to monitor large and often inaccessible areas what makes this method exceptional. On the other hand, GPR records reflected signals from subsurface structures and because of this it seems to be a good source of data for glacier's facies detection purposes. Based on methods mentioned above, this project is an attempt of distinguishing glacier zones on Vestfonna.

Area of interests of this research is western part of Vestfonna, where in May 2009 GPR data acquisition was performed. From the same time ERS SAR images were provided by European Space Agency in PRI format. After SAR data processing, thresholding and unsupervised classification was executed in order to receive information about extensions of glacier's zones. In addition, backscatter coefficient (*sigma0*) values from SAR image were obtained for GPR profile's area. GPR data were processed as well, including their visual interpretation and internal reflection energy (*IRE*) values calculation. As both *sigma0* and *IRE* present strength of reflectivity it was possible to compare those two sources of information and distinguish glacier's zones by analyzing *IRE* values. Finally, comparison of results of unsupervised classification, thresholding, *IRE* analysis and visual interpretation of GPR data are presented and discussed.

Greenlands outlet-glacier sensitivity to submarine melting

J. Beckmann

Potsdam Institute for Climate Impact Research, Potsdam, Germany

Over the last few decades Greenland ice mass loss has strongly increased due to surface melt and dynamic changes in marine-terminating outlet glaciers. A major reason for the retreat of these glaciers is believed to be related to increased submarine melting, which in turn is caused by surrounding ocean warming and the enhanced subglacial water discharge. These complex physical processes are not yet fully understood. Inspecting the sensitivities of submarine melting to model formulation and model parameters is crucial for investigations of outlet glacier response to future climate change.Different approaches have been used to compute submarine melt rates of outlet glaciers using experimental data, numerical modelling and simplified analytical solutions. To model the process of submarine melting for a selection of Greenland outlet glaciers, a simple submarine melt parameterization is incorporated into a one-dimensional dynamic ice-flow model. The behaviour of this submarine melt parameterization is demonstrated by running a suite of simulations to investigate the sensitivity of submarine melt to changes in ocean properties and the amount and distribution of subglacial water discharge for a set of different glacier. A comparison of the simple parameterization with expreimental data is conducted to asses the quality of this parameterization and improve the parameterization of submarine melting.

Potential of Pléiades stereo images for measurement of snow accumulation in Drangajökull Ice Cap (NW Iceland)

J.M.C. Belart[1,2], E. Berthier[2], E. Magnússon[1], L. Anderson[1], A.H. Jarosch[1], T. Thorsteinsson[3], F. Pálsson[1]

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[2] Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Centre National de la Recherche Scientifique (LEGOS - CNRS), Université de Toulouse, Toulouse, France
[3] Icelandic Meteorological Office, Reykjavík, Iceland

Sub-meter satellite stereo images open new possibilities of creation of series of high resolution, accurate Digital Elevation Models (DEMs). Using repeated acquisitions of Pléiades stereo images over the Drangajökull Ice Cap (NW-Iceland), in October 2014 and May 2015, we create and compare DEMs for measuring the glacier-wide Winter Mass Balance (WMB) of the ice cap. Three methodologies are tested for Pléiades DEM generation: (1) Using a LiDAR DEM acquired in summer 2011 for extraction of Ground Control Points (GCPs) to support the orientation of the Pléiades images. (2) Adjusting simultaneously the orientation of all the Pléiades images in a combined block adjustment using tie points in unchanged features, prior to the DEMs creation and (3) Creating separate DEMs based on the Rational Polynomial Coefficient (RPC) information and applying coregistration methods based on ice-free areas to correct horizontal and vertical biases. Results of elevation changes are compared with 8 in-situ mass balance measurements carried out in June 2015 by the Icelandic Meteorological Office (IMO). This comparison shows differences in a meter-level between the remote sensing and in situ data, resulting from (1) the difference in time between in-situ and satellite observations and (2) the fact that DEM differencing measures elevation changes while specific mass balance is measured in the field. Our preliminary results show the capabilities of repeated Pléiades stereo images for measuring WMB, independently of availability of GCPs. The estimated glacier-wide WMB of Drangajökull

for the period of study is 3.00 ± 0.42 m w.e., based on the processing of Pléiades supported by GCPs. The study also indicates the importance of an adequate interpretation of the results of seasonal mass balance obtained from remote sensing methods, in particular in matter of density assumptions, acquisition dates and connection with direct mass balance measurements.

Area, elevation and mass changes of the two southernmost ice caps of the Canadian Arctic Archipelago between 1952 and 2014

C. Papasodoro[1], **E. Berthier**[2], A. Royer[1], C. Zdanowicz[3], A. Langlois[1]

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Centre d'Études Nordiques, Québec, Canada
[2] Laboratoire d'Etudes en Géophysique et Océanographie Spatiales, Centre National de la Recherche Scientifique (LEGOS - CNRS), Université de Toulouse, France
[3] Department of Earth Sciences, Uppsala University, Sweden

Grinnell and Terra Nivea Ice Caps are located on the southern Baffin Island, Nunavut, in the Canadian Arctic Archipelago. These relatively small ice caps have received little attention compared to the much larger ice masses further north. In this study, we describe historical and recent changes of area, elevation and mass of both ice caps using in situ, airborne and spaceborne data sets, including recent stereo-imagery from the Pléiades satellites.

The area of Terra Nivea Ice Cap has decreased by 34% since the late 1950s, while that of Grinnell Ice Cap has decreased by 20% since 1952. For both ice caps, the areal reduction accelerated at the beginning of the 21st century. The estimated glacier-wide mass balance was -0.37 ± 0.21 m a^{-1} w.e. over Grinnell Ice Cap for the 1952 - 2014 period, and -0.47 ± 0.16 m a^{-1} w.e. over Terra Nivea Ice Cap for the 1958/59 - 2014 period. Terra Nivea Ice Cap has experienced an accelerated rate of mass loss of -1.77 ± 0.36 m a^{-1} w.e. between 2007 and 2014. This rate is 5.9 times as negative when compared to the 1958/59 - 2007 period (-0.30 ± 0.19 m a^{-1} w.e.) and 2 times as negative when compared to the mass balance of other glaciers in the southern parts of Baffin Island over the 2003 - 2009 period. Sparse measurements of elevation changes suggest a similar acceleration in mass loss for the Grinnell Ice Cap. The recent increase in mass loss rates for these two ice caps is linked to a strong near-surface regional warming and a lengthening of the melt season into the autumn. On a methodological level, our study illustrates the strong potential of Pléiades satellite data to unlock the under-exploited archive of old aerial photographs.

Recent Changes in Thickness and Mass of the Meighen Ice Cap, Canada

D. Burgess[1], L. Gray[2]

[1] Natural Resources Canada
[2] University of Ottawa, Ottawa, Canada

Meighen ice cap (79°N, 80°W) is a small stagnant ice mass occupying ∼60km^2 of eastern sector of Meighen Island, Nunavut, Canada. Despite its low elevation profile (maximum height reaches 270 m a.s.l.), the Meighen Ice Cap has maintained a relatively healthy mass balance since measurements began the early 1960's with 6 out of 10 years experiencing growth prior to 2005. The persistence of this low elevation ice cap has been attributed to its proximity to the Arctic Ocean from which frequent fog events suppress summer melt. Since 2005 however, the Meighen Ice Cap has experienced rapid shrinkage in both area and thickness due to a sharp increase in the magnitude and duration of summer warming. This presentation will integrate results from in-situ glacier measurements, airborne laser (NASA ALTM) data, Satellite (CryoSat-2) altimetry, and optical image data to quantify changes in mass of the Meighen Ice Cap since 1960.

Iceberg identification and characteristics in Yelverton Bay, Ellesmere Island, Canada

L. Copland, A. Dalton, A. White

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Recent breakups of floating glacier tongues and retreat of tidewater glacier on northern Ellesmere Island have produced the largest number of icebergs ever observed in this region. These icebergs can reach diameters of >2 km, and have the potential to provide significant hazards to shipping and offshore oil exploration in the Arctic Ocean and Queen Elizabeth Islands of the Canadian Arctic. In this study we assess the ability of SAR vs. optical imagery to detect these icebergs in Yelverton Bay based on comparison with direct field observations. In summer conditions, Landsat-8 provided the superior detection method, enabling identification of >2600 icebergs, compared to only ∼5% of this number in Sentinel-1 imagery and ∼3% of this number in Radarsat-2 imagery. Direct landings on icebergs were also undertaken to measure their thicknesses with a 10 MHz ground-penetrating radar system. We use this data to evaluate the usefulness of LIDAR measurements of iceberg freeboard collected during NASA IceBridge flights in April 2014 to provide information on total iceberg thickness.

Assessing controls on oceanic heat delivery to Greenland's marine-terminating outlet glaciers

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The recent retreat of many of Greenland's marine terminating glaciers has been coincident with a period of anomalously warm ocean temperatures. It has been hypothesised that warming ocean waters may affect the stability of glacier termini through an increase in the rate of submarine melting, or a decrease in the buttressing influence of sea ice and icebergs, both of which could drive an increase in the rate of mass loss through calving. As Greenland's outlet glaciers typically terminate at the head of lengthy fjord systems, the availability of oceanic heat at the calving front is however dependent not only on the temperature of the water around the Greenland coast, but also on the advection of this heat towards the glaciers by the circulation of the fjord. Assessment of spatial and temporal variation in this up-fjord heat transport may therefore provide a means of examining the role of the ocean in forcing the dynamic variability of these glaciers.

The rate at which oceanic heat is delivered to a particular glacier is likely to depend on a range of environmental factors. These may be oceanic (e.g. shelf water temperature), atmospheric (e.g. glacial melt water input, the strength of along-fjord and along-shelf winds) or topographic (e.g. fjord depth, length, width or sinuosity). Here we assess the sensitivity of up-fjord heat flux to these parameters by undertaking a suite of experiments using an ocean model (MITgcm), applied to an idealised fjord system and to Kangerdlugssuaq Fjord in east Greenland. Through this, we identify those factors that are of greatest importance in controlling the delivery of oceanic heat to Greenland's marine-terminating glaciers. Our experiments facilitate assessment of 1) how the influence of the ocean may differ from one marine-terminating glacier to the next and 2) how the oceanic forcing of these glaciers may have changed, and continue to change, over time in response to varying environmental conditions.

Comparison of the supraglacial drainage system on different timescale from remote sensing data on Werenskioldbreen, land-terminating Svalbard glacier

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In a context of climate change and, in particular, rapid melt of glaciers around the world, it is important to characterize the evolution of the meltwater drainage system and its consequences on glaciers behavior. Due to its direct impact on englacial and subglacial drainage system, supraglacial drainage system studies are a first crucial step in order to better quantification of water supply to them. Our study is focus on the land-terminating Werenskioldbreen located in the southern part of the Svalbard archipelago. It is characterize by a polythermal regime with entire surface composed by cold ice. That implies an impermeable layer which results to a well channelized dendritic supraglacial drainage system. A recent study on this glacier shows discontinuous changes in glacier surface through the time.

The Werenskioldbreen supraglacial drainage system has been mapped thanks to the orthophotomap based upon the NPI aerial photos of 1990, the Geoeye satellite image from 2010, the NPI orthophotomap from 2011 and field observations. This allows us to compare it on a decadal and inter-annual timescale. Remote sensing methods are limited mostly by the available number of cloud free high resolution imagery acquired in a late part of ablation season. Indeed, we have to use imagery from at least one meter resolution due to the size of the supragacial drainage features.

Due to the non-linear thinning of the glacier we observe changes in the supraglacial drainage system of Werenskioldbreen through the time. Despite larger geometry changes, in the lower part the drainage pattern is more stable due to greater incision of the channels, linked to higher discharges of water than in the upper part of the glacier. Finally, moulins locations (and their changes) inform us on areas of concentrated water supply to englacial and subglacial drainage systems. Having data on areas drained by particular moulins or their groups, estimation of water discharge could be done. Spatiotemporal variability of main penetration areas may influence the evolution of water circulation within the glacier.

Svalbard glacier-mass balance: Freshwater discharge and possible implications for the marine ecosystem

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Socio-economic impacts of glacier-mass loss are not limited to sea-level rise. Glacial freshwater discharge into the ocean also affects the physical and chemical properties of the fjord systems and adjacent shelves and enhances estuarine circulation and nutrient input, with effects on biological productivity. Within the project GreenMAR (Green growth based on marine resources: ecological and socio-economic constraints) we will investigate possible links between glacial-derived freshwater and the marine ecosystem. Here, we focus on Svalbard in the Eurasian Arctic. 34000 km^2 or 57% of the total land area on Svalbard is covered by glaciers and ice caps. 68% of the glacierized area drains through tidewater glaciers with a total calving-front length of $\sim$740 km.

A 10-year simulation of the climatic mass balance of Svalbard-glaciers using the Weather Research and Forecasting model (WRF) coupled to a climatic mass balance model shows large interannual variation, especially in terms of the summer balance. As a first step, we will compare simulated surface meltwater production and monthly net primary production, i.e. the growth of phytoplankton, forming the base of the marine food web. Summer ablation in 2008 was low, whereas in 2013 it was very high, resulting in a small and large freshwater contribution. Primary production in Svalbard fjord systems and adjacent shelves was higher and more widespread in August 2013 then in 2008, indicating a possible correlation with meltwater runoff.

Austfonna, the largest ice cap on Svalbard started to surge in autumn 2012. The associated iceberg discharge in the period April 2012 to May 2013, amounted to 4.4 ± 1.6 Gt, increasing the long-term calving flux from the entire Svalbard archipelago by >50%. The surge-initiation was accompanied with large amounts of nutrient-rich subglacial meltwater. Is there a possible relation between the surge and an unusual abundance of fish off the coast of Nordaustlandet in 2013?

Subglacial topography and geometry changes of glaciers forming Sørkapp Land and Torell Land junction (S Spitsbergen)

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The head of Hornsund Fiord is occupied by the glacial system Hornbreen - Hambergbreen, empting into both: Greenland Sea and Barents Sea. This system is sensitive to climatic changes, resulting in very dynamic shrinkage of glaciers since LIA. Consequently, the glacial isthmus is systematically narrowing. Recent works predict that within next few decades the Sørkapp Land - Torell Land junction will be free of ice. Previous studies in this area don't conclude unequivocally on subglacial topography in relation to the sea level. However consequences of potential isolation of Sørkapp Land from the main island may be regionally significant for the oceanic circulation pattern, climate, marine ecosystem etc.

This work provides new information on the ice thickness and basal topography obtained from radio echo-soundings carried out in this area in spring 2013 and 2014. The low frequency (30 MHz) radar system combined with GPS receiver working in differential mode were used for profiling on total distance more than 30 km. Recent surface elevation data was coupled with results of broad GPS campaign performed in 2000. That allow to calculate the changes of surface topography and the lowering rate in the last 14 years. Novel data on the glacier thickness and subglacial topography shed new light on the functioning of the system of Hornsund environment and its evolution.

Use of GPR and Photogrammetry to study glacier change for Baby Glacier, Axel Heiberg Island, Canada, 1959-2015

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To assess the magnitude of recent glacier changes in the Canadian Arctic, we conducted an oblique aerial photographic survey in summer 2015 of Baby Glacier, a small alpine glacier on Axel Heiberg Island. Using structure from motion photogrammetry, along with ground control points, we created a high-resolution DEM and orthophoto of the glacier. To quantify volume changes over time, the new DEM was differenced from a DEM created from 1959 historical stereo-aerial photography. Area change was measured by outlining the glacier against the 1959 air photo, as well as ASTER imagery from 2001 and 2006, and the 2015 orthophoto. In addition, a ground-penetrating survey was conducted in May 2015 to determine ice thickness, which can be used to project the future evolution of Baby Glacier under a warming climate.

Overall, Baby Glacier has reduced in size, thinned and become narrower at its terminus over the study period. A prominent nunatak at the upper extent of Baby Glacier has become much more exposed, indicating that ice loss has occurred across the entire elevation range. This study has also demonstrated that the structure from motion technique can provide precise DEMs of an area from oblique air photos, which greatly facilitates the collection of topographic data compared to previous photogrammetric techniques that required nadir (vertical) photos as inputs.

Mass balance measurements on the Austfonna Ice Cap, Svalbard 2004-2013

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The Austfonna ice cap (∼8000 km^2) is by far the largest ice cap in Svalbard. Direct surface mass balance measurements were started in 2004 and have been run continuously since then. Specific net-mass balances are measured at ∼20 stakes across the ice cap, and winter balances inferred from snow soundings, snow pits and GPR profiles of the snow distribution. The south-west facing drainage basin of Etonbreen covering ∼630 km^2 has the best continuous data indicating a slightly negative mean net surface mass balance of -0.1 m ± 0.1 m w.eq./yr for the period 2004 - 2013. Extrapolated for the whole of Austfonna, this corresponds to a total mass loss of -0.8 ± 0.5 Gt/yr. Yearly variations in the net mass balance are large, and mainly driven by the summer ablations that shows larger variability than the winter accumulation. The years 2004 and 2013 were strongly negative while 2008 was strongly positive. The annual net balance is well correlated to the mass balance of Kongsvegen in Kongsfjorden on North-West Spitsbergen.

The geodetic specific mass balance of entire Austfonna based on ICESat data for the period 2003 - 2008 revealed a mean annual balance close to zero of +0.01 ± 0.04 m w.eq./yr, in good agreement with the direct measurements. Calving is important (2.5 Gt/yr in the period 1990 to 2001) and stands for 30-40% of the total mass loss, or -0.3 m w.eq./yr. The elevation change measurements on Austfonna show a thickening in the interior of c. 0.5 m/yr, and a thinning closer to the coast of 1-2 m/yr, indicating a large dynamic instability. A recent surge in Basin 3 resulted in a temporary tripling of the calving loss from the entire ice cap with c. 4.4 Gt calving loss from the basin during one year from May 2012 to May 2013.

Glacier-Ocean Interactions in the Arctic: Past Work and Future Directions

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A significant fraction of the recent increase in mass loss from Arctic land ice has been attributed to processes occurring at the ice-ocean boundary, where glaciers are in contact with relatively warm seawater (temperatures several degrees above the pressure-adjusted melting point for ice). On the glacier side, circulation of this water against the terminus can drive large submarine melt rates (∼m/d) which may, in turn, promote increased iceberg calving. On the ocean side, enhanced production of buoyant meltwater at the terminus or from icebergs can alter the stratification and circulation of adjacent coastal waters which, in turn, will have important consequences for marine ecosystems. Work carried out over the last decade has provided insights on several aspects of ice-ocean interactions in Arctic fjords: for example, we now know that warm waters of subtropical origin are present in many fjords, and that active circulation systems ensure a steady delivery of oceanic heat to glacier margins. We have also constructed detailed time series of terminus position changes for many glaciers, and are starting to understand the basics of fjord hydrography (water mass characteristics and variability; presence or absence of sills, etc.). Yet, there is no unifying mechanism that explains how and why glaciers respond to changes in oceanic forcing. This presentation will review our current understanding of glacier-ocean interactions and point out important knowledge gaps where future research efforts should be focused.

Global-scale glacier modeling - Challenges and recent progress

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Modeling future glacier changes on a global scale is challenging due to scarcity of data for model initialization and calibration and biases in climate data in mountainous terrain. Only few global-scale models have been published during the last ten years. Approaches to project global-scale mass changes broadly fall into three categories: (1) models based on simple extrapolation, (2) models based on mass balance sensitivities to temperature and precipitation changes, and (3) direct modeling of transient surface mass balance forced by climate data. Results from several global mass-balance models driven by 8 to 15 Global Circulation Models and 4 different emission scenarios indicate multi-model mean net mass losses of all glaciers on Earth (outside the ice sheets) between 66 mm and 242 mm sea-level equivalent by the end of the 21st century. Amounts vary greatly depending on the choice of the forcing climate and emission scenario. Large differences are also found between studies even when the models are forced by the same climate models and emission scenario, especially on regional scales. Insufficiently constrained model parameters and different initial glacier volumes are likely important reasons for the discrepancies. A new "Targeted Activity" under the Climate and Cryosphere (CliC) program, seeks to understand these differences, and for the first time provides a framework for a coordinated intercomparison of global-scale glacier mass change models with the ultimate goal to foster model improvements and reduce uncertainties in global glacier projections and associated contributions to sea-level rise.

Subglacial drainage of Werenskioldbreen (SW Spitsbergen) based on numerical modelling

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Subglacial drainage of the Werenskioldbreen glacier (SW Spitsbergen) based on numerical modelling using finite elements method (FEFLOW) was made. Numerical modelling was preceded by field research carried out on Werenskioldbreen during the summer periods of 2009 - 2011. The 3D model covers 36.2 km^2 of a polythermal glacier basin, 75% of which is filled with ice (27.1 km^2). The steady-state model illustrates the subglacial drainage in a till layer and the top of the bedrock. In the model, presence of permafrost and active layer of a maximum thickness up to 2 m under the glacier snout and in its forefield are prescribed. The main aim of this study was to obtain the subglacial groundwater flow field and the spatial distribution of hydraulic pressures beneath the glacier and in its forefield. The spatial distribution of hydraulic pressure and groundwater flow paths beneath the glacier are controlled by its geometry (thickness), thermal conditions, recharge estimated and calibrated from the ablation and precipitation and the hydrogeological parameters of the modelling layers. The subglacial groundwater budget shows that over 98% of this water (4542 m^3 day) is discharged by rivers (65% of which is the Kvisla river drainage). Less than 2% discharges directly to the sea. The assumption of permafrost under the snout of the glacier profoundly modifies water flowlines in the area and contributes to the formation of three preferential drainage paths (northern, southern and middle).

Investigating Svalbard's climate using a regional climate model

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Due to their gentle slopes the glaciers and ice caps on Svalbard are very sensitive to changes in climate. Nevertheless, for many glaciers the surface mass balance (SMB) of the last decades is unknown. Using the regional climate model RACMO2, including an interactive snow module, the climate and SMB of Svalbard from 1957 till 2014 is modeled. RACMO2 has been run on 11 and 3.5 km resolution. Furthermore, several shorter simulations were carried out to investigate the sensitivity of the modeled SMB to snow impurity content and snowdrift tuning parameters.

The RACMO2 output is evaluated with data from weather stations operated by the Norwegian Meteorological Institute and with SMB observations on several locations spread over the archipelago. We present the modeled spatial and temporal variability of the SMB on Svalbard and individual regions such as Austfonna ice cap, and analyze the dependency of the results on model resolution as well as the performance of RACMO2 on 3.5 km resolution. We will present the most recent results of this study, including several performed sensitivity tests and preliminary conclusions that we can draw.

On seasonal changes of calving flux from Hansbreen, S Spitsbergen

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Studies on calving intensity from glaciers are important for both: better understanding of glacier processes and more precise calculation of mass budget. Seasonal rhythm of dynamics of tidewater glaciers is generally known. After advance of glacier front during winter, summer recession occurs thanks to higher calving in the warmer period of the year. Nevertheless, annual course of calving flux intensity is not calculated frequently. Such studies have been done for Hansbreen a polythermal glacier ending down into Hornsund Fiord in Southern Svalbard. They provide information for apprehension of calving mechanism and iceberg supply to the fiord as a freshwater source. The key source data on glacier front geometry, bathymetry of the fore bay, seasonal fluctuation of ice-cliff position and glacier velocity were collected by field survey (dGPS, multi-beam echo sounders) and remote sensing methods (panoramic radar, time lapse camera, laser scanner, multispectral and radar satellite data). Time lapse photos, repeated terrestrial laser scanning and measurements of sea water temperature, salinity and dynamics as well (CTD and ADCP), together with record from meteorological stations enable to search leading factors of calving intensity. Dry calving vs. melting of submarine part of the ice-cliff has been calculated. Thanks to the older and recent data calving flux was calculated for about fortnight intervals. Interannual differences in calving flux were also estimated.

The relationship between ice velocity and synoptic weather patterns for Vatnajökull outlet glaciers, Iceland

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The monitoring of valley glaciers and small ice caps is of importance as although they only account for a small volume of all land ice, they contribute significantly to sea-level fluctuations due to their short response time to climatic driving forces. Understanding the relationship between climate and glacier behaviour, with a focus on surface velocity, is therefore of upmost importance as this provides significant information regarding the underlying hydrological system, which subsequently effects the entire glacial system. This is of particular relevance within Iceland as Iceland is predicted to experience a 3°C increase in temperature by 2140 (Gent and Danabasoglu, 2014). This would have a significant effect upon all of Iceland’s major ice sheets, which are particularly sensitive to fluctuatating synoptic weather patterns.

This PhD therefore aims to create a simulated glacier velocity model for the Vatnajökull ice sheet; surface velocity measurements on all Vatnajökull outlet glaciers will be obtained for 1985-2015 through the use of both speckle and optical image feature tracking. This information will then be used alongside both AWS data and a Degree Day Model to determine the extent of the relationship between weather and glacier behaviour, with focus upon whether glacier velocity is primarily driven by rainfall and/or temperature. This relationship will then be used to calibrate a forward-facing simulation model to provide new insight regarding the spatial-temporal patterns of glacier velocity under different synoptic weather situations.

Preliminarily results to be implemented into the model show a clear trend between mean yearly velocity and the occurrence of rainfall events at the Skeiðarárjökull outlet glacier for 1985-2011. The mean glacier velocity increased with the occurrence of rainfall events that lasted ≥two days with a value of $\geq 20\,\mathrm{mm\,d^{-1}}$. The glacier also experienced significant increases in seasonal velocity with the increasing occurrence of >20 mm d^{-1} of precipitation.

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Drifting across the Arctic Ocean 50 years ago

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This presentation gives an account of investigations of seasonal and multi-year sea ice, based on two drifting stations in the spring of 1964. ARLIS 2 (Arctic Research Laboratory Ice Station) was a 2X3 km large, 30 m thick piece of Ward Hunt ice shelf that was then drifting eastward between Greenland and the pole. ARLIS 3 was built on seasonal pack ice circling in the Beaufort Gyre 200 miles north of Pt. Barrow. Cores of growing sea ice were taken daily and analyzed for crystal orientation, grain size and salinity. A mix of scientific results, ocean circulation, climate conditions, and historic working conditions is presented.

Subglacial topography of the marginal zone of Múlajökull surge-type glacier, central Iceland

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Múlajökull is surge-type glacier in central Iceland. It is one of the outlets draining the Hofsjökull ice cap. An active drumlin field, which consist of 110 drumlins, is found in the forefield of Múlajökull (Johnson *et al.*, 2010; Jónsson *et al.*, 2014) making it an excellent area for studies of glacial geomorphology as well as subglacial topography, which is supposed to hold unexposed drumlins.

In this study ground penetrating radar (GPR) Zond 12-e was used to map subglacial topography of the marginal zone of Múlajökull. GPR measurements were performed using low frequency 38 MHz antenna system. In total, approximately 10.5 km of GPR profile lines were recorded parallel to the glacier margin covering an area of 65 ha. The coordinates and altitude of start and end points of each GPR profiles were determined by centimetre accuracy GPS system. As a result a model of the subglacial topography and ice surface was created.

In obtained radar images it was possible to trace not only reflections from the glacier bed but also internal reflections from englacial channels. The subglacial topography of the study area consists of several streamlined landforms interpreted as drumlins. They have dimensions of few hundred metres and height up to 19 metres, so they could be regarded as a modern analogue to the former Pleistocene drumlins.

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A study of the errors in the estimate of glacier ice volume from GPR data

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One of the most extended glaciological applications of the ground penetrating radar (GPR) is the ice thickness assessment. Since the distribution of the GPR measurements on the glacier is often irregular, it is usually necessary to build a digital elevation model (DEM) of the glacier-ice thickness. This type of DEM is often used to assess the glacier volume. To estimate the error of this volume calculation, we need to know the error of the thickness values at the grid points of the DEM.

Our error study divides the process of error calculation in three steps. First, the

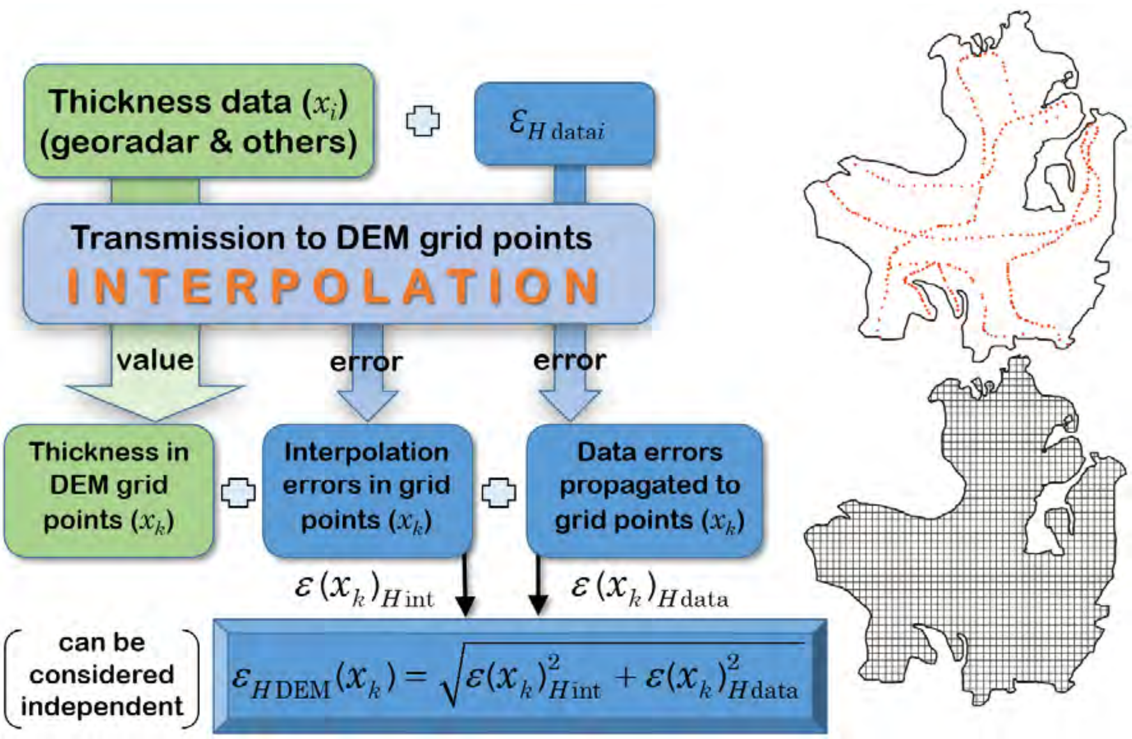

Figure 1. Step 2: The ice-thickness error at the grid points is the composition of two independent errors, the interpolation error and the propagation of the data errors to the grid points.

estimate of the data errors. Second, the estimate of the errors at the grid points of the DEM, which involve data errors and interpolation errors. And finally, the estimate of the errors related to the volume assessed from the DEM.

As a first step, we study the errors of the ice-thickness data ($\epsilon_{H\,data}$). We consider GPR as the main source of glacier ice-thickness data. In the estimate of the accuracy of ice-thickness measurements retrieved by GPR ($\epsilon_{H\,GPR}$), we take into account the errors in radio-wave velocity (ϵ_c) and the errors in timing (ϵ_τ). The accuracy of the boundary delineation of the glacier is also taken into account, as well as the positioning error of each data. For this purpose we consider the positioning uncertainty (e.g by GPS, thus we also take into consideration the refreshing period of the GPS measurement), the velocity of the GPR convoy while profiling, and the triggering period of the GPR. Using these parameters we evaluate a region of uncertainty in position, around each data point. Evaluating the variability of the ice-thickness field in this region we estimate the error in thickness of a data due to its uncertainty in position (ϵ_{Hxy}).

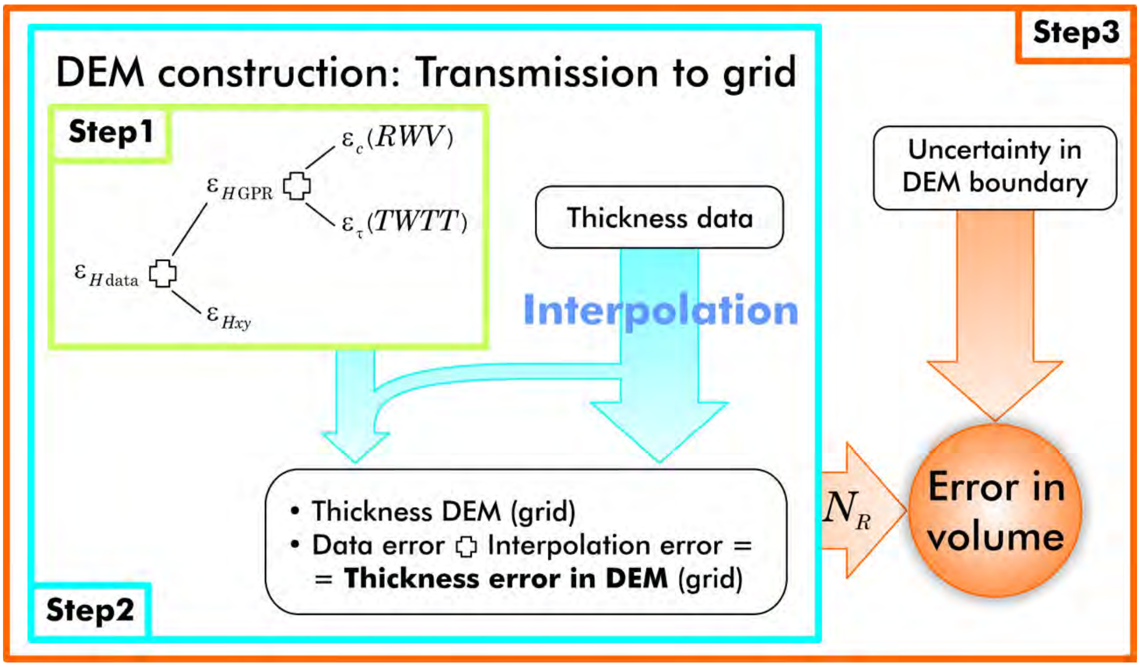

Figure 2. Sequence of steps in the volume error estimate. In step 1 the data error is obtained, from the error in the value of the GPR ice thickness measurement and from the error in thickness due to the uncertainty in position. In step 2 the ice thickness error at the DEM is estimated by the combination of the interpolation error and the propagation of the data error to the grid points. In the step 3 the error in volume is obtained, both considering the degree of independence in the ice-thickness values of the DEM and taking into account the error in volume due to the uncertainty of the DEM boundary.

In a second step we obtain the error of the DEM of ice-thickness ($\epsilon_{H\,DEM}$). The interpolation error ($\epsilon_{H\,int}$) is not the only source of error at the grid points (x_k) of the ice-thickness DEM, since a propagation of the data error to the grid points is also produced (Figure 1). To estimate both the possible interpolation bias and the interpolation error at a given grid point, we use two functions relating these parameters with the distance to the closest GPR profile. These functions are obtained using a cross validation method, which applies blanking circles around each data point to interpolate at the circle centre using only the data points located outside of the circle. Repeating it at each data point using a set of blanking circles of different radius, and comparing this data value with the resulting interpolated values, we can estimate biases and random errors. By least squares approximation we obtain both functions of interpolation bias (to correct the interpolation values) and of interpolation error vs distance to the closest GPR profile.

In a third step, we finally obtain the error associated to the volume estimate assessed from the DEM. With this aim, we provide a method to evaluate the degrees of freedom in the data, derived from their variogram, assuming the range as the distance from which pairs of data are uncorrelated. It is used to obtain the number of independent values within the DEM (N_R), which is used for calculating the error in volume of the DEM by combining the errors in volume at the grid cell level.

In addition, also the error in volume derived from the uncertainty in the DEM boundary must be taken into account. The total error in glacier ice volume is obtained as the combination of the error in volume derived from the DEM amplitudes and that derived from the uncertainty in the DEM boundary.

Heat sources within the Greenland Ice Sheet: dissipation, temperate paleo-firn and cryo-hydrologic warming

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Ice temperature profiles from the Greenland Ice Sheet contain information on the deformation history, past climates and recent warming. We present full-depth temperature profiles from two drill sites on a flowline passing through Swiss Camp, West Greenland. Numerical modeling reveals that ice temperatures are considerably higher than would be expected from heat diffusion and dissipation alone. The possible causes for this excess heat are evaluated using a Lagrangian heat flow model. The model results reveal that the observations can be explained with a combination of different processes: enhanced dissipation (strain heating) in ice-age ice, temperate paleo-firn, and cryo-hydrologic warming in deep crevasses.

Dramatic mass loss of Svalbard land-terminating glaciers by the end of the 21st century under an RCP 8.5 scenario

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The high Arctic archipelagos are among the most strongly glacierized landscapes on earth apart from the Greenland and Antarctic ice sheets. Svalbard, one of

these archipelagos, holds about 36,000 km^2 of glaciers and ice caps and is the region that has shown the least negative mass balance of all the high Arctic regions. However, future projections suggest that the archipelago will experience an unprecedented -for the Arctic- glacier recession over the 21st century.

We here present a high-resolution modelling study of the future ice-mass evolution of 29 individual land-terminating glaciers on the Svalbard archipelago under an RCP 8.5 climate forcing, a rather pessimistic scenario that unfortunately seems to be becoming realistic. Our model calculates glacier mass balance and area/volume changes using a temperature-index approach in combination with a surface elevation change parameterization. The initial glacier topographies and volumes have been assessed from extensive ground-penetrating radar measurements carried out in recent years. The calculations are performed for the 21st century and are forced by statistically downscaled output of ten different global circulation models representing the RCP scenario 8.5. By a topography-based extrapolation of the simulation results to the entire archipelago we show that a complete loss of most of Svalbard's land-terminating glaciers and even a deglaciation of certain subregions of the archipelago might occur by the end of the 21st century. 98% of the land-terminating glaciers will have retreated to less than one tenth of their initial extent by 2100, resulting in a loss of 7392 ± 2481 km^2 of ice coverage.

Ice thickness distribution and hydrothermal structure of Elfenbeinbreen and Sveigbreen, Eastern Spitsbergen, Svalbard

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In recent decades, Svalbard glaciers have been widely radio-echo sounded. However, despite the rather high number of radar studies the eastern coast of central Spitsbergen is still devoid of ice-thickness measurements. To partly fill this gap, we carried out a radio-echo sounding campaign on Elfenbeinbreen and Sveigbreen. Both glaciers are of comparable size (∼30-40 km^2, see Table 1) and extend from 600-700 m a.s.l. down to almost sea level. The radar campaign was done in April 2014, before the onset of spring melting, using a VIRL-7 ground-penetrating radar with central frequency of 25 MHz. We collected a total of 105 km of radar profiles on Elfenbeinbreen, and 36 km on Sveigbreen. The layout of radar profiles is shown in Figure 1. The main processing steps consisted of bandpass filtering, normal move-out correction, amplitude correction and Stolt 2D F-K migration. From the radar data we constructed, using a radio-wave velocity of 0.168 m ns^{-1}, the ice-thickness maps shown in Figure 2. We found that the mean ice thickness is slightly higher for Elfenbeinbreen than for Sveigbreen (see Table 1), while the

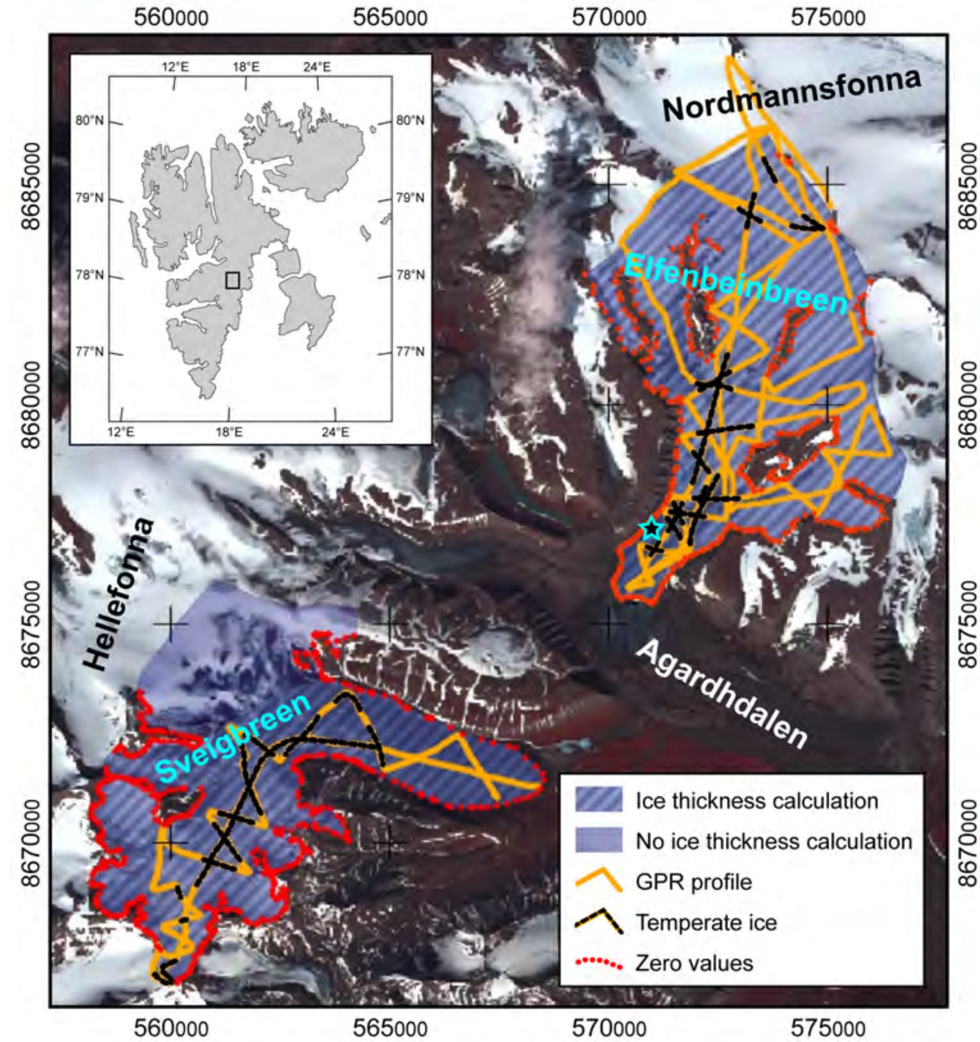

Figure 1. (From Navarro *et al.* (2015)) Layout of the radar profiles on the studied glaciers. The black dashed line indicates sections of the profiles where a temperate ice layer was clearly identified. The red dots denote boundary points with zero ice thickness. UTM coordinates for sheet 33X are included. The inset shows the location of the study zone within Svalbard. The satellite image used as background was available from ASTER © METI and NASA (2005), for 23 July 2005 (all rights reserved), thanks to the courtesy of the University of Silesia, Poland, within the frame of cooperation of SvalGlac project.

Table 1. Area, volume, and mean and maximum ice thickness of the studied glaciers. The area given for Sveigbreen excludes the portion of the glacier not radio-echo sounded shown in Figure 1.

Glacier	Areau (km^2)	Volume (km^3)	$\overline{H}$ (m)	H_{max} (m)
Elfenbeinbreen	39.96 ± 3.20	3.368 ± 0.173	85.28 ± 8.84	285.12 ± 6.62
Sveigbreen	28.59 ± 2.29	2.004 ± 0.107	73.58 ± 7.42	212.43 ± 5.42

maximum ice thickness of Elfenbeinbreen is close to 300 m, considerably larger than that of Sveigbreen, just above 200 m (Table 1). We computed the ice volume of both glaciers, which is also given in Table 1.

The radargrams depict a clear structure of polythermal glacier, though the volume of cold ice is larger than that usually found by the authors for glaciers of similar size in central and western Nordenskiöld Land, and in Wedel Jarlsberg Land. The volume of cold ice is especially large for Elfenbeinbreen and its tributary glaciers. By contrast, the thickness of the cold layer of Sveigbreen is much thinner.

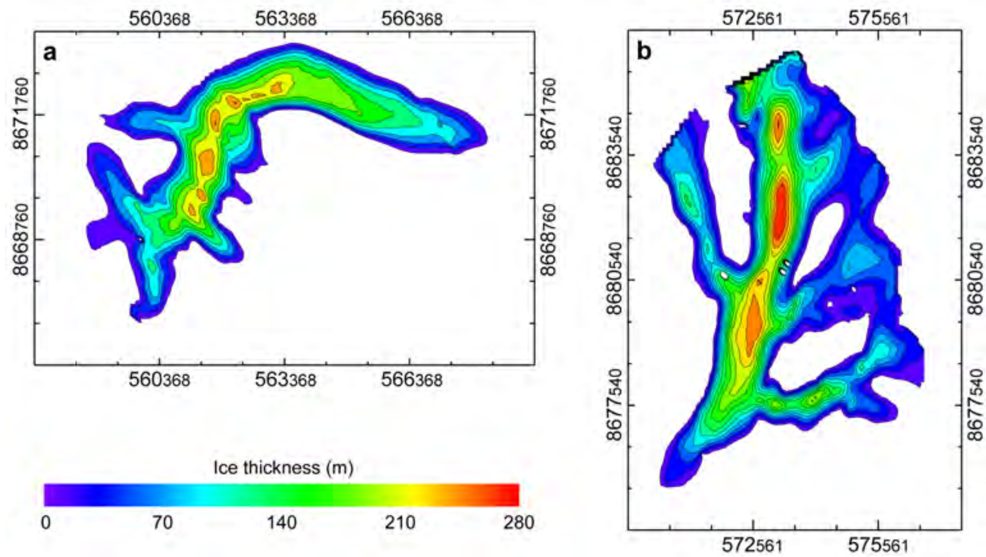

Figure 2. (From Navarro *et al.* (2015)) Ice-thickness maps of Sveigbreen (a) and Elfenbeinbreen (b). Contour line interval is 20 m. UTM coordinates for sheet 33X are shown.

In Figure 1 we show the sections of the radar profiles where a temperate ice layer has been clearly identified. Comparing figures 1 and 2, it can be seen that, in general, the temperate ice appears in the zones with thickest ice. An exception to this is the zone of thickest ice of Elfenbeinbreen, which appears to be made up mostly of cold ice, though it could be temperate-based. The firn layer of Elfenbeinbreen is generally thicker as compared with Sveigbreen. This difference is not likely due to climatic reasons, but could be partly explained by snowdrift processes. However, the different distributions of the thickness of the firn layers of both glaciers do not provide an explanation for the differences in thickness of their cold and temperate ice layers. This calls for further research, with focus on the accumulation pattern and the dynamics of these glaciers.

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Decadal slowdown of a land-terminating sector of the Greenland Ice Sheet during sustained climate warming - implications for wider ice sheet hydrology-dynamics coupling

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The relationship between surface melting and ice motion will affect how the Greenland Ice Sheet (GrIS) responds to climate and the structure of the subglacial drainage system may be crucial in controlling how changing melt-rates impact ice motion. Ice sheet motion varies over seasonal time-scales in response to varying surface meltwater inputs to the ice-sheet bed which lubricate the ice-bed interface, resulting in periods of faster ice motion. However, the impact of hydro-dynamic coupling on ice motion over decadal timescales remains poorly constrained. Here we utilise Landsat imagery to generate a record of annual motion spanning three decades extending back to 1985. Our observations cover an ~8000 km^2 area along ~170 km of predominantly land-terminating margin of the west GrIS, and extend ~50 km inland to 1100 m asl. We find that that annual ice motion was 12% slower in 2007 - 2014 compared to 1985 - 1994, despite a corresponding 50% increase in surface meltwater production. Less than 1/3 of the observed slowdown can be explained by a reduction in internal deformation caused by marginal ice sheet thinning, and we therefore hypothesise that increases in subglacial drainage efficiency, associated with sustained larger melt volumes, have reduced basal lubrication resulting in slower ice flow. Our findings suggest that hydro-dynamic coupling in this section of the ablation zone resulted in net ice motion slowdown over decadal timescales - not speedup as previously postulated. Increases in meltwater production from projected climate warming may therefore further reduce the motion of land-terminating margins of the ice-sheet indicating such margins are more resilient to the dynamic impacts of enhanced meltwater production than previously thought. The implications of these observations for wider ice sheet hydrology-dynamics coupling are considered.

Understanding the control mechanisms of the front position changes of tidewater glaciers

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Hansbreen is a grounded tidewater glacier in southern Spitsbergen, Svalbard, with a rich history of field and remote-sensing observations. These include: glacier surface topography from the SPIRIT DEM; subglacial topography from GPR; surface mass balance from the European Arctic Reanalysis (EAR); centerline glacier velocities measured from a set of stakes (May 2005 - April 2011); weekly front positions from time-lapse photos (Sept. 2009 - Sept. 2011) and ASTER images; and sea-ice concentrations from time-lapse photos and Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data.

The available data make this glacier a good candidate for evaluating and comparing various mechanisms and controls of calving, some of which are tested in this contribution. In particular, we use a full-Stokes thermomechanical flow model (Elmer/Ice), incorporating a crevasse-depth calving model, to estimate Hansbreen's front position at a weekly time resolution. The basal sliding coefficient is calibrated after each month by solving an inverse model. We investigate the effect of some possible controls of calving, such as the ice mélange back-stress, or the amount of water filling the crevasses (parameterized through the surface meltwater), by examining the model's ability to reproduce the observed seasonal cycles of frontal advance and retreat.

We find that calving rate under such a regime is highly dependent on the depth of water in crevasses, with a change of just a few meters in water depth causing the glacier to change from advancing to retreating. If a constant amount of water filling the crevasses is set, the model is not able to reproduce the observed seasonal changes of the front. However, if we parameterize the amount of water filling the crevasses by the surface meltwater our model is capable of reproduce the seasonal advances and retreats of the calving front.

Finally, we found that the effect of the ice mélange backstress on the front position was significant, even under low stresses.

Observations of oceanic waters reaching tidewater glaciers in Hornsund, Svalbard

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Recently there has been an increased focus on research in Arctic fjords, as they constitute a link between the land and the ocean. This is the place where different water masses meet, mix and transform and can significantly influence the stability of marine terminated glaciers.

Hydrographic measurements in Hornsund, the southernmost fjord of Spitsbergen, span the period 2001 - 2015. Data on water temperature and salinity were collected every July during summer Arctic cruises onboard RV Oceania, the ship belonging to the Institute of Oceanology PAS. Moreover, field expeditions realized under Polish-Norwegian projects AWAKE and AWAKE-2 allowed to obtain a unique data collection including time series from mooring systems and measurements carried out every week along fixed sections starting from April/May until late August between 2011 - 2015. The main focus was to look into water mass evolution in a small glacial bay, Hansbukta, in close vicinity of Hans Glacier.

Summer measurements allowed us to obtain a general overview of water masses observed in the fjord and reveal significant changes between 2001 - 2015. On the basis of weekly measurements in front of Hans Glacier the evolution of oceanic waters reaching the Glacier could be described. The shift between an Arctic (winter) and Atlantic (summer conditions has been observed.

Data analysis shows that the general annual cycle of water mass transformation is modified by local events observed on a short time scale (like changes in sea ice conditions or waters entering Hornsund) and thereby waters of the fjord can play an important role as a factor controlling and modifying calving processes.

Integrated firn elevation change model for glaciers and ice caps

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My motivation is to address uncertainties which result from converting geodetic volume change into glacier mass balance. The uncertainties result from an inadequate conversion factor (density) which neglects altitude dependent firn density variations, firn layer thickness and not homogenous density variations with varying climate conditions. I am developing a transferable firn densification resp. elevation change model to minimize this systematic error and to raise the accuracy of glacier mass balances measured in geodetic manner. In this context, I devote myself to the question, what is the change in height by the densification of firn on glaciers and ice caps.

In the present stage of development, the model is mainly based on an existing integrated snowpack and ice surface energy and mass balance glacier model. It consists of a Surface Energy Balance (SEB) section coupled with a subsurface section. The model will have a not equidistant layer based subsurface structure. The vertical lower limit will be the pore closure boundary.

The aim is to develop a firn elevation change model forced by SEB parameters (incoming shortwave radiation, air temperature, relative humidity, air pressure, wind speed, all-phase precipitation, cloud cover fraction). For this purpose I selected the Vestfonna ice cap in the northeast of the Norwegian archipelago Svalbard as a test site. Further study sites with a magnificent in situ measurement archive are welcome.

For calibration and validation of forcing climate data and the model itself, I use the in situ data archive of field campaigns between 2007 and 2010 (e.g. climate data, firn density profiles and ablation measurements) and multimission satellite data from 2003 to 2015 (to derive elevation data and the transient snow line).

Supraglacial and Ice-Marginal Lakes on the Devon Ice Cap and their Response to Recent Climate Warming

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Supraglacial and ice marginal lakes occur widely on and around major ice caps in the Canadian Arctic. Sudden drainage of such lakes can occur during the summer melt season and, in some cases, after the melt season has ended and the lake has frozen over. Such drainage events often have a discernible impact on the flow of the glacier where the draining lake exists and they may be important drivers of the evolution of subglacial meltwater drainage systems. To date, however, there have been few systematic studies of the glaciological and topographic settings in which such lakes form, or of how these influence the drainage behaviour of the lakes. The effect of recent summer climate warming on lake distribution, density, size, and drainage behaviour has also received little attention.

We present an inventory and glaciological classification of supraglacial and ice marginal lakes on the Devon Ice Cap. This includes information on the number of lakes of each type present in 2001, the total area covered by each lake type, the mean size of lakes in each category, the mean elevation at which each lake type occurs, and the mean persistence (in years) of individual lakes in each category. We explore how lakes of each type are distributed across the ice cap, and how changes in summer climate affect both the altitudinal distribution of lakes and the total area covered by each lake type. We describe the morphology and drainage style of lakes in each category, and how the glaciological setting in which they form influences this. We investigate how the total and mean areas of each lake type vary over a single melt season (2007), and how this is related to the style of lake drainage (i.e. overflow versus drainage through the lake floor).

While the total area of lakes at high elevations on the ice cap is responsive to changes in summer mean air temperature, this is not the case at lower elevations. The number and total area of plateau and headwall type lakes, which are found most commonly at high elevations, are especially responsive to changes in mean summer air temperature.

Evolution of tidewater glacier calving front morphology in a high resolution ocean model

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Rapid dynamic changes at the margins of the Greenland Ice Sheet, synchronous with ocean warming, have raised concern that tidewater glaciers can respond rapidly and sensitively to ocean forcing. One way in which ocean forcing would manifest is through the melting of the submerged parts of tidewater glacier calving fronts, with the spatial distribution of submarine melt a control on their morphology. Calving front morphology has thus far received little attention and yet has the potential to significantly impact calving rates and therefore tidewater glacier dynamics.

Here we present a model which allows us to study the evolution of calving front morphology in two dimensions. We outline a new routine for calculating submarine melt rates from ocean models at calving fronts of arbitrary geometry, and for adjusting this geometry according to the calculated melt rates. This routine is applied to a high resolution (∼1m) non-hydrostatic ocean model (MITgcm) with a glacier boundary (calving front) which evolves in time according to the simulated submarine melt rates.

The model shows, consistent with recent observations, that submarine melting leads to undercutting of tidewater glacier calving fronts. We examine how undercut magnitude, undercut depth and potential steady states respond to variation in subglacial discharge, ice velocity, and fjord stratification. In undertaking this work we aim to elucidate a process which - supposing tidewater glaciers are sensitive to ocean forcing - must provide a fundamental link between ocean and ice.

Snow cover as a freshwater input to the glacier surface. Hansbreen as an example

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Melting of glaciers is very important component of freshwater resources in the polar environment. Seasonal fluctuations of the freshwater supply to glacial drainage systems determine numerous processes e.g. glacier's dynamics and indirectly water circulation in fjords. Hansbreen is a tidewater glacier ending down to Hornsund Fjord (SW Spitsbergen). It is one of better studied Arctic glaciers with data which allow comprehensive analysis of functioning both: glacial system and its couplings with other components of the polar environment.

This paper aims to calculate an amount of freshwater comes from the snow cover deposited on the glacier surface. In spring 2014, the snow cover thickness was measured using the high frequency GPR on Hansbreen. Simultaneously studies of snowpack structure and its physical properties were performed in couple of snow pits in different glacier elevation zones. Based on both: interpolation of snow thickness and spatially variable snow cover density, the snow water equivalent ,has been calculated. The temperature index model was used to estimate snow ablation intensity. An average temperature lapse rate along the glacier together with digital elevation model of its surface were applied. The calculated melting rate was calibrated using data on ablation from the SR-50 ultrasonic sensors of automatic weather stations at the reference glacier sites. Paper presents spatial distribution of potential meltwater supply from snow cover as calculated for this glacier. Validation of this approach applies traditional snowmelt measurements on ablation stakes. Use of this method seems to be an alternative way to quantify freshwater supply to fjords from other glaciers of the area.

Multi-decadal trends in seasonal snow conditions on Svalbard

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The climate in Svalbard is undergoing amplified change with respect to the global mean in response to sea-ice retreat around the archipelago ('Arctic amplification'). Temperature trends in the most recent decades exhibit strong seasonal inhomogeneity and lateral variability across Svalbard is apparent. Changing climate conditions directly affect the evolution of the seasonal snow pack, through its impact on accumulation, melt and moisture exchange. We analyze long-term trends and spatial patterns of seasonal snow conditions in Svalbard between 1961 and 2012. Regional climate model output at 10-km resolution is projected onto a 1-km grid and precipitation downscaling is optimized against winter stake balance data on a set of glaciers around Svalbard. The climate data drive a snow modelling system (SnowModel), with coupled modules simulating the surface energy balance and snow pack evolution. Climate fields reveal a strongly positive temperature trend, particularly in winter, and a weakly positive precipitation trend. In response to changing climate conditions both the dates of snow removal (spring) and onset (autumn) show positive trends, with the latter being dominant implying extension of the snow-free season. Maximum snow depths in winter/spring show a modest increase (+0.01 m w.e. decade^{-1}), while the minimum perennial snow cover in summer declined strongly (from 48% to 36%). As a result, the equilibrium line altitude shows a clear positive trend (22 m decade-1). Rain-on-snow in winter, affecting ground-ice formation and limiting access of grazing animals to food supplies, peaks during specific years (1994, 1996 and 2000) and is found to be concentrated in the lower-lying coastal regions in (south-)western Svalbard.

Simulating the present and future state of firn conditions in Svalbard

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Firn is known to act as a buffer for glacier runoff, since it may store water in both frozen form, due to refreezing, and liquid form, as irreducible or slush water. Ongoing and projected changes in the climate on Svalbard lead to firn thinning and firn line retreat, which amplifies glacier mass loss. We perform synthetic experiments to assess the role of firn conditions on the mass balance of glaciers in Svalbard in a present and future climate. A coupled surface energy balance - firn model is used and a climate forcing for the past (1976 - 2014) and future (2015 - 2100) is constructed from observational data from the Svalbard Airport meteorological station, combined with a seasonally dependent projection scenario from an ensemble of future climate runs for Svalbard. We simulate the mass balance and firn conditions for a range of temperature and precipitation conditions, and discuss the impact for a typical Svalbard glacier. Preliminary results illustrate rapid firn warming, densification and retreat in response to higher melt rates. The significance of winter rainfall and melt on snow and firn conditions becomes increasingly important in a warming climate, causing refreezing in winter to become more pronounced than in summer. In order to assess the impact of refreezing on the surface mass balance, experiments were repeated without allowing for refreezing. In most cases the direct effect of refreezing on the mass balance, namely to reduce the amount of melt that runs off, is found to dominate indirect effects, related to firn heating and surface albedo changes.

Characterizing the recent speed-up (1999-2015) of the Trinity and Wykeham Glaciers, Prince of Wales Icefield, Nunavut, Canada

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Speckle tracking of Radarsat-1/2 data and feature tracking of Landsat-7 imagery is used to determine the velocity structure of Trinity and Wykeham Glaciers (Prince of Wales Icefield, Nunavut) from 1999 - 2015. Over the observation period, the surface velocity of Wykeham Glacier nearly doubled (increasing from ∼200 m a^{-1} in 2000 to ∼400 m a^{-1} in 2015 in the lowermost terminus region), while the surface velocity of Trinity Glacier nearly tripled (increasing from ∼400 m a^{-1} in 2000 to ∼1200 m a^{-1} in 2015 in the lowermost terminus region). As a consequence, ice flux to the oceans from these two glaciers rose from 0.55 ± 0.12 Gt a^{-1} in 2000 to 1.43 ± 0.23 Gt a^{-1} in 2015, accounting for ∼62% of total dynamic discharge from the Canadian Arctic in 2015. A comparison of glacier surface elevations in 2008 (using a DEM derived from SPOT imagery (± ∼6 m)) and 2014 (using NASA ATM data (± ∼10 cm)) indicates surface lowering of ∼-5 m a^{-1} in the lowermost ∼15 km section of Trinity Glacier over this period. Mass balance measurements and modeling suggest that surface ablation in this area is <2 m a^{-1} (Mair *et al.*, 2009; Marshall *et al.*, 2007), which implies that at least half of the observed thinning is dynamically driven. Finally, examination of aerial photos and Landsat-7 imagery reveals that the combined termini of these two glaciers has retreated by ∼5-9 km since the 1960s. This combination of terminus acceleration, thinning and retreat is similar to the dynamic behavior of other Arctic Glaciers (e.g. Helheim Glacier, Greenland) that has been attributed to reductions of resistive stresses at the terminus. If the same process is occurring on Trinity Glacier, the fact that it is grounded below sea level for ∼45 km upglacier from the current calving front may make it particularly prone to significant retreat before re-stabilization can occur.

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Ocean and glaciers interactions in Svalbard area

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Arctic fjords are a link between land and ocean. The inshore boundary of the fjords system is usually dominated by the tidewater glaciers and seasonal freshwater input while its offshore boundary is strongly influenced by oceanic waters. Improved understanding of the fjords-ocean exchange and processes within Arctic fjords is of a highest importance because their response to atmospheric, oceanic and glacial variability provides a key to understand the past and to forecast the future of the high latitude glaciers and Arctic climate.

Rapidly changed Arctic climate requires multidisciplinary and complex investigations of the basic climate components and interactions between them. The aim of the Polish-Norwegian project 'Arctic climate system study of ocean, sea ice and glaciers interactions in Svalbard area' (AWAKE-2) is to understand the interactions between the ocean, atmosphere and cryosphere.

The main oceanic heat source in Svalbard region is the West Spitsbergen Current consisting of multi-branch, northward flow of warm, Atlantic origin water (AW). During its transit through the Nordic Seas, AW releases a large amount of heat to the atmosphere. When entering the Western Svalbard fjords, AW modifies hydrographic conditions, reduces winter ice cover and directly influences tidewater glaciers.

An impact of the AW variability on atmosphere and sea ice is clearly visible with strong correlations between AW properties and air temperature or sea ice coverage. For tidewater glaciers these effects can be recognized, but correlations are weaker due to different processes that influence the intensity of glaciers melting and calving. The dedicated, multidisciplinary approach was adopted to achieve the AWAKE-2 project's aims by carrying out the coordinated meteorological, oceanographic, glaciological and geophysical observations in the Hornsund fjord, the adjacent shelf and ocean.

The measurement strategies, preliminary results of the project and plans for the future research will be presented and discussed.

Dynamics and climate sensitivity of Hans Tausen Iskappe (Greenland)

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Hans Tausen Iskappe (Greenland), situated at 82.5°N, 27.5°W, is the world's northernmost ice cap. During several field campaigns in the 70s and 90s, its ice thickness was measured, mass balance and meteorological measurements were made, and a 345 m deep ice core was drilled (Hammer, 2001). From this ice core it is known that the ice cap (largely) disappeared during the Holocene Thermal Maximum. The present-day ice cap started building up some 3500-4500 years ago in a wetter and slightly warmer climate than at present.

Here we present first thermo-mechanical ice flow modelling results of the ice cap's fundamental climate sensitivity. A 3-D higher-order ice flow model (Fürst *et al.*, 2011; Zekollari and Huybrechts, 2015; Zekollari *et al.*, 2013, 2014) is used, which includes longitudinal and transverse stress gradients (Pattyn, 2003). The surface mass balance model considers snowfall and meltwater runoff. Net precipitation is based on RACMO2.3 output at a 1 km horizontal resolution. Runoff is calculated from a positive degree-day model that includes water retention in the snowpack with parameters derived from field measurements. The simulations are validated and calibrated with field observations complemented with satellite derived surface velocities. The ice cap geometry evolves to a state close to the presently observed for average 1961-1990 climate conditions, but the ice cap is found to already lose a large part of its volume and area under 1981-2010 conditions. Sensitivity analyses point out that the ice cap's northern part, situated on a plateau, is fairly stable under changing climatic conditions, whereas the southern part is much more sensitive. In our analysis we also investigate the effect of higher-order dynamics (compared to the Shallow Ice Approximation) and pay particular attention to what thresholds in the system could lead to a (partial) decay of the ice cap in the future.

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