IASC Workshop on the dynamics and mass budget of Arctic glaciers & proglacial marine ecosystems

Abstracts and Programme

IASC Workshop, 22-24 January 2018
University Center Obergurgl, Obergurgl, Austria.

IASC Network on Arctic Glaciology

IASC Workshop on the dynamics and mass budget of Arctic glaciers & proglacial marine ecosystems

Abstracts and program

Network on Arctic Glaciology annual meeting &
IASC cross-cutting activity on the importance of Arctic glaciers for the Arctic marine ecosystem
22-24 January 2018, Obergurgl, Austria

Organised by Thorben Dunse and Michael Kuhn

Organizing committee of cross-cutting activity:
Thorben Dunse (NAG chair), Renate Degen (MWG), Monika Kędra (MWG), Marit Reigstad (MWG), Martin Sharp (CWG/NAG) and Shin Sugiyama (CWG)

IASC Network on Arctic Glaciology

Cover photo: Basin-3 of the Austfonna ice cap, Svalbard, surging into the Barents Sea. Landsat 8 scenes as captured from TopoSvalbard (Norwegian Polar Institute)

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Preface

The success or failure of field work in the Arctic critically depends on weather conditions. That weather conditions can threaten an international workshop is a different story. Austria on the 21st of January experienced heavy snowfall and strong winds. For the first time in 19 years, the Austrian commission for avalanche forecasting announced the highest level of avalanche danger (level 5). Several roads in the Alps were closed, among them the 20 kilometer stretch leading via Sölden to the alpine resort of Oberurgl. Ten early-birds, including myself, had arrived one day ahead of the workshop. Luckily, both wind and snowfall calmed down during Sunday afternoon, allowing the helicopter to fly and drop explosives in order to release potentially hazardous avalanches. Most workshop participants managed to arrive during this temporary opening of the road. The remaining participants made it on Monday, calling for some flexibility in the original workshop program.

The 2018 annual workshop of the IASC Network on Arctic Glaciology (NAG) took place at the Obergurgl University Center, Obergurgl, Austria. The meeting attracted 42 participants from 16 different countries. The workshop integrated two special activities. The first, “Understanding atmosphere-glacier-ocean interactions and their implications for the pan-Arctic glacier mass budget” represents a long-term strategy of the Cryosphere Working Group and NAG. The second theme broke new ground: an IASC cross-cutting activity of the Cryosphere and Marine working goups of IASC, addressing “The importance of Arctic glaciers for the Arctic marine ecosystem”. Such interdisciplinary work helps to produce research results of relevance to society, in our case especially for people living in the Arctic or benefitting from Arctic ecosystem services, directly or indirectly. Interdisciplinary work requires that researchers from the involved disciplines get to know each-other and learn to understand each-others scientific jargon. I am confident that the IASC cross-cutting activity contributed in building a bridge between the cryosphere and biosphere community. I hope that we can keep up the momentum and elaborate this initiative in the years to come, also involving members from other relevant disciplines, such as physical oceanography, ocean biogeochemistry, as well as terrestrial ecology.

Thanks to everyone contributing to the workshop, making the program as rich and diverse as the weather conditions. During the last two days, participants continued the discussions on the local ski slopes, enjoying their extended lunch breaks in sunshine and fantastic alpine scenery. We will be back in Obergurgl, 27–31 January 2020. In the meantime, I hope to see you all again in Geilo, Norway, 20–24 January 2019!

Thorben Dunse

February 2018

Program

The meeting takes place at the Obergurgl University Center in Obergurgl, Austria, 22 - 24 January, 2018.

Sunday 21 January

ARRIVAL

19:00 - 20:30	**Dinner**

Monday 22 January

08:20 - 08:30	Registration: pick up your name badge and copy of program
08:30 - 08:40	**Welcome** *Michael Kuhn and Thorben Dunse*
08:40 - 10:10	**The importance of Arctic glaciers for the Arctic marine ecosystem - Part 1**
Convener:	*Jason Amundson*
08:40 - 09:10	**Keynote talk** The effect of glacier runoff on Arctic fjord circulation and ecosystem ***Harald Steen****, H. Hop, A.Sundfjord, P. Duarte, P. Assmy, K.M. Kovacs, C. Lydersen, G. Wing Gabrielsen, J. Aars, A.Everett, C. Hamilton. H. Strøm, S. Descamps, J. Kohler*
09:10 - 09:30	On the link between glacier-freshwater runoff and summer phytoplankton growth in seas around Svalbard ***Thorben Dunse****, K. Dong, K.S. Aas, L.C. Stige*
09:30 - 09:50	Can increased meltwater fluxes 'fuel' enhanced productivity in the North Atlantic? ***Mark Hopwood****, T. Browning*
09:50 - 10:10	Functional Trait patterns in Arctic fjord ecosystems ***Renate Degen***
10:10 - 10:40	**Coffee break**
10:40 - 12:10	**The importance of Arctic glaciers for the Arctic marine ecosystem - Part 2**
Convener:	*Emilia Trudnowska*
10:40 - 11:10	**Keynote talk** Nutrient delivery from polar glaciers to downstream ecosystems **Andy Hodson**
11:10 - 11:30	Biogeochemical and microbial variability in subglacial systems on the Devon Ice Cap, Canadian Arctic ***Ashley Dubnick****, M. Sharp*

11:30 - 11:50	Estimating the contribution of trace metal contaminants from Devon Ice Cap, NU to the Ocean (2005-2015) ***David Burgess***, *J. Zheng, W. van Wychen*
11:50 - 12:10	Particles and plankton facing the glaciers around Svalbard ***Emilia Trudnowska***, *K. Draganska-Deja, A.M. Kubiszyn, K. Blachowiak-Samolyk*
12:10 - 12:30	Physical and Biogeochemical ocean studies at the boundary region of Bowdoin Glacier and its Fjord, Northwestern Greenland ***Naoya Kanna***, *S. Sugiyama, D. Sakakibara, Y. Fukamachi, D. Nomura, S. Fukumoto, S. Yamasaki, E. Podolskiy, A. Yamaguchi*
12:30 - 14:40	**Lunch break**
14:40 - 16:00	**Glacier mass balance & glacier-atmosphere interactions**
Convener:	*Carleen Reijmer*
14:40 - 15:00	Long-term projection of Arctic valley glaciers based on finite element simulations ***Songtao Ai***, *Z. Wang, G. Lin, Y. Yang*
15:00 - 15:20	Preferential water flow in snow and firn: evidences, consequences and simulation ***Sergey Marchenko***, *V. Pohjola, R. Pettersson, W. van Pelt, H. Machguth, C. Reijmer*
15:20 - 15:40	Global-scale 21st century glacier mass and runoff changes ***Regine Hock***, *M.Huss, B. Marzeion, A. Bliss, R. Giessen, Y. Hirabayashi, V. Radic, A. Slangen*
15:40 - 16:00	Mass balance of Svalbard glaciers 1957–2015 ***Jon Ove Hagen***, *T. Dunse, T. Eiken, J. Kohler, G.Moholdt, C. Nuth, T.V. Schuler, T. Østby*
16:00 - 16:30	**Coffee break**
16:30 - 17:20	**Understanding atmosphere-glacier-ocean interactions and their implications for the pan-Arctic glacier mass budget - Part 1**
Convener:	*Andreas P. Ahlstrøm*
16:30 - 17:00	**Keynote talk** A consistent estimate of Pan-Arctic glacier frontal ablation, 2000-2015 ***Luke Copland***
17:00 - 17:20	An analysis of the errors in the calculation of ice discharge through flux gates. Application to Nunavut tidewater glaciers, Canada. *P. Sánchez-Gámez,* ***Francisco Navarro***
17:20 - 17:45	**Poster introduction by authors** (1 slide and max. 2 minutes per person)
17:45 - 19:15	**Poster session** Note: posters remain up until Wednesday
19:30 - 21:00	**Dinner**

Tuesday 23 January

08:30 - 10:30	**The importance of Arctic glaciers for the Arctic marine ecosystem - Part 3**
Convener:	*Andy Hodson*
08:30 - 09:00	**Keynote talk** Retreating glaciers impacts on Arctic marine fjord ecosystem *Monika Kędra, J.M. Węsławski,* ***Renate Degen***
09:00 - 09:20	Variations in subglacial discharge and submarine melting during tidewater glacier retreat ***Jason Amundson****, D. Carroll*
09:20 - 10:10	**Open discussion:** Collaboration between glacier and marine biology/ecology communities ***Moderator: Andy Hodson***
10:10 - 10:40	**Coffee break**
10:40 - 12:00	**Atmosphere-glacier-ocean interactions - Part 2**
Convener:	*Michael Kuhn*
10:40 - 11:00	Climate, and Surface energy and mass balance of Nordenskiöldbreen, Svalbard ***Carleen H. Reijmer****, V. Pohjola, W.J.J. van Pelt, R. Petterson*
11:00 - 11:20	Spatio-Temporal Variability of Refreezing in Firn in Southwest Greenland ***Federico Covi****, R. Hock, G. Corti, A.K. Rennermalm, M. Tedesco, C. Miège, J. Kingslake, S.Z. Leidman, S. Munsell*
11:20 - 11:40	The relationship between albedo and spring warming over Canada's largest glaciated elevation gradient ***Scott Williamson****, L. Copland, D. Hik, G. Clarke*
11:40 - 12:00	A coincidental measure of tidal stress propagation in Bowdoin Glacier, Northwest Greenland ***Julien Seguinot****, M. Funk, S. Sugiyama*
12:00 - 16:00	**Very long lunch break / Skiing**
16:00 - 16:30	**Coffee break**
16:30 - 17:30	**Atmosphere-glacier-ocean interactions - Part 3**
Convener:	*Federico Covi*
16:30 - 16:50	Greenland ice sheet equilibrium line altitude variations: 2000–2017 ***Jason Box****, H. Machguth, R.S. Fausto, W.T. Colgan, Roderik, P. Smeets, P.L. Langen*
16:50 - 17:10	A minimal model of tidewater glacier evolution ***Martin Lüthi****, R. Mercenier, A. Vieli*
17:10 - 17:30	Enhanced models for mass balance and ice dynamics of Svalbard glaciers ***Thomas Zwinger****, Y. Gong*[2]*, D. Vallot, I. Välisuo, J. Åström*
17:30 - 17:45	**Short break**
17:45 - 19:15	**IASC Network on Arctic Glaciology Open Forum meeting** *Thorben Dunse, Francisco Navarro, ...*

19:30 - 21:00	**Dinner**

Wednesday 24 January

08:30 - 10:30	**Glacier mass balance & glacier-atmosphere interactions**
Convener:	*Bernhard Hynek*
08:30 - 08:50	The importance of shear-margin softening for abrupt velocity variations at Upernavik Isstrøm, Greenland *S. Hillerup Larsen* ***Andreas P. Ahlstrøm****, A. Kusk, P.L. Langen, C.S. Hvidberg*
08:50 - 09:10	Factors influencing asymmetric pattern of snow distribution on Hansbreen (Svalbard) ***Mariusz Grabiec****, D. Ignatiuk, M. Laska, A. Uszczyk, T. Budzik*
09:10 - 09:30	Dynamics of hydrological and hydrogeological processes on the Werenskioldbreen forefield in ablation season 2017 - short hydrological balance. ***Katarzyna Stachniak****, S. Sitek, K. Janik, D. Ignatiuk, J. Jania*
09:30 - 09:50	10 years of mass balance over a small Arctic basin. The example of Austre Lovénbreen (Svalbard) ***Eric Bernard****, Sophie Schiavone, F. Tolle, M. Griselin, A. Prokop, J.M. Friedt, D. Joly*
09:50 - 10:20	**Coffee break**
10:20 - 11:40	**Ice dynamics & glacier-elevation change**
Convener:	*Regine Hock*
10:20 - 10:40	Assesment of the current state and development of Austre Grønfjordbreen glacier by a complex of glaciological, physico-mathematical and remote methods ***Nelly Elagina****, S. Kutuzov, R. Chernov, I. Lavrentiev, T. Vasilyeva, B. Mavlyudov, A. Kudikov*
10:40 - 11:00	ASTER-derived glacier volume changes in Alaska or Norway ***Robert McNabb***
11:00 - 11:20	Elevation changes of Greenland's glaciers using AeroDEM, ArcticDEM and TanDEM-X ***Jacqueline Huber****, L. von Albedyll, H. Machguth, M. Zemp*
11:20 - 11:40	Continuous monitoring of ice motion and discharge of outlet glaciers of Greenland and Artic ice caps by Sentinel Satellites *Thomas Nagler,* ***J. Wuite****, M. Hetzenecker, S. Scheiblauer, H. Rott*
11:40 - 11:50	Final words *M. Kuhn / T. Dunse*
11:50 -	**Lunch / Skiing / Side events / Early departure**
19:00 - 20:30	**Dinner**

Posters

- Quantification of sediment transport into Kongsfjorden due to the glacier melt dynamics of Austre Lovenbreen using terrestrial laser scanning ***Alexander Prokop***, *F. Tolle, E. Bernard, J. M. Friedt*
- RES ice thickness and frontal ablation of outlet glaciers in Russian Arctic *A. Glazovsky, I. Lavrentiev, E.Vasilenko,* ***Nelli Elagina***
- Towards a remote monitoring of surface mass balance at Freya Glacier (NE-Greenland) ***Bernhard Hynek***, *W.Schöner, Binder, G. Weyss*
- Controls on glacier surging and velocity variations in the St. Elias Mountains, Yukon ***Brittany Main***, *L. Copland, W. Van Wychen, C. Dow*
- A.P. Olsen Ice Cap (NE-Greenland): What drives the snow distribution? ***Daniel Binder***, *S. Hillerup Larsen, M. Citterio*
- Characterizing the ice-ocean interaction at the Upernavik Glacier using in-situ and satellite observations ***Dora Kovacs***, *A.P. Ahlstroem*
- Using photogrammetry for quantitative glacier analyses back to the 1800's ***Erik S. Holmlund***, *P. Holmlund*
- Surge dynamics of western basin of the Vavilov Ice Cap assessed by remote sensing data *I. Bushueva, A. Glazovsky, G. Nosenko,* ***Nelli Elagina***
- Greenland, Canadian and Icelandic land-ice albedo grids (2000–2017) ***Jason Box***, *R. Fausto, K. Mankoff, D. van As, K. Steffen, and the PROMICE project team (GEUS)*
- Fresh water input to Arctic fjord - Hornsund (Svalbard) as an example ***Małgorzata Błaszczyk***, *D. Ignatiuk, A. Uszczyk, K. Cielecka, M. Grabiec, J. Jania, M. Moskalik, W. Walczowski*
- Assessment of proglacial moraine response to climate shift, an Arctic basin as a witness ***Sophie Schiavone***, *F. Tolle, A. Prokop, E. Bernard, J.M.l Friedt, M. Griselin, D. Joly*

Participants

Group photo: The 2018 IASC-NAG workshop attracted 42 participants from 16 countries.

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Wuhan University, China

(Young scientists receiving IASC travel support are marked *).

Minutes of the Open Discussion: Collaboration between glacier and marine biology/ecology communities

Moderator: Andy Hodson
Minutes: Carleen Reijmer, Renate Degen and Thorben Dunse

The cross-cutting activity ***The importance of Arctic glaciers for the Arctic marine ecosystem*** between the Cryosphere and Marine Working Groups of IASC was distributed over three workshop sessions (see program for full overview). A wide range of topics was covered as part of 10 oral presentations, thereof 3 keynote talks:

- *The effect of glacier runoff on Arctic fjord circulation and ecosystems* by Harald Steen, Norwegian Polar Institute;
- *Nutrient delivery from polar glaciers to downstream ecosystems* by Andy Hodson, The University Center in Svalbard;
- *Retreating glaciers impacts on Arctic marine fjord ecosystem* by Monika Kedra, Institute of Oceanology, Polish Academy of Sciences (presented by Renate Degen, University of Vienna

The final session of presentations lead into an open discussion.

Andy Hodson opens the discussion by providing a brief overview on changes in the Arctic system due to climate change and their impact on the marine ecosystems and sea birds. These changes include the retreat of tidewater glaciers to form land-terminating glaciers with glacier forefields and related changes in the characteristics of sediment and nutrient transport, changes in glacier runoff, the lack of fast ice in fjords and rising sea-surface temperatures. These issues have also been addressed by several speakers during the cross-cutting session. **Harald Steen** and **Mark Hopwood** give their additional views on this.

Central questions of the discussion are:

- What glaciological information/data are useful for the marine biology/ecology community and vice versa?
- What data/information can glaciologists readily provide to the marine biology/ecology community and vice versa?
- Collaborations between glacier and marine ecology communities in field work, etc.?

Renate Degen poses the following questions on behalf of the marine biology/ecology communities:

- Is glacier freshwater discharge uniform and predictable or dominated by unpredictable events?
- Is mineral sedimentation rate predictable and how much do mineral sedimentation rates change over time?
- Is freshwater discharge and sediment flux directly linked or independent from each-other?
- Is relevant data readily available? Are there data bases you can login and retrieve the data? Quick answer: there is data, but not readily available in data bases. There are papers and websites with some data. Efforts towards a database on glacier freshwater, sediment and nutrient supply in the past and predictions into the future would be of great interest to the marine ecology community.

Some members of the glacier community like to learn more about the specific requirements of the data, e.g. what are the specific data needs; is gridded data enough; on what temporal or spatial scales; separation from surface runoff, subsurface water flow and ice berg discharge of tidewater glaciers?

Mark Hopwood mentions that coupling of models providing local meltwater input volumes (split into ice melt, subglacial and supraglacial components) with models providing water dynamics in the fjords as well as the impact on chemistry and biology at a fjord scale would be valuable- but are presently beyond reach because of the unique characteristics of each individual fjord and the fact that processes critical to controlling fjord circulation are subscale with respect to ocean biogeochemical models.
Unfortunately, physical oceanography is not represented in the audience, to discuss this in greater detail. To a first degree very useful are changes in time: diurnal cycle, the increase of the melt area in time, the impact of (increased) rain amounts. Of special interest is how this affects discharge in general and sedimentation rates, in particular. Information on where and when water enters the system is of interest as well, but depends on the type of study.

Sedimentation rates are not easily determined and especially difficult to determine for tidewater glaciers. Polish researchers have a long term program in determining turbidity (with traps in the water) in Hornsund. Not all data is published yet.

Martin Lüthi suggests that a lot of the freshwater discharge is episodic in nature and linked to e.g. rain events, lake drainage and other extreme events that potentially contribute more sediment per water volume than at average rate of freshwater runoff/discharge.

Concerning sediment discharge captured in satellite-derived ocean color products, **Mark Hopwood** remarks that satellites only pick up sediments reaching the surface in plumes, while a lot of the particles suspended deeper in the water column are not detected and these sub-surface plumes can have important biogeochemical impacts, e.g. on organic carbon removal from the water column and on organism feeding strategies.

Harald Steen informs that the marine biology/ecology communities are interested in information on glacier freshwater, sediment and nutrient discharge, as well as temperature and light regime in proglacial marine environments. All of these are more or less useful depending on the goal of the research.

Luke Copland reminds of the ongoing IASC-NAG initiative to provide the first consistent estimate of glacier frontal ablation, i.e. ice berg discharge and submarine melting of the glacier front on a pan-Arctic scale for the time period 2000 - 2015. Together with existing model estimates of glacier runoff from surface melt, this will provide a complete picture of glacier freshwater discharge over the Arctic.

What can the marine biological/ecological community provide for the glaciological community?

Andreas Ahlstrøm poses the question if the history of sediment yield or the presence of specific organism can tell us something about the changes in glacier behavior?

Andy Hodson is interested in info on bacterial secondary production to track carbon. How much carbon gets buried in the sediments?

Thorben Dunse suggests that collaboration between the glacier and marine communities offer opportunities in field investigations with respect to proglacial marine environments. Glaciological field investigations are generally restricted to easily and safely accessible regions of glaciers, avoiding in particular active dynamic regions, such as crevassed terminus regions of fast flowing tidewater glaciers. Marine investigations of proglacial marine environments approach the glacier front from the seaward side. Boat access would allow to study glacier-ocean interactions, including ocean forcing of frontal ablation and the magnitude of undercutting of the calving front by submarine melting, e.g. by multi-beam echo sounding. CTD measurements provide information on freshwater discharge and water samples insights into the nutrient content of the discharge.

Several people remark that sharing of resources on vessels is often difficult, since the amount of people and the amount of research to be done is much larger than the time available. **Renate Degen** mentions that the Marine Working Group may function as a mediator, here.

Someone suggests that collaborations between glacier and marine biology/ecology communities should rather be established on an individual basis. The CWG (NAG) and MWG may, however function as a mediator.

Francisco Navarro stresses once more that a follow-up of the present activity should try to engage physical oceanographers, not present at this meeting. **Harald Steen** notes that project TIGRIF (Tidewater Glacier Retreat Impact on Fjord circulation and ecosystems) by the Norwegian Polar Institute and partner institutions succeeded in bringing together glaciologists, marine ecologist/biologists, as well as oceanographers.

Follow-up activities of the present cross-cutting initiative were also discussed during the IASC-NAG open forum meeting (see separate minutes).

Minutes of the IASC-NAG Open Forum meeting

Chair: Thorben Dunse
Minutes: Carleen Reijmer
Invited to attend: all participants of the workshop.

Agenda

1. Introduction to IASC and NAG
2. Funding
3. Discussion on future possible activities
4. Future meetings
5. Book of extended Abstracts
6. Anything else?

Ad. 1

- IASC: International Arctic Science Committee (https://iasc.info/; non-governmental organization promoting Arctic research in general
- IASC works mainly through its five working groups: (Atmosphere, Cryosphere, Marine, Social & Human, Terrestrial)
- IASC does not fund actual research but promotes research by providing seed money for workshops and summer schools.
- NAG: Network Arctic Glaciology (https://nag.iasc.info/), started out as a working group in 1994, then was renamed Network, in which networks worked separately from the working groups, now NAG is integrated under the umbrella of the Cryosphere working group. The main objective of NAG is to facilitate research on the dynamics and mass budget of Arctic glaciers (more objectives on the website) and its main activity is the annual meeting.
- The network has a loose organizational structure build around a chair (Thorben Dunse), a vice chair (Martin Sharp) and national representatives from 18 countries engaged in Arctic Research.

Ad. 2

The activities of NAG (the annual meeting) are mainly funded by grants from IASC and its Cryosphere Working group (CWG). The Obergurgl 2018 meeting is sponsored by the CWG (€6750) as part of its focus area on tidewater glacier dynamics and response to climate change, focusing on atmosphere-glacier-ocean interaction. Additional funding (€3500) comes directly from IASC being a cross cutting initiative. Most of the funding is used for travel funds for early career scientists, the rest (± €2750) for the venue (conference room and coffee breaks).

The funding structure of IASC and its working groups has changed recently. In 2017, IASC provided k€35 for cross cutting initiatives. In addition, the working groups could spend k€20, each, of which at least k€5 also had to be spend on cross cutting activities. In 2018,all funding will be distributed through the working groups and not by IASC, directly. Each working group will allocate k€27, of which k€12 must be spend on cross cutting initiatives. In coming years, NAG can again try to get funding from IASCs CWG and maybe for cross cutting initiatives also from other working groups.

Ad. 3

Jason Box opens the discussion by suggesting to go back / keep focusing on atmosphere - glacier - ocean interactions, focusing on the physics. Or focus on the role of glaciers in transport of nutrients/sediment /biochemistry. A note to make here is that the physicists in the Marine WG did not show any interest in joining the current activity. **Mark Hopwood** notes that there are no marine fjord physicists in the Marine WG.

Martin Lüthi points out that we should not think in terms of IASC working groups but in what we would like to do. That means including fjord physicists, even though they are not active in the Marine working group.

Mark Hopwood suggests a few names/groups that are leading in this topic for the Arctic regions, it might be useful to include them in this initiative:
- Fiamma Straneo, Scripps Institution of Oceanography
- David Sutherland, Earth Sciences University of Oregon
- John Mortenson, Greenland Institute of Natural Resources
Problem is to get them to the meeting since the PARCA meeting is around the same time as this meeting and most of these people will more likely go to the PARCA meeting.

Thorben Dunse, Jon Ove Hagen, Heinz Miller and Carleen Reijmer all suggest to go further on the path that we are on now: thus continue the collaboration with the marine biological/ecological community. This meeting is a promising start, we should develop some joint projects, plus continuity is important as well. **Harald Steen** adds that continuity might also help to promote the existence of this network and its activities better.

Andy Hodson suggests that perhaps not only tidewater glaciers are interesting sources of nutrients and sediments, but land terminating glaciers provide them as well through glacier fed rivers. He suggests to connect to two groups, ESSAS (Ecosystem Studies of Subarctic and Arctic Seas) and GLAC-HYDROECO-NET, addressing marine and freshwater ecosystems, respectively. The group are, however, not related to IASC.

Martin Lüthi adds a new suggestion: add long term perspectives, perhaps have a special session on the long time scales. Martin Sharp and Jason Box already are involved in initiatives to look at processes and data sets over long time scales.

Coming back to the lack of physical oceanographers and fjord physics specialists, **Renate Degen** suggests to first contact people from that disciplines that might be interested and then involve the Marine WG in order to qualify for cross cutting funding.

Jason Amundson notes that not only physical oceanographers are missing, but also experts on sediment transport. We should perhaps also include geomorphologists in this initiative.

Francisco Navarro suggests that we should do something together in the mean time, such as writing a cross-disciplinary paper, in order to get some momentum in this initiative. Else there will not be much progress until the next meeting. **Mark Hopwood** had some ideas for potential synthesis papers and remains in contact with Andy Hodson and a few other workshop participants.

Martin Lüthi suggests to look at the need of the biologists and see if we can provide that need. Renate Degen mentions that sedimentation rates will be very useful, as will information to relate sedimentation rates to melt rates/flux.

Andreas Ahlstrøm mentions that there will be an IGS conference on sedimentation in May 2019.

Ad. 4

In the 2016 meeting in Maine (US), Norway was suggested to host the 2019 meeting. Another option was Japan. Timing of the meeting will be similar to this year, in either the last two weeks of January, or the first week of February. January is preferred regarding holidays and teaching schedules. For Norway, both Finse and Geilo are suggested. Geilo seems to be a better location with respect to access, options for outdoor activities and is also considerably cheaper. It will then be at the same venue as the 2004 IGS conference. **Thorben Dunse** will contact Geilo and, if necessary, other potential meeting venues in Norway for availability and specific offers and follow up the arrangements.

Obergurgl is chosen unanimously as the venue for the 2020 meeting. **Michael Kuhn** will arrange that.

Update: Venue and dates for the next two annuals meetings are now settled.

- **2019**: Bardøla Hotel, Geilo, Norway, 20–24 January 2019
- **2020**: University Centre Obergurgl, Obergurgl, Austria, 27–31 January 2020

The workshops will be anounced via Cryolist during late summer of the previous year and more information will also be available on the IASC-NAG website (https://nag.iasc.info/workshop).

Ad. 5

As every year, there is the possibility to submit an extended abstract for the final book of abstracts. Deadline is 1 March 2018. Please provide the abstract in a word document and separate figure documents, and send everything to Thorben Dunse.

Ad. 6

No other issues.

Abstracts

Quantification of sediment transport into Kongsfjorden due to the glacier melt dynamics of Austre Lovenbreen using terrestrial laser scanning

Alexander Prokop[1], Florian Tolle[2], Eric Bernard[2], Jean Michel Friedt [2]

1 UNIS, The University Centre in Svalbard
[2] ThéMA Laboratory - CNRS - Université Bourgogne Franche-Comté

Climate warming causes a decrease of glaciers in Svalbard. This results in significant changes of the geomorphology of areas in glacier catchments where ice and permafrost is melting. In particular the snout of the glacier melts drastically and the water outflow of the glacier changes sometimes its direction. Sediment and bed load transport forms new river beds in the moraine, and the sediments involved are transported downstream into the fjords. In recent years terrestrial laser scanning technology has developed significantly, so it is possible to measure the surface of a whole glacier catchment such as the Austre Lovenbreen in high resolution just in a few days or even in one day. The measuring range of 6000 m combined with a very low beam divergence of the laser beam allows fast and accurate measurements of an area of 4 km^2 just from one scan position. This advances made it possible that we could track all surface changes via differentiating digital surface models of the Austre Lovenbreen catchment using repeated terrestrial laser scanning surveys in 20 cm resolution and with 10 cm accuracy. In this work we show how the geomorphology of the scanned area changed in just 2 years from 2016 to 2017. In this time frame the glacier outflow changed its riverbed and significant amounts of sediments where transported through the moraine into the fjord, which changed the morphology of the coastline as well. Reflectance values of the laser allowed us to distinguish between snow, ice and rock material. In our presentation we explain the methodology of the terrestrial laser scanning surveys and discuss the results of how much material was removed in the new river bed throughout the moraine, how much sediments where accumulated at the coast line and how much of the material disappeared in the fjord.

RES ice thickness and frontal ablation of outlet glaciers in Russian Arctic

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1 Institute of Geography RAS, Department of Glaciology, Moscow, Russia
2 Institute of Industrial Research 'Akadempribor', Uzbekistan Academy of Sciences, Tashkent, Uzbekistan

Frontal ablation (the sum of ice loss through calving and submarine melt) of tidewater glaciers and ice caps in the Russian Arctic is poorly known. Meanwhile it is an important component of their mass balance, and its knowledge is strongly required when considering the iceberg risk in off-shore industrial activities.

Study area is located in three archipelagoes of the Russian Arctic with total glacierized area 51,591 km^2, including Novaya Zemlya (NZ) 22,128 km^2, Franz Josef Land (FJL) 12,762 km^2, and Severnaya Zemlya (SZ) 16,701 km^2 [1].

To assess the frontal ablation the data on ice thickness, ice velocity and glacier front change are required. Data on ice thickness of 31 glaciers (12 on NZ, 11 on FJL, and 8 glaciers on SZ) were obtained during our airborne 20 MHz RES campaigns in 2014–2016. Data on variations of glacier fronts from 2001 to 2016 were extracted from Landsat satellite imagery. Glacier surface velocities from 2014 to 2016 were based on feature tracking on repeat Landsat-8 imagery using COSI-Corr package and from GoLIVE v.1 [2] data set combined with continuous records from seven GPS beacons installed on five glaciers. ArcticDEM data on glacier ice surface combined with RES ice thickness data were used to compile glacier bedrock maps and transects.

Frontal ablation is estimated for each glacier as a sum of the ice flux through a fixed fluxgate above the position of the calving front, and the ice volume change in the terminus below the fluxgate due to advance or retreat. The spatially fixed fluxgate is defined approximately perpendicular to the ice flow, 250–1500 m up-glacier from the actual calving front. The depth-averaged speed is extracted from the surface velocity field in increments of 25 m along the fluxgate and weighted by a correction factor 0.9. The ice thickness is extracted in the same points from the ice thickness maps or transects. Radar two-way time data were converted to ice thickness using radio wave propagation speed 168 m mcs^{-1}. We do not include in our estimations all glaciers without RES data, and also the surging western basin of the Vavilov Ice Cap and disintegrating Matusevich Ice Shelf (both SZ). Mean ice thickness at glacier fronts is in average: from 60 at eastern coast to 105 m at western coast of NZ; 107 m on FJL, and 117 m on SZ. Maximum ice thickness at glacier front has the Inostrantsev Glacier on NZ: 216 m in average (maximum ~400 m) (Fig.1).

Frontal ablation rate of RES surveyed glaciers is assessed as: 2.05 km^3 a^{-1} on NZ (12 glaciers) including 0.51 km^3 a^{-1} on eastern coast (4 glaciers) and 1.54 km^3 a^{-1} on western coast (8 glaciers); 1.66 km^3 a^{-1} on FJL (11 glaciers); and 3.07 km^3 a^{-1} on SZ (8 glaciers). Share of terminus position changes in total frontal ablation is: 28% on NZ (32% eastern coast and 26% western coast), 27% on FJL, and 24% on SZ.

Our assessment of annual frontal ablation of outlet glaciers in the Russian Arctic as 7 km^3 of ice is a minimal one, because it based on the data set of only 31

RES-surveyed glaciers. This set covers less than a quarter of calving glaciers on NZ and SZ, and even less on FJL. But a simple increasing of our assessment in proportion to the number or area of all calving glaciers will not give the correct overall estimate. Input of studied glaciers in our assessment is very unequal. The following 6 glaciers provides nearly 60% of frontal losses in our estimate: No 8, No 7 and Issledovateley Glaciers on SZ, Inostrantsev and Vershinskiy Glaciers on NZ, and Znamenitiy Glacier on FJL (1.04, 0.63, 0.76; 0.71, 0.3; and 0.69 km a^{-1}, respectively). Terminus retreat is an important component, constituting near a quarter of the frontal ablation of studied glaciers.

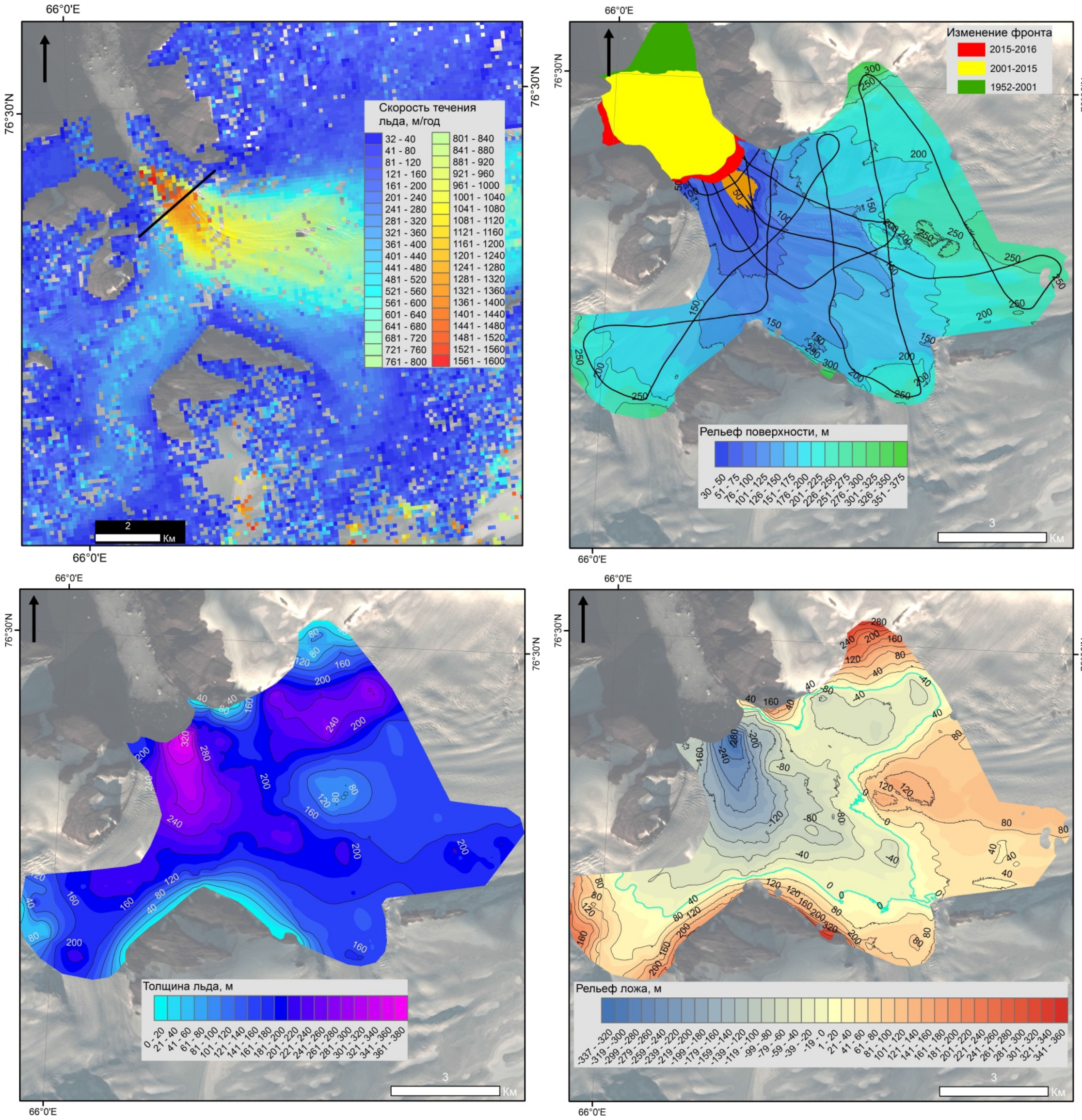

Figure 1. Inostrantsev Glacier, Novaya Zemlya: a) ice surface velocity (m a^{-1}); b) ice surface (m a.s.l.); c) ice thickness (m), d) bedrock elevation (m)

Acknowledgments. This study is supported by the Russian National Foundation, grant 14-37-00038, and the Arctic Program of the Presidium of the Russian Academy of Sciences. ArcticDEM is provided by the Polar Geospatial Center under NSF OPP awards 1043681, 1559691 and 1542736, and Landsat images is a courtesy of the U.S. Geological Survey. We thank Dr S. Leprince and his team for

making available their COSI-Corr.

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Nutrient delivery from polar glaciers to downstream ecosystems

Andy Hodson[1]

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The export of nutrients from polar glaciers to downstream ecosystems can be simplified into small fluxes of highly labile, aqueous products of microbially-mediated rock weathering reactions, and large fluxes of sparingly labile nutrients associated with sediments derived from physical erosion. However, the relative importance of the two pathways can change markedly: for example when tidewater glaciers retreat onto land and glacial tills accumulate organic matter and evolve into soils. At present, almost none of these changes have been integrated into models that represent the past, present or future state of ice-marginal marine ecosystems. This presentation therefore attempts to improve our conceptual understanding of these processes and help us move toward a more interdisciplinary examination of coastal ecosystem dynamics in glacially-influenced polar waters.

In the first part, the importance of constraining nutrient mass balance within glacial systems will be discussed, and its advantages over basic short-term runoff flux calculations made clear. In so doing, it will be shown how glaciers export significant NO3- and sediment-bound (or readily extractable) Fe, P and Si fluxes via runoff and calving. By contrast, glaciers will be shown to be significant sinks of dissolved NH4+ and PO43- after they are leached from snowpacks and subject to assimilation and adsorption to suspended sediments. Nutrient mass balances through proglacial floodplains will also be used to consider their potentially important regulation of riverine glacial inputs. Secondly, linked to the above, the longer-term changes associated with the transition from active calving to riverine glacial inputs, caused by a combination of glacio-marine sedimentation and isostatic uplift, will also be emphasised. Here attention will be given to the role of the sediment infills that greatly affect rock-water interaction due to the establishment of groundwater flowpaths through very reactive fine materials that, at least in the High Arctic, also often contain marine pore waters whose mobility can be climate-dependent due to permafrost. Finally, several case studies of polar fjords will be used to emphasise the above issues and make clear the range of different glacial influences upon polar coastal ecosystems.

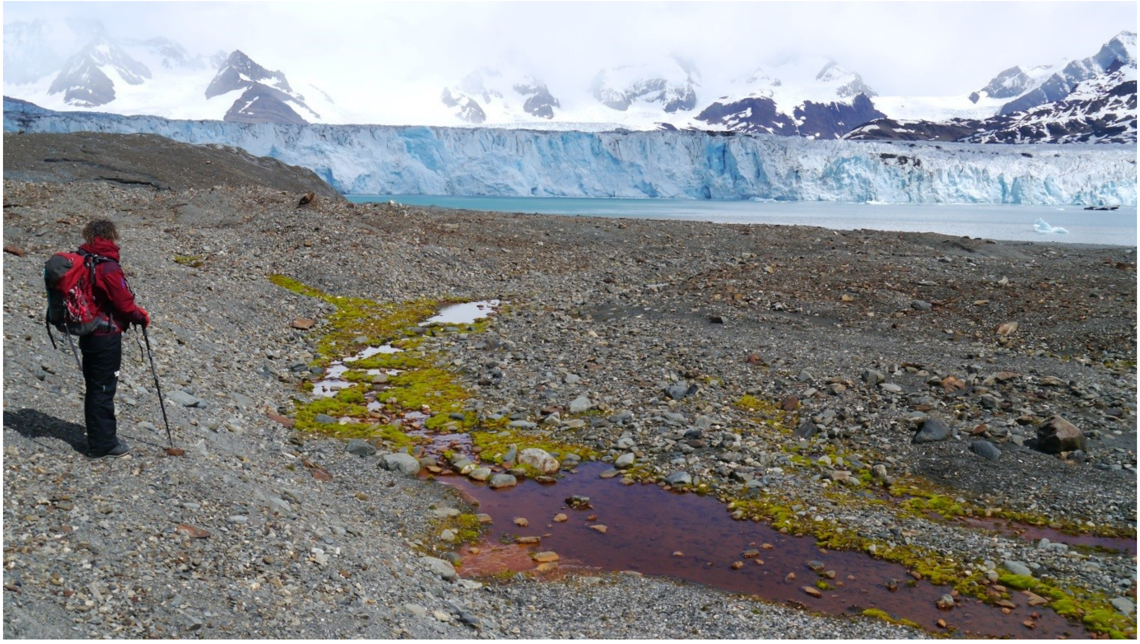

Figure 1. Iron reduction in anoxic flowpaths through young tills re-oxidises before entering Cumberland Bay, South Georgia (photo: A. Hodson)

Biogeochemical and microbial variability in subglacial systems on the Devon Ice Cap, Canadian Arctic

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Keywords: basal ice, biogeochemistry, microbiology

Ice at the base of glaciers and ice caps can interact with the underlying substrate and produce a thin layer (up to 10s of m thick) of "basal ice" that is chemically and/or physically distinct from the overlying "glacier ice". Previously assumed to be biogeochemically inactive, basal ice and the subglacial system have been shown to host active microbial communities that can mediate redox reactions at glacier beds, play an active role in rock weathering, and produce and/or consume ecologically important nutrients. However, there have been few studies of the biogeochemistry of basal ice, the structure of the microbial communities that are found within it, or the variability in these characteristics within and between glacier systems. This is despite the fact that basal ice may 1) supply freshly deglaciated landscapes with sediment and meltwater from which postglacial landscapes can evolve, 2) be melted by geothermal, frictional, and conductive heat sources allowing it to influence the biogeochemistry of glacial runoff that enters downstream aquatic ecosystems, and 3) may impart a distinctive biogeochemical signature on supraglacial meltwaters as they are routed through the subglacial environment to downstream ecosystems. In a study of a polythermal glacier in SW Greenland, we found that the passage of meltwater through the subglacial environment was the first-order control on the composition of microbial assemblages exported from the glacier, while water source (i.e., supraglacial or extraglacial) and subglacial residence times were second-order controls. To more fully characterise the biogeochemistry and microbial community structure of subglacial environments under a range of physical, chemical, and hydrological conditions we investigated basal ice from 7 subglacial systems on Canada's Devon Ice Cap. Here, we discuss the environmental controls that might explain the observed variability in the dissolved organic matter, inorganic nitrogen and phosphorus content of the basal ice, and describe the variability apparent in the microbial communities we encountered.

Towards a remote monitoring of surface mass balance at Freya Glacier (NE-Greenland)

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3 Geological Survey of Denmark and Greenland (GEUS), Copenhagen

Keywords:
glacier mass balance, automatic weather station, automatic cameras

The aim of the combined research and education project GLACIO-LIVE is to install a widely automatic glacier measurement system, which is able to measure the glacier mass changes on a daily or hourly basis in near real time and present the results on the web to a broader public. To make the data available in real-time, students are developing a peripheral wireless data network, which is able to collect data of various measurement stations on the glacier and transmit the data via Iridium on a daily timescale. In a next step all the data from automatic kameras and automatic weather stations (AWS) is assimilated into a distributed mass balance model, which calculates the acutal rate of mass change of the glacier. In a final step students are developing a website, where the actual state of the glacier will be presented to a broader public. This operational system has been installed on 3 Alpine glaciers and on Freya Glacier in Northeast Greenland.

Freya (Fröya) Glacier is a 6km long valley glacier situated on Clavering Island 10km southeast of the Zackenberg research station at the northeastern coast of Greenland. Its surface area is 5.3 km^2 (2013), reaching from 1300 m to 280 m a.s.l. and mainly oriented to NW with two seperated accumulation areas oriented to NE and NW. The thickest ice found during a GPR survey in May 2008 is 200m, located at the confluence of the two accumulation areas. GPR-data suggest, that Freya Glacier is a polythermal glacier with temperate ice in a limited area only, at the ELA near the bottom of the glacier. Mass Balance Monitoring was initiated during IPY in 2007. Figure 1 shows the current monitoring network on Freya glacier and the mass balance time series (Hynek, 2014).

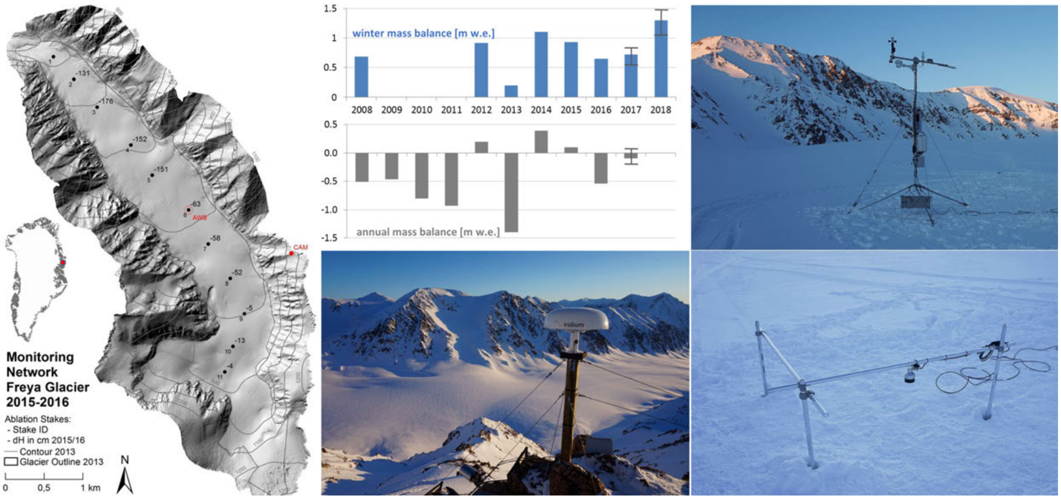

Figure 1: Current monitoring network on Freya Glacier with ablation stakes, an automatic weather station (Promice type) and 2 automatic cameras with Iridium data connection. The barplot shows the timeseries of winter and annual mass balance.

Within the project Glacio-Live two automatic stations have been put up on the glacier in May 2016. An automatic weather station that measures the surface energy balance and the surface height change and two automatic cameras that monitor the snowline retreat during summer. Both stations transmit the data in near real time via Iridium Satellite network. Figure 2 shows the surface height change during the last two years and figure 3 show pictures of the automatic cameras in spring and late summer of 2017. After having completed the installation of an appropriate station network for a remote mass balance monitoring on Freya Glacier we currently work on the assimilation of all data into an operational glacier mass balance model and on the visualisation of near real time data and model output via glacio-live.at

This research is carried out within the Sparkling Science project Glacio-Live, funded by the Austrian Federal Ministry of Science, Research and Economy. We thank the staff of the Zackenberg Research Station for providing logistic support during field work and Gerhard Keuschnig and Flori Radlherr from foto-webcam.eu for the good collaboration and especially their commitment and efforts to adapt the automatic camera system to Arctic conditions.

Hynek, Bernhard; Weyss, Gernot; Binder, Daniel; Schöner, Wolfgang; Abermann, Jakob; Citterio, Michele (2014): Mass balance of Freya Glacier, Greenland since 2007/2008. Zentralanstalt für Meteorologie und Geodynamik, Wien, PANGAEA,
https://doi.org/10.1594/PANGAEA.831035

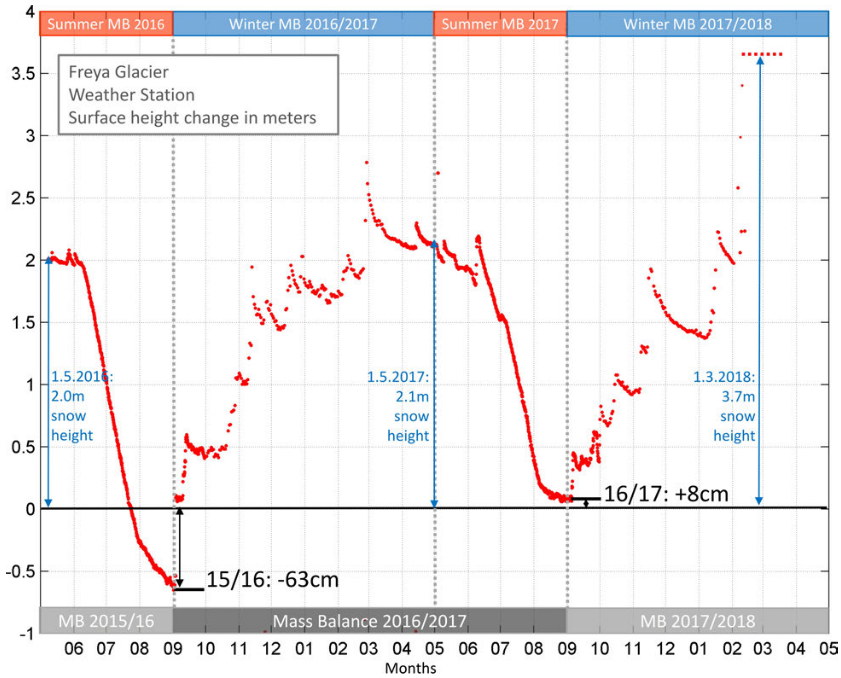

Figure 2: The surface height change at the AWS from May 2016 to March 2018. In summer 2016 there was 63cm of firn ablation, and in summer 2017 we had 8cm of accumulation at the AWS at an elevation of 688m a.s.l. Repeated heavy snowfall events in February 2018 accumulated a snowheight of at least 3.7 meters and burried the AWS in snow.

Figure 3: Fotos of the two Webcams on Freya Glacier, which have been installed for near realtime snowline monitoring on the glacier. Top: Fotos from 7.5.2017. Bottom: Fotos from 14.8.2017, showing the end of summer snow cover on the glacier. Fotos are available online here: foto-webcam.eu/webcam/freya1 and /freya2

Controls on glacier surging and velocity variations in the St. Elias Mountains, Yukon

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Keywords:
glaciology, surge glaciers, remote sensing, glacier dynamics

Records of glacier velocities and their variation through time are crucial for monitoring watershed resources, managing local hazards, and initializing flow models, which are used to refine future projections of sea level rise. In addition, a major uncertainty is whether glaciers will respond dynamically to changes in climate: some argue that increased surface melt will lead to glacier acceleration through increased basal lubrication, but others argue that increased melt will result in a net slowdown due to an increase in efficiency of the subglacial drainage system. Dynamic change processes are especially complicated for surge-type glaciers as the main influences on motion are inadequately understood. The largest cluster of surge-type glaciers in Canada occurs in the St. Elias Mountains, Yukon, a region that has been experiencing rapid reductions in glacier mass. The main objective of this research is to understand the mechanisms that control the surging of these glaciers, quantify changes in ice motion across this region over time, and assess whether the periodicity of glacier surging is changing in a warming climate.

Using speckle-tracking of ALOS PALSAR imagery for the winters of 2007-08 and 2009-10, and speckle tracking of Radarsat-2 imagery for winters since, glacier velocity maps for the St. Elias Mountains were generated. An icefall between the Lowell and Dusty Glaciers is explored as a possible dynamic connection between the two glaciers, which appears to have implications for the surge behaviours of both. New information concerning the development and progression of the 2009-10 surge of Lowell Glacier is also presented, and placed in regional context of other recent surges. Future work will include in-situ monitoring of Lowell Glacier through a complete surge event with a centreline network of dGPS receivers, from a quiescent period through the active surge stage. This provides new insights into the controls on ice motion in this region.

Climate, and Surface energy and mass balance of Nordenskiöldbreen, Svalbard

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Keywords:
Svalbard, climate change , observations, energy balance modelling

In spring 2006 a climate monitoring program on Nordenskiöldbreen, Svalbard, was initiated, which is still on going. The program focuses on the dynamics and mass budget of the glacier, and includes mass balance (stake and sonic height ranger) and automatic weather station (AWS) observations (AWS since 2009). At the AWS site (∼550 m a.s.l.) the average annual temperature is ~ -6.7°C. Annual mean wind speed is ∼4.5 ms-1 and is predominantly directed down glacier with a directional constancy of ∼0.59, a predominant katabatic wind. The annual mean temperature on the glacier over this period (2009-2016) increases with 0.16°C/year. However, this increase is not significant due to the short observational period and large inter-annual variability.

The AWS observations are used to calculate the individual surface energy fluxes using a surface energy balance model. From all energy fluxes, net radiation contributes about 80% to melt, with sensible heat as the second important flux contributing most of the remaining 20%. The calculated amount of energy available in the summer months corresponds to a total melt of about 1.5 m w.e. of which 1.1 m w.e. is ice melt. The total melt is a bit higher than derived from the stake observations (1.1 m w.e. of which 0.8 m w.e. is ice melt), which is partly explained by multiple melting of the same mass due to refreezing of melt water in the winter snow pack. Although not significant, there is a positive trend in melt and runoff. Furthermore, the melt season appears to be shifting in time, with start of melt later in spring and especially with melt occurring later in the autumn and even in winter. This is likely related to the decrease in sea ice in the fjord in front of the glacier. Based on the stake observations the summer, winter and annual mass balance of the total glacier is derived, which shows large inter-annual variability, but no significant trends. The same holds for the Equilibrium Line Elevation which varies between 550 and 800 m a.s.l with no visible trend.

Figure 1. Photo of the Automatic weather station on Nordenskiöldbreen in April 2011. (Photo: A. Waxegard)

A.P. Olsen Ice Cap (NE-Greenland): What drives the snow distribution?

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1 Geological Survey from Denmark and Greenland (GEUS)

Keywords:
mass balance, GPR, snow distribution, snow variability

A.P. Olsen ice cap (74.6°N, 21.5°W) is situated about 30 km inland of the Zackenberg Research Station in Northeast Greenland. Since 2008 the GlacioBasis project is running a mass balance monitoring programme which focuses on the SE outlet of the A.P. Olsen ice cap. Mass balance is measured by the glaciological method based on an ablation stake network and three automatic weather stations. Every spring the over the winter season accumulated snow mass is determined for the SE outlet by a GPR survey and snow pits. However, adequate interpolation and modelling approaches are necessary to convey measured field data to the whole ice cap.

Spatially distributed winter snow accumulation is a crucial input parameter for mass balance modelling. First results of the A.P. Olsen ice cap's snow distribution show high interannual and spatial variability. Snow depth-elevation correlations show a non-linear behavior with minimum snow depths at half way of the terminus to the summit region. We hypothesize that A.P. Olsen ice cap's spatial variability is mainly driven by the dominant topography surrounding the ice cap's outlets and the redistribution by wind. Seven years of GPR-derived snow depths provide the data base to further investigate the interannual and spatial variability. Furthermore, the potential of modelling the spatial snow depth variability by basic assumptions of wind-redistribution based on terrain-based parameters is evaluated.

Estimating the contribution of trace metal contaminants from Devon Ice Cap, NU to the Ocean (2005-2015)

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2 Defence Research and Development Canada

Keywords:
Arctic, ice cap, contaminants, freshwater

Natural and anthropogenic contaminants that accumulate in glaciers and ice caps are highly susceptible to re-mobilization through melting, run-off, and ice dynamics. Intense melting of Arctic glaciers and ice caps since the mid-2000's has significantly increased the volume of glacier meltwater released from ice caps and tidewater glaciers implying a strong potential for increases in the mass of contaminants at point locations where glacier meltwater and/or glacier ice is discharged directly into the ocean. Through combined knowledge of the concentration of contaminants in the ice, firn, and snow of Devon Ice Cap (DIC) found in ice core studies, and the rates of surface melting and iceberg calving fluxes from the major drainage basins of the DIC, we provide a first-order estimate of the amount of trace metals (Pb, Cd and Sb) discharged to the ocean. Ice and meltwater fluxes are modeled for the period 2005–2015 using a combination of output from the Regional Atmospheric Climate Model (RACMO) 2.3 and annual in-situ glacier measurements. Rates of iceberg calving derived in previous studies are used to estimate glacier ice flux discharged from main tidewater glaciers draining the DIC. Of particular concern are contaminants deposited since the industrial revolution, which have been stored in high elevation firn as they are particularly vulnerable to remobilization due to upward migration of the long-term equilibrium line altitude (ELA). Results from this work provide a first order estimation of the total mass of trace metals removed from the DIC over the past 15 years, into the local marine ecosystems and eventually to Oceans.

Characterizing the ice-ocean interaction at the Upernavik Glacier using in-situ and satellite observations

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1 Geological Survey of Denmark and Greenland
2 Niels Bohr Institute, University of Copenhagen

Keywords:
glacier-ocean interaction, calving, satellite and time-lapse imagery

Quantifying the calving mass loss at marine-terminating glaciers is a non-trivial first step in understanding the physical processes behind the mass loss at the ice-ocean interface. Here we present the first results from combining Extreme Ice Survey hourly time-lapse imagery from the Greenland ice sheet outlet glacier Upernavik Isstrøm with satellite imagery from COSMO-SkyMed to quantify the volumetric mass loss over a melt season. Other sources of data ranging from in-situ weather stations, on-ice glacier trackers and tidal models will be compared to the mass loss record to examine the causes and consequences of calving on glacier flow and its relation to observed sudden changes in glacier velocity.

Particles and plankton facing the glaciers around Svalbard

Emilia Trudnowska[1], Rafal Boehnke[1], Katarzyna Draganska-Deja[1], Anna Maria Kubiszyn[1], Kajetan Deja[1], Katarzyna Blachowiak-Samolyk[1]

1 Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland

Keywords:
particles, plankton, Arctic, glacier

Most of Svalbard coastal waters are strongly affected by the intensified glacier retreat as an effect of progressing climate warming. The glacial runoff, observed as 'brown plumes', is transporting large amounts of fresh waters and suspended matter over many kilometres, which has a substantial impact on many physical and ecological processes occurring in the marine ecosystems. However the recognition of this phenomenon is still unresolved and remains a matter of conceptual and methodological challenge. Therefore our aim was to study the marine plankton and particles in the close vicinity of glacier fronts.

The abundance and composition of various components of the 'glacial soup', i.e. protists, zooplankton, particles and marine aggregates were analysed inside the fjords affected by intense glacier retreat (Hornsund, Kongsfjord, Vijdefjord, Rijpfjord) as well as in coastal waters close to the glaciers that terminate on large islands (Nordaustlandet, Edgeøya) (Fig. 1).The investigation was performed in the

summer of 2016 along the transects that spread from the glacier fronts towards clear open waters. The size spectra and abundance of particles and plankton were assessed via the high resolution automatic measurements of the Laser Optical Plankton Counter (LOPC), which was equipped with CTD and fluorometer sensors in order to analyse the hydrographical and algal conditions. Traditional plankton samples via nets and Niskin bottles were collected at stations to investigate nano- to mesoplankton taxonomic composition and abundance. Additionally, at some locations the underwater camera was used.

Figure 1. A map presenting the sampling locations.

As expected, the lowest salinity of seawater was observed at stations located near the glacier fronts, which were characterized by very high abundances of particles as well as marine aggregates. Protists and zooplankton were rather abundant at most of the glacier front stations. However, the multivariate statistics performed either on protists, zooplankton or on particles indicated no effect of the station locations, which suggested that all of the investigated stations were highly influenced by the glacier runoff. Only vertical distribution of particles and plankton seemed to differed significantly between the upper (50 m) and lower water layers. It was mainly caused by the high abundances and different composition of protists, zooplankton and particles in the upper layers contrary to the lower parts of the water column (Fig. 2). Analyses of fauna and flora taxonomic composition, underwater camera observations and particle characteristics modelling, showed that the upper water layer was full of typical summertime protists and zooplankton taxa, accompanied by the swarms of sea snail (Limacina helicina) and small particles. Whereas the highly abundant benthic larvae occurred together with large particle aggregates within the lower layers of the water column. Our observations indicate that the horizontal extent of glacier plumes can reach tens of kilometres and that their vertical range is very extensive near the front and is getting shallower moving away from the glacier.

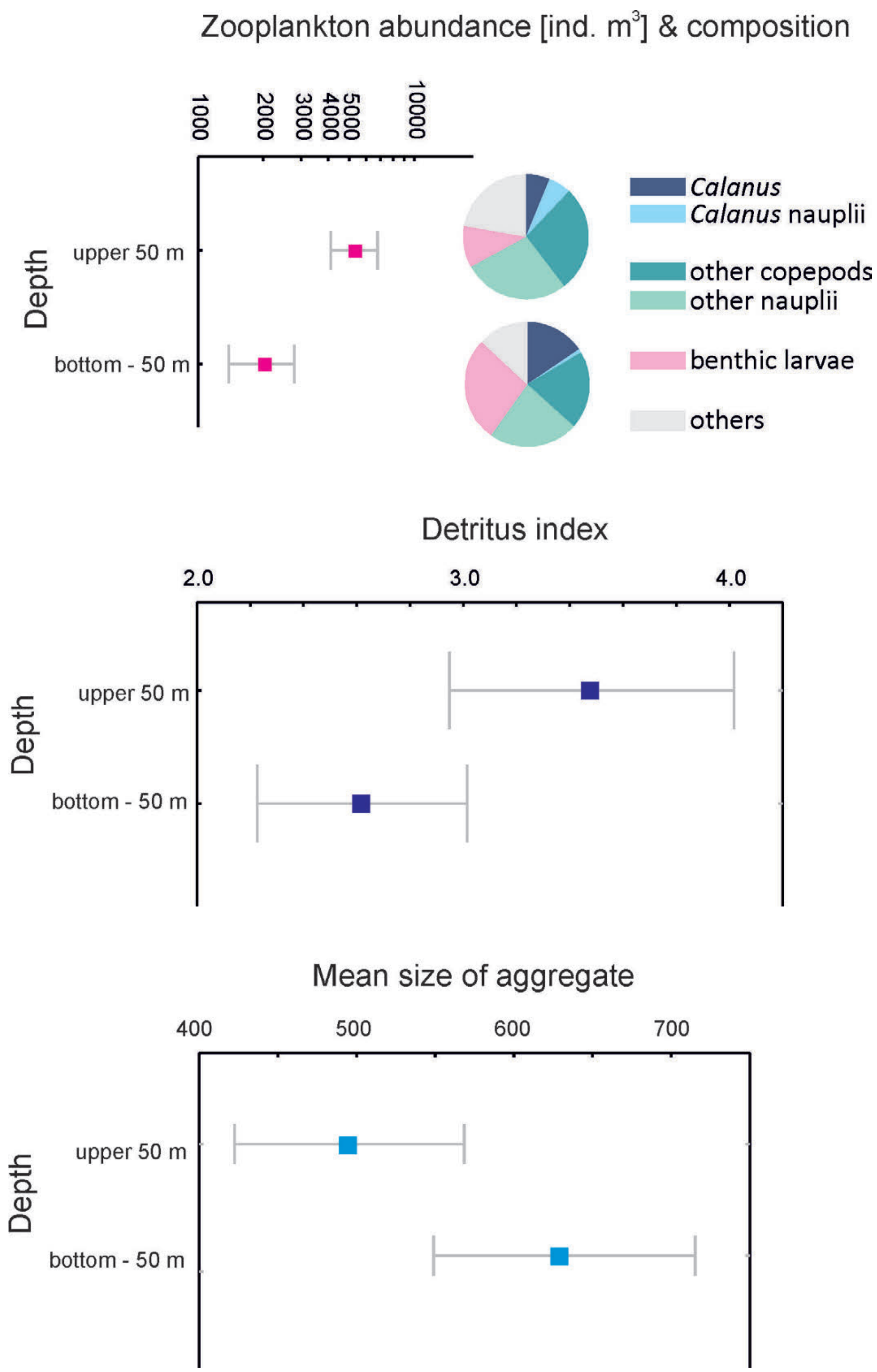

Figure 2. The results of zooplankton abundance and composition, contribution of particles, assessed as detritus index and the mean size of the aggregates (mm), presented as averages of the upper 50 m layer and water column underneath.

10 years of mass balance over a small Arctic basin. The example of Austre Lovénbreen (Svalbard)

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1 CNRS

Keywords: Mass balance, glaciology, climate shift

Arctic glaciers are good indicators of the ongoing climate change as their dynamics are strongly linked to it. This study focuses on the Austre Lovén glacier, in the Brøgger peninsula (Spitsbergen, 79°N), which have been systematically instrumented and monitored since 2007. The aim of this presentation is to highlight the response of the glacier through 10 years of mass balance measurements. Under climate shift impacts, both temperatures and precipitations strongly vary in a very short time frame. In that framework, we will also discuss climatic and snow conditions and their combination as explaining factors of the measured mass balance each year.

The Austre Lovén glacier (4,5km^2) is equipped with a fine measurement network. Mass balance is measured yearly at the end of September with evenly-spaced 36 stakes. At the end of April, before the start of the melting season, snow accumulation is also measured through drillings. Air temperatures have been recorded continuously since 2007 with 20 sensors on the glacier. Precipitation data is acquired by the Ny Alesund station (6km away). Thanks to several collaborations and the growing interest into new technologies, Terrestrial Laser Scanning data and aerial images acquired by UAV have contributed significantly to the understanding of the glacier basin dynamics (from hillsides to the moraine). Many morphological features (volumes, snow densities, front lineĚ) were firstly used in this study in order to evaluate the overall evolution of the Austre Lovén glacier over ten years. Then, a statistical study based on explanatory modelling were ran to identify and quantify the combination of factors that played a role on the mass balance over time and space.

Using photogrammetry for quantitative glacier analyses back to the 1800’s

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Keywords: photogrammetry, structure from motion, glacier change, historical imagery

In 2012–2016, we digitalised about 10000 old photographs taken 1861-1980 on glaciers and alpine environments in Sweden and on Svalbard. Using the modern

Structure from Motion photogrammetrical workflow, new quantitative measurements can be made on almost any image sequence, provided enough overlap is present. These include measurements of volume, terminus positions, area estimates and analyses of the glaciers' appearances. With new data from the last turn of the century, considered the maximum of the Little Ice Age in Sweden and on Svalbard, we open potential for a higher understanding of their prior dynamics, and their latter response to climate change. If modern elevation data are available, a single image of a glacier's terminus can be orthorectified and measured, increasing the potential temporal resolution and range of terminus measurements in frequently visited regions. Tarfala is a well-researched valley in northern Sweden, with image material dating as far back as 1886. In 1910, a geography student photographed the valley photogrammetrical purpose, whose photographs have now been used for quantitative reconstruction. Comparing the surface with elevation data from 2015 shows a mean elevation decrease of 57 meters over the three largest glaciers. Several glacier fronts were also reconstructed in 3D from photographs, not taken with photogrammetry in mind, between 1945 and 1948 around Tarfala. Plans include expanding these reconstructions to other areas in Sweden and on Svalbard. Modern photogrammetrical software, such as Agisoft PhotoScan, makes historical photogrammetry increasingly simple. We present a short summary of these workflows, going from scanned images to DEM's, orthophotos and surface change analyses.

Spatio-Temporal Variability of Refreezing in Firn in Southwest Greenland

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Half of the current annual mass loss from the Greenland Ice Sheet is currently estimated to be due to surface losses. Most of surface runoff happens in the ablation area, where exposed bare ice is impermeable to meltwater. At higher elevations, in the percolation zone, a significant portion of surface meltwater percolates, refreezes, and is stored in the firn. During the last decade, increased melting has caused the formation of near surface thick (>5 m) ice layers in the firn. These layers can seal off underlying porous firn, forcing meltwater to generate runoff instead of refreezing.

To investigate the spatio-temporal variability of refreezing in firn, field observations were conducted in the spring of 2017 in proximity of the DYE-2 site, in the percolation zone of the Southwest Greenland ice sheet at elevations between 1963 and 2355 m a.s.l.. Here, we present initial results from the field season.

Five 20-m deep firn cores were extracted and analyzed for density and stratigraphy, two full energy balance weather stations were deployed, equipped with 16 m long thermistor strings to measure firn temperature, and over 300 km of ground penetrating radar data were collected. Preliminary firn cores analysis reveals increasing frequency and thickness of ice lenses toward lower ice-sheet elevations, in agreement with other recent work in the area. The collected data will facilitate advances in our understanding of the spatio-temporal distribution and variability of firn refreezing and its role in the surface mass balance of the Greenland Ice Sheet.

An analysis of the errors in the calculation of ice discharge through flux gates. Application to Nunavut tidewater glaciers, Canada.

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Keywords:
ice discharge, flux gate, error estimate, Canadian Arctic

Frontal ablation of tidewater glacier, whose main components are calving and submarine melting at the glacier front, is an important mechanism of mass loss from Arctic glaciers. Frontal ablation is usually estimated calculating the ice discharge through predefined flux gates close to the glacier terminus. However, published results often lack a detailed error estimate. In the flux calculation, both errors in cross-sectional area and errors in velocity are relevant. While for estimating the errors in velocity there are well-established procedures, the calculation of the error in the cross-sectional area requires the availability of ground penetrating radar (GPR) profiles transverse to the ice-flow direction and close to the glacier terminus. Yet quite often there are only available GPR profiles collected along the centreline of glaciers, and thus it is necessary to make some assumption about the cross-sectional shape and area. In this contribution, we use GPR ice-thickness data from the IceBridge operation collected in Ellesmere and Devon Islands, Nunavut, Canada, to compare the cross-sectional areas estimated using various approaches (parabolic, quartic) with the cross-sections estimated from the observed ice thickness data. These error estimates are combined with those for ice-velocities calculated from Sentinel-1 SAR data, to get the error in ice discharge.

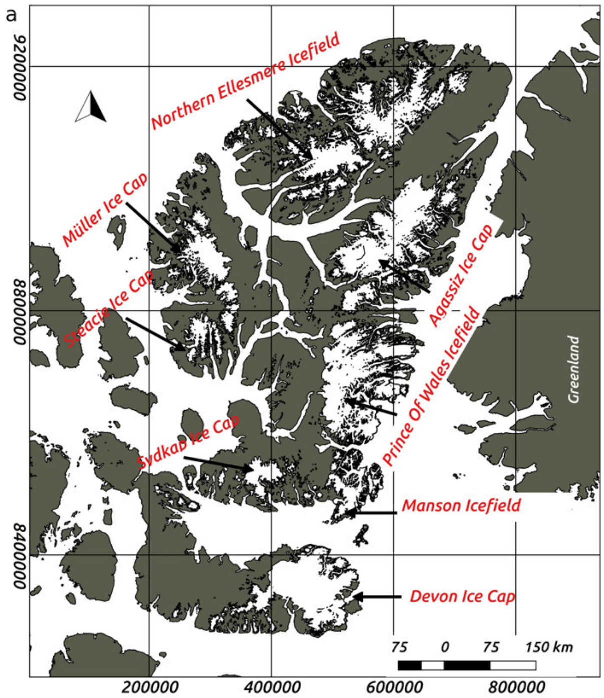

Figure 1. Study area: Ellesmere and Devon islands, Nunavut, Canadian Arctic.

Our results indicate that the velocity field is the main error source for small glaciers with low velocities, while for large glaciers with high velocities the error in cross-sectional area dominates. Ice thinning or thickening between times of ice-thickness and glacier velocity measurements should be considered, as it implies systematic errors up to 8% in our case study. The U-shaped parabolic approach, with allowance for ice-thickness measurement point displaced from the glacier centerline, performs best, with small bias and admissible standard error. In general, the quartic U-shaped approach tends to overestimate the cross-sectional area, though it works best for large glaciers.

Regarding ice discharge results, we observe an increase of ice discharge from the main glaciers of the Prince of Wales Icefield (Trinity and Wykeham) from 2015 to 2016, by 5% and 20%, respectively, followed by a decrease in 2017, by 10% and 15% respectively. Belcher glacier, in the Devon Ice Cap, maintains similar discharges during 2015–2017.

The focus of this contribution was the analysis of the errors in the calculation of ice discharge through given flux gates. However, other factors might influence the approximation of the frontal ablation by the mentioned method. Among these factors are the surface mass balance between the flux gate and the calving front, the ice-thickness changes, the front position changes and the seasonal and interannual variations of ice velocity. The ice discharge corrections for these factors can be large and should therefore not be disregarded.

Acknowledgements: This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 727890 and by project CTM2014-56473-R of the Spanish State Plan for R&D. Ground-penetrating radar data used in this paper were acquired by NASA's Operation IceBridge Project. Copernicus Sentinel data 2016-2017.

The effect of glacier runoff on Arctic fjord circulation and ecosystem

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1 Norwegian Polar Institute

As the Arctic sea-ice is diminishing the arctic environment in front of tidewater glaciers may become a refuge for arctic species. Tidewater glaciers terminating in fjords create a local ”arctic“ environment and affect the fjord circulation through katabatic wind and sub-glacial melt water discharge. The resulting upwelling of nutrient-rich water from the deeper part of the fjord contributes to sustaining phytoplankton productivity throughout the summer. In contrast, land-terminating glaciers lack upwelling mechanisms and is characterized by lower productivity, as has been shown for glaciers in Greenland fjords. We will present a multidisciplinary study aiming at understanding the mechanisms through which the tidewater glacier affect the fjord circulation, nutrient dynamics, primary production, zooplankton availability and ultimately fish and top predators. Birds, seals and polar bears are iconic to the arctic environment and we will show how loss of fjord ice causes diet shifts in birds and divergent spatial use by seals and polar bears.

Surge dynamics of western basin of the Vavilov Ice Cap assessed by remote sensing data

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The glaciers and ice caps in the Arctic are experiencing significant changes, manifested, in particular, in the intensification of their dynamic instability.

Here we present data on a large-scale surge in the western basin of the Vavilov ice cap on Severnaya Zemlya. The ice cap is located at 79.30°N, 95.47°E, with total ice cap area 1781.4 km^2 according the Randolph Glacier Inventory (Fig. 1a). The data were derived from satellite imagery (Landsat-1, 5, 7, 8, Terra ASTER, Sentinel-1 and Corona), goLIVE and Sentinrel-1 ice velocity data sets, and also from our airborne RES survey in 2014.

Analysis of 28 space images from 1963 to 2017 showed that front advance has evolved during all this period (Fig. 1b). In the first decade from 1963 to 1973 the advance was very slow from 2-5 to 12 m a^{-1}. Since the 1980s, the advance began to accelerate from the first tens of m a^{-1} to the first of hundreds m^{-1} in the 2000s. The turning point came in 2012, when the front was advancing with a velocity about 0.5 km a^{-1}. In 2014 the volume of advanced snout was at least 4 km3. The rate of advance reached the maximum of 7 km a^{-1} in 2016. From

1963 to 2017 the glacier front moved forward by 11.7 km and its area increased by 134,1 km^2 (by 47% relative to basin area in 1963), that was accompanied by spreading of crevasse zone up the glacier.

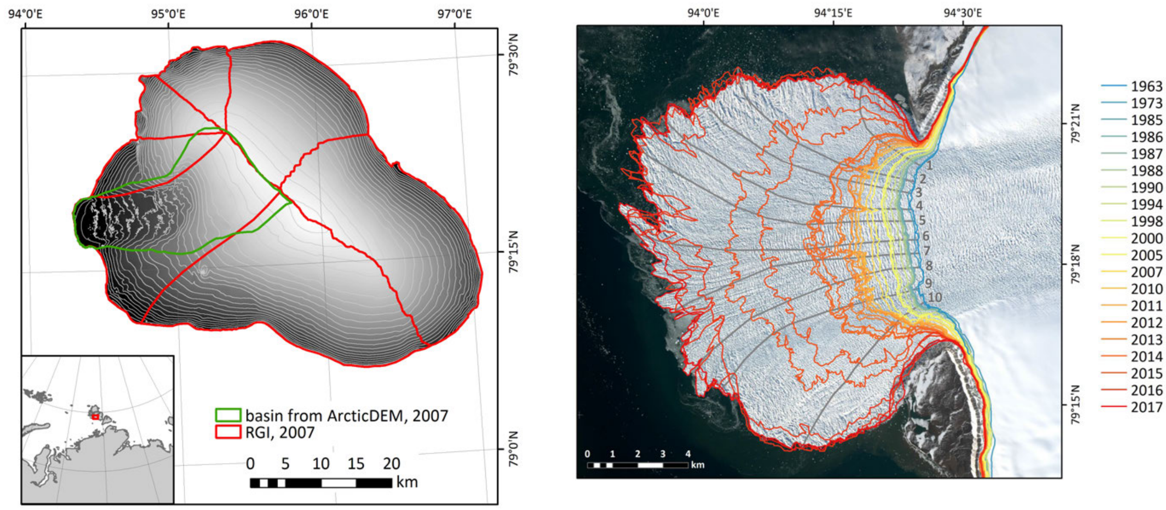

Figure 1. Vavilov ice Cap, Severnaya Zemlya: a) ice cap location and outlines of its western basin; b) glacier front position from 1963 to 2017.

Ice surface velocity reached a maximum of 25.4 m d^{-1} in 2016, and in 2017 reduced to 6.8 m d^{-1}. We assume that the initial activation of the southern and western margins of the ice cap in second half of XX c. might be a response to the climate signal occurred possibly several centuries ago. As a result, the ice crevassing accompanied with cryo-hydrologic warming and reinforced by positive feedback, led to the instability of the glacier and displacement of the marginal stagnant belt of debris-laden ice frozen to the bed. The surge was facilitated by change of bedrock conditions as the ice lobe progressed offshore from permafrost coastal zone to the area of soft marine bottom sediments with low shear strength. The surge seems to be also stimulated by anomalously warm summer of 2012.

Acknowledgements: This study is supported by the Russian Foundation for Basic Research, grant 16-35-00333, and by Russian National Foundation, grant 14-37-00038.

Elevation changes of Greenland's glaciers using AeroDEM, ArcticDEM and TanDEM-X

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Keywords: Greenland, glaciers, geodetic mass balance

Greenland peripheral glaciers and ice caps are sensitive key indicators of climate chance but recent evolution of ice volume along Greenland's periphery is still poorly understood. The restricted number of geodetic glacier thickness changes on Greenland is probably related to the absence of digital elevation models (DEM) of sufficient accuracy. In this study we used the reanalyzed AeroDEM (late 1970s to mid-1980s) and the two recently released high resolution DEMs ArcticDEM (2012–2015) and TanDEM-X (2010–2014) to calculate geodetic glacier elevation changes. Thereby, the main challenge was to appropriately deal with the data voids and artefacts occurring in all three DEMs. In the framework of a pilot study, the ArcticDEM was subtracted from the AeroDEM over the Holm Land ice cap, northeast Greenland. The data voids were filled (A) by spatial interpolation and (B) by interpolating the mean of the respective elevation bin, resulting in a mean elevation changes of 9.3 m and 9.9 m, respectively. Based on the results of this pilot study, we are applying these approaches to calculate glacier elevation changes for larger regions on Greenland.

This work is carried out in the framework of the Copernicus Climate Change Service (https://climate.copernicus.eu/about-c3s) for which the World Glacier Monitoring Service (WGMS) aims at generating glacier specific elevations changes for regions around the world.

Variations in subglacial discharge and submarine melting during tidewater glacier retreat

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Keywords: tidewater glacier; subglacial discharge; submarine melting

To first order, subglacial discharge depends on climate, which determines precipitation fluxes and glacier mass balance, and the rate of glacier volume change. For tidewater glaciers, large and rapid changes in glacier volume can occur independent of climate change due to strong glacier dynamic feedbacks. Using an idealized tidewater glacier model, we show that these feedbacks produce secular variations in subglacial discharge that are influenced by subglacial topography. Retreat along retrograde bed slopes (into deep water) results in rapid surface lowering and coincident increases in subglacial discharge of up to ∼20%. Since subglacial discharge is a key driver of nutrient-rich upwelling plumes, these topographically modulated variations in subglacial discharge may have consequences for fjord ecosystems. Moreover, submarine melting of glacier termini, which depends on subglacial discharge, also increases during retreat into deep water. Our results therefore indicate that submarine melting acts in concert with iceberg calving to cause tidewater glacier termini to be unstable on retrograde beds. The full impact of submarine melting on tidewater glacier stability remains uncertain, however, due to poor understanding of the coupling between submarine melting and iceberg calving.

Greenland, Canadian and Icelandic land-ice albedo grids (2000–2017)

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1 Geological Survey of Denmark and Greenland
2 WSL

Keywords: albedo Greenland MODIS Sentinel-3

Albedo, Latin for ”whiteness“, is a term used to describe the amount of sunlight reflected by the ground. Fresh snow albedo can exceed 85%, making it among the most reflective natural substances. Warm conditions promote snow crystal metamorphosis that, like the presence of liquid water, bring snow albedo down below 65%. With the darkening, caused by the metamorphosis, absorbed solar energy thus increases by roughly a factor of two. Seasonal snow melts over the lower reaches of a glacier leading to the exposure of bare ice with albedo below 55%. Impurities such as dust, black carbon or microbes can bring glacier-ice albedo be-low 30%, meaning that snow ablation gives way to impurityrich, bare glacier ice which increases absorbed sunlight by more than a factor of three.

The thickness of the winter snow layer and the intensity of spring melt are important determinants of the annual glacier-ice melt, as the amount of snow cover governs the timing of darker ice exposure; the earlier the exposure, the more ice can melt. Because snow and ice albedo properties make it an amplifier of climate change, surface albedo has been designated as an Essential Climate Variable and a Target Requirement for climate monitoring (WMO 2011).

Polar orbiting satellites facilitate albedo mapping with Arctic coverage multiple times per day in clear-sky conditions. Satellite-based retrievals of surface albedo depend on accurate compensation of the intervening atmosphere. Thus, without ground truth, the satellite retrievals are uncertain. In Greenland, snow and ice albedo is monitored by automatic weather stations (AWSs) from The Greenland Climate Network (GC-Net; Steffen et al. 1996) since 1995 and after 2007 from The Programme for Monitoring of the Greenland Ice Sheet (PROMICE; van As et al. 2013). Using the GC-Net data, satellite-derived albedo values are compared with ground data (e.g. Stroeve et al. 2013). Here, we present comparisons of daily GC-Net and PROMICE albedo data to satellite-derived albedo from the NASA Moderate Resolution Imaging Spectroradio- meter (MODIS) MOD10A1 product (Hall et al. 1995). MOD10A1 data have been available since May 2000 and are here de-noised, gap-filled and calibrated into a daily 500 × 500 m grid covering Greenland, Iceland and the Canadian Arctic glaciers.

Greenland ice sheet equilibrium line altitude variations: 2000–2017

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2 World Glacier Monitoring Service (WGMS), Department of Geography, University of Zurich, Switzerland
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5 Danish Meteorological Institute (DMI)

Keywords: MODIS PROMICE HIRHAM

In this study, the position of daily snow (or firn) line around the Greenland ice sheet is classified using NASA MODIS MOD10A1 daily albedo data where values are equal to average bare ice onset value of 0.544±0.082 observed in 44 station-years of PROMICE ground station data. The maximum snowline each year (hereafter "FirnlineMODIS") is taken as an estimate for equilibrium-line altitude (ELA). FirnlineMODIS is cross validated using 41 independent ELA estimates from PROMICE ice ablation values and 18 values from the west Greenland ice sheet K-trasect in 18 mass balance years (1999/2000 to 2016/2017). The validation work indicates FirnlineMODIS can underestimate ELA in some areas where multiyear superimposed ice occurs. Comparison with historical ELA values beginning in the 1950s are few and via comparing coincident FirnlineMODIS averages do not indicate a long term ELA shift because the RMS differences are larger than the average differences. The technique exhibits a satisfactory spatial varion (correlation above 0.95). The only statistically significant FirnlineMODIS changes in time over 2000-2017 indicate an overall increasing ELA. The western ice sheet FirnlineMODIS change has increased of 138ś99 m from 2000 to 2017. On the eastern slope, the increase is insignificant (35±81 m).

Mass balance of Svalbard glaciers 1957–2015

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The most recent inventory of Svalbard glaciers show reduced ice masses and gives an area of 33775 km^2 of glaciers covering 57% of the total land area of the archipelago. The glacierized area over the entire archipelago has decreased by an average of 80 km^2 yr^{-1} over the past ~30 years, representing a reduction of 7 %. Mass balance monitoring was started by the Norwegian Polar Institute in 1950 at Finsterwalderbreen in West Spitsbergen by measurements every second year until 1968. Since then a number of mass balance measurement have been conducted in different periods on selected glaciers, the longest and most continuous on glaciers in the Kongsfjorden area since 1967. However, they cover only a small fraction (< 2 %) of the total glaciated area. The larger glaciers

are in general less negative than the small, since their accumulation area ratio is higher. On all glaciers, summer ablation is more variable than winter accumulation, thus summer temperatures provide most of the control on the net balance. However, summer snowfall may significantly reduce ablation by increasing the surface albedo and thus lowering the summer melt.

Geodetic mass balance over entire Svalbard has been obtained by analyzing the Ice, Cloud, and land Elevation Satellite (ICESat) data from 2003–2009 and by combining satellite data with older maps. This shows that most glacier regions in Svalbard have experienced low-elevation thinning combined with high-elevation balance or thickening, but with large regional variability.

Mass balance modelling has been run for the period 1957–2014, forced by ERA–40 and ERA–Interim reanalysis data, and downscaled to 1 km resolution. The modelling shows a general positive surface mass balance in the period from 1957 to early 1980ies and negative since then with a linear climatic mass balance trend of -1.4 ± 0.4 cm w eq. yr^{-1}.

The calving loss is an important part of the overall mass budget and estimates varies from 4 to 8 Gt yr^{-1} (12 to 24 cm w eq. yr^{-1}) Many glaciers are of surge-type and surges may alter the area-altitude distribution and for calving glaciers give a temporary increased mass loss. The current total mass loss estimates of Svalbard glaciers vary from -5 to -12 Gt yr^{-1} or -14 to - 36 cm w eq. yr^{-1}.

A coincidental measure of tidal stress propagation in Bowdoin Glacier, Northwest Greenland

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Keywords: glacier, tide, pressure, monitoring

The observed acceleration, thinning and retreat of marine-terminating outlet glaciers of the Greenland ice sheet account for about half of its mass loss. This so-called dynamic thinning, which has now propagated along much of the ice margin, nevertheless involves feedback processes between ice thickness, basal sliding, subglacial water and oceanic tides, that are not yet fully understood.

Here, we present a three-year record of ice pressure measured en-glacially at Bowdoin Glacier, a small and relatively accessible tidewater glacier in Northwest Greenland which has been monitored continuously since 2014. Although Bowdoin Glacier appears to have been very stable since its frontal position was first documented by late 19th century explorers, its calving front has recently experienced a rapid retreat of ca. 2 km between 2007 and 2013, followed by a continued surface lowering since then.

About 2 km upstream from the calving front, two boreholes were drilled and equipped with thermistors, inclinometers and pressure sensors. Although pressure sensors were meant to locate instruments in the water-filled boreholes immediately after the drilling, they continued to record after the complete refreezing of the boreholes and the stabilisation of ice temperatures well below the pressure melting point. All sensors recorded in-phase pressure variations with clear 12–hour and 14–day periodicities, leaving no doubt on the tidal nature of the signal. Surprisingly, the amplitude of pressure variations recorded in ice is comparable to that of sea level tides measured 130 km away at Pituffik. This lets us conclude, that tidal stresses applying to marine calving fronts can propagate several kilometres upstream in subfreezing glacier ice.

Dynamics of hydrological and hydrogeological processes on the Werenskioldbreen forefield in ablation season 2017 - short hydrological balance.

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Studies on the Werenskioldbreen (catchment - 44.1 km^2, glacier area - 27.1 km^2, forefield - 6 km^2), located on the Wedel Jarlsberg Land (Spitsbergen) have been conducted for more than 60 years. The main aims of glaciological and hydrological researchers were focus on: identifying the catchment hydrography, determining the hydrological balance of the catchment, estimating the amount of glacial meltwaters, calculating outflow in comparison to glacier mass balance and modelling of surface energy balance.

Complex set of interdisciplinary studies have been conducted on Werenskioldbreen during ablation season in 2017. Measurement of permafrost thaw, sedimentology analysis and GPR profiles have been made, to recognize the hydrogeological and physical properties of the periglacial sediments. Studies have been supplemented by additional measurements of the water inflow and outflow from the catchment, the groundwater level, glacier mass balance and meteorological conditions on glacier and its forefield.

Our results provide unique hydrogeological data for glacier forefield. The first analysis allow us to create model which will help to reduce inconsistencies in the hydrological balance of the glacier's catchment and better understanding of processes occurring in expanding zone between glacier and sea during the global warming.

A consistent estimate of Pan-Arctic glacier frontal ablation, 2000–2015

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Keywords: Frontal ablation, glacier dynamics, icebergs

Over the last several decades, glaciers and ice caps in the Arctic have been losing mass at an accelerating rate. However, the way in which this mass is being lost is inadequately understood, particularly for tidewater glaciers, where the relative importance of surface runoff vs. frontal ablation is not well quantified. This information is required to properly quantify glacier and ice cap contributions to sea level rise, to assess freshwater fluxes to the ocean (in both liquid and solid form), and to understand the future evolution of tidewater glaciers in a warming climate.

This presentation will provide a review of a project designed to provide the first consistent pan-Arctic estimate of frontal ablation for the period 2000–2015. This will include all regions where glaciers and ice caps terminate in the ocean (i.e. Alaska, Canadian Arctic, Russian Arctic, Svalbard), as well the periphery of Greenland. To achieve this goal, measurements of the width, depth, velocity and terminus retreat rate of every tidewater glacier in the Arctic is required. Recent satellite and airborne measurements make this possible for many locations, although data gaps remain in locations where information on ice thicknesses is poor, such as the Russian Arctic. Methods that can be used to address these data gaps, recommendations for common methodologies, and preliminary results, will be presented.

Fresh water input to Arctic fjord - Hornsund (Svalbard) as an example

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Keywords: Frontal ablation, glacier dynamics, icebergs

Significant retreat and mass volume loss of glaciers have been observed in the drainage basin of Hornsund (Southern Spitsbergen, Svalbard) over last decades. Melting of glaciers has its consequences in increased discharge of fresh water to Svalbard fjords. Here, we present the leading and minor sources of the freshwater supply to Hornsund. Evaluation were based on glaciological and meteorological data from the period 2006–2015.

Long-term yearly average input of fresh water to Hornsund is 2517 Mt a—1. Main components are: surface ablation (986 Mt a—1) and frontal ablation of the glaciers (634 Mt a—1). In studied period tidewater glaciers in Hornsund lose c. 40 % of their mass by frontal ablation. Terminus retreat component contributed c. 30 % of the mass loss by frontal ablation, ranging between 17 and 44 % due to influence of marine, atmospheric and geomorphic factors. Thus, in multiannual scale, input of freshwater due to calving in individual seasons can significantly deviate from the average. Liquid precipitation over the land (520 Mt a—1), total precipitation over the fjord area (180 Mt a—1) and ablation of snow cover on unglaciated area (197 Mt a—1) have smaller contribution than glacial factors. According to recent climate models, the freshwater supply to the sea will increase in the near future, while importance of individual components may alternate.

Factors influencing asymmetric pattern of snow distribution on Hansbreen (Svalbard)

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Defining the factors controlling the snow cover properties has a great importance for understanding glacial systems, mainly their mass balance, heat exchange and temporary water retention. The snow cover characteristics were studied on Hansbreen, an outlet glacier in southern Spitsbergen, over winter seasons 2011–2017. Shallow radio-echo sounding has been used in order to determine spatial snow distribution. Additionally meteorological data from automatic weather stations working on the glacier as well as topographic properties of glacier and its surroundings have been analysed.

Obtained results confirmed that asymmetrical snow distribution pattern on Hansbreen, with the maximum accumulation in the western part of the glacier, is constant over longer period. Lower accumulation and smaller interseasonal variability of snow depth occur in the remaining parts of the glacier. The snow distribution is controlled by the topography of the area surrounding the glacier, especially the orographic barriers in its western and south-western parts. Predominating advection of moist air masses from these directions produces orographic precipitation. That results into favourable conditions for snow deposition on the leeward side of the obstacles (western part of Hansbreen). The central and eastern parts of the glacier, on the other hand, are exposed, which favours snowdrift. Even though winds from the east prevail, their transport capabilities are limited due to the lack of mobile material to be redeposited. Mobile snow particles are available mostly during snowfall or shortly afterwards. Deposited snowpack undergoes a rapid compaction and further displacement of snow particle is hardly feasible.

Can increased meltwater fluxes ’fuel’ enhanced productivity in the North Atlantic?

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Keywords: Nutrients, Chlorophyll, limitation, biogeochemistry

Whilst much attention has been paid to the nutrient content of meltwater and the potential effect of increased nutrient supply to shelf areas of the high latitude North Atlantic from increasing meltwater fluxes, it is not clear to what extent such a supposed ’increase’ can positively affect marine primary production. Here we demonstrate that all meltwater sources (icebergs, surface runoff, sub-glacial discharge) are an imbalanced nutrient supply enriched in lithogenic Si and Fe, but with negligible direct contributions to marine NO3 and PO4 budgets. In several cases the supposed ’increase’ in nutrient supply exists only as a calculated mass flux, because stratification by low NO3/low PO4 meltwater actually lowers the macronutrient content of surface coastal waters. Furthermore, in all cases (NO3/PO4/Si/Fe) fluxes are non-linear with respect to meltwater input due to the phenomenon of localized upwelling which depends strongly on the grounding line depth of marine terminating glaciers. Non-conservative estuarine behavior for Si (approximately 10% enrichment), Fe (90-99% removal) and possible also a modest PO4 sink (some evidence of a PO4-Fe sink from Svalbard) then further moderates these inputs. In addition to supplying modest quantities of Si and Fe to the marine environment, freshwater input has other effects on the marine environment (acidification, stratification, localized upwelling, suppression of light) which are inter-connected with nutrient availability. Here using a satellite derived data product to assess the balance between NO3 and Fe co-limitation on a regional scale in the North Atlantic, and the results of fieldwork around Greenland and Svalbard, we will provide a synopsis of how Atlantic ecosystems may respond to increasing freshwater fluxes with respect to both changes to the glacial supply of, and biological demand for, the nutrients Fe and NO3 which can be used to explain observed patterns of surface productivity across the Atlantic.

A minimal model of tidewater glacier evolution

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Keywords: calving, tidewater, minimal model

The iceberg calving process influences the geometry of a tidewater glacier,and is in turn controlled by the terminus geometry through the stress field which controls damage and fracture of the ice. We analyze the feedbacks in this intricately coupled process with an explicitly formulated model, consisting of evolution equations for three state variables representing glacier geometry. The simplicity of the model allows for formal investigation of stability of glacier states on different basal geometries during advance and retreat. This model, complemented with a simple parametrization of glacier calving rates, can also be used to understand tidewater glacier change rates. Model runs on realistic bathymetries yield evolution histories which compare favorably with recorded tidewater glacier histories.

Retreating glaciers impacts on Arctic marine fjord ecosystem

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Keywords: glacier retreat, ecosystem functioning, biodiversity, fjord

Arctic fjords often host rich and diverse communities that further supply upper trophic level animals. Glaciers' activity is among one of the most important factors shaping Arctic marine fjord ecosystems influencing both pelagic and benthic communities, their structure and diversity.

The key physical - chemical phenomena that are connected with the retreating glaciers include massive summer discharge of meltwater, strong stratification, extreme turbidity,

enhanced mineral and organic carbon sedimentation, reduction of euphotic zone, and extreme acoustic climate. All those factors result in steep environmental gradients along the fjords' axes with highest disturbance in areas close to the glaciers and in the glacial bays. Data collected from over 30 glacial bays of Svalbard shows, that soft bottom benthos, micro- and mesozooplankton follow the same pattern - with a distinct impoverishment of biomass, density and species diversity compared to outer part of the fjord (Lydersen et al., 2014). Within glacial fjords phototrophic microplankton in the outer and central parts of the fjords is replaced by mixotrophic microplankton in glacial bays. The latter have distinct microplankton composition with prevalence of small mixo- and heterotrophes like cryptophytes and other nanoflagellates (Piwosz et al., 2015; Piwosz et al., 2009; Wiktor and Wojciechowska, 2005). Also, the glacier meltwater discharge leads to low chl a concentrations but high mesozooplankton concentrations (Trudnowska et al., 2014). As the meltwater driven estuarine circulation leads to an entrapment of zooplankton in the inner fjord basin, mass mortality events of stenohaline zooplankton are observed in the glacial bays (Węsławski et al., 2000). Up to 15% of standing plankton biomass during the 100 days of melting season is removed from the water column due to osmotic shock (Węsławski et al., 2000; Zajaczkowski and Legeżyńska, 2001). The sinking dead zooplankton fuels the high abundance of scavenging benthic fauna in the glacial bays (Zajaczkowski and Legeżyńska, 2001). Krill avoids freshwater outflow and aggregates below 20 m in the glacial bays (Węsławski et al., 2000), thus attracting predators like fish, seabirds, seals and white whales (Lydersen et al., 2014). Fjords are also home to specific benthic fauna, which in large is characteristic for fjords only (Włodarska-Kowalczuk et al., 2012). The benthic fauna follows the environmental gradients in the fjord with highest macrobenthic diversity in the transition zone and impoverished species and functional diversity in the glacial bays (Włodarska-Kowalczuk et al., 2005). Similar trends of increasing abundance and biomass along with increasing distance from the glacier are observed for foraminifera, meiofauna and macrofauna (Grzelak et al., 2016; Kędra et al., 2013; Włodarska-Kowalczuk et al., 2013). A multifrequency acoustic survey showed that large fish were present in the outer deep part of fjords (Kongsfjorden and Hornsund), while smaller fish dominated in the shallower waters (Szczucka et al., 2017). Glacier cracking and calving is a very strong source of underwater noise with unknown effect on animal hydrolocation.

With ongoing climate warming, glaciers' retreat, accompanied by an increase in meltwater outflow and flux of inorganic particles, is predicted to strongly influence both pelagic and benthic fjord communities including the upper trophic levels of the food chain. Loss of transition zones between inner (highly stressed) and outer (stable conditions) parts might be expected (Kędra et al. 2010). The retreat of tidewater glacier on land results in creation of tidal flat, brackish lagoons and loss of the glacial bay typical fauna, thus the ecosystem functions. On the other hand, permanent cold water pockets near the glacier fronts may also provide refugia for the Arctic species in warming fjords.

Here we present an overview of functioning of the Svalbard marine fjord ecosystems and include results from large project conducted at IOPAN Marine Ecology Department during last 20 years (e.g. GAME http://www.iopan.gda.pl/projects/Game/project-pl.html, GLAERE http://www.iopan.gda.pl/projects/GLAERE/). We include the influence of glaciers' and their retreat on the fjord communities, and present predicted future scenarios for the warming Arctic.

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Physical and Biogeochemical ocean studies at the boundary region of Bowdoin Glacier and its Fjord, Northwestern Greenland

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Keywords: Plume, mooring, biogeochemistry, nuritient

The boundary region between a tidewater glacier and a fjord is a key to understand glacier-ocean interaction in the Arctic. In terms of physical oceanography, ocean heat affects the glaciers by controlling subaquaous melt rate of the ice front. In terms of biogeochemistry, glacial meltwater discharge affects the ocean by controlling nutrient cycles and consequent marine ecosystems in the fjord. Despite the widely recognized importance, these processes occurring near the glacier front are poorly understood because of the difficulty of oceanographic observations in this boundary region. As a part of Japanese interdisciplinary Arctic research project ArCS (Arctic Challenge for Sustainability), we performed physical and biogeochemical observations in proglacial fjords in northwestern Greenland. In the summer 2017, we conducted oceanographic measurements in the fjord in front of Bowdoin Glacier, a tidewater glacier near Qaanaaq. We installed temperature, conductivity, and pressure sensors in the fjord, by lowering the sensors with 200-m long cables from the edge of the glacier calving front. The instruments successfully recorded changes in water properties at the ice-water boundary for ten days. Another mooring system was deployed in the fjord approximately 1 km off the calving front to monitor water properties for an year. Fjord water was sampled near the calving front using a ~5-m long boat to analyze biogeochemical components (nutrient, trace metal (e.g. iron), dissolved inorganic carbon, methane and so on). We also utilized an ROV (Remotely Operated Vehicle) to perform zooplankton sampling within 100 m from the glacier front. In this contribution, we present an overview of our research activities in Bowdoin Fjord, and show results obtained by the campaign in the summer 2017.

Assesment of the current state and development of Austre Grønfjordbreen glacier by a complex of glaciological, physico-mathematical and remote methods

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Keywords: mass balance, modelling

Recent efforts by the Institute of Geography RAS have been aimed at establishing mass balance observation at Austre Grønfjordbreen (7.6 km^2) located 16 km south of Barentsburg. The Arctic archipelago Svalbard consists of a vast glacierized area which contributes significantly to the sea level rise outside of Greenland and Antarctica due to recent warming. The glaciers of Svalbard have already experienced an unprecedented increase in average summer temperatures, melt periods, and rainfall in late autumn and early summer.

Current goal is to determine the most appropriate approach for mass balance simulations and its application for long time periods assessments by comparing uncertainties of physical modeling with the results obtained from temperature-index simulations.

We apply spatially distributed model A-MELT (Rets et al., 2012) using all available glaciological and meteorological measurements carried out since 2012 and energy balance determination according to spatial grid. The empirical model implies the use of an extended methodology for calculating seasonal mass balance in relation to temperature and radiation and calibrating by data obtained from stakes measurements. The obtained mass balance gradients are compared with the geodetic mass balance changes in 1990–2015 and recent Arctic DEM data. All available satellite imagery has been used to reconstruct the snowline elevation changes from 1986 to 2017. Remarkably almost a total absence of accumulation area has been registered in recent years.

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Global-scale 21st century glacier mass and runoff changes

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Glaciers other than the ice sheets in Greenland and Antarctica cover an area of 705,000 km^2 and include approximately 210,000 individual glaciers. Worldwide these glaciers are losing mass at an accelerating pace with profound implications for global sea-level rise. Although only making up less than 1% of the Earth's global ice volume (<0.5 m sea-level equivalent), these glaciers contributed almost just as much to sea-level rise during the first decade of this century as the Greenland and Antarctic ice sheets combined, and are expected to remain significant contributors for decades to come.

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 complex mountainous terrain. Here we project the mass changes of all glaciers over the 21st century based on transient climate projections. We compare six global glacier models published in the literature including a range of different modeling approaches. Using forcing from 8 to 15 Global Circulation Models and four different emission scenarios, the glacier models project multi-model mean net mass losses of all glaciers between 7 cm and 24 cm sea-level equivalent by the end of the 21st century. Projected mass losses vary greatly depending on the choice of the forcing climate and emission scenario. Insufficiently constrained model parameters likely are an important reason for large differences found among these studies even when forced by the same emission scenario, especially on regional scales. A "Targeted Activit" under WCRP's Climate and Cryosphere (CliC) program of the World Climate Research Program (WCRP), 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.

Using one of the models we also project the response of glacier runoff to future climate change. We define glacier runoff as all runoff from the initially glacierized area and assess the changes in runoff amounts, timing and seasonality for all 56 macro-scale drainage basins outside Antarctica and Greenland (>5,000 km^2) with at least 30 km^2 of ice cover and >0.01% glacierization. We find substantial regional differences in the timing of annual peak runoff. In many basins future glacier runoff is projected to increase in early summer but decrease in late summer. Overall, we find that even in macro-scale basins with minimal ice-cover fraction (mostly <3%), the downstream hydrological effects of continued glacier mass loss can be substantial, but projected changes vary greatly among basins and throughout the melt season.

Functional Trait patterns in Arctic fjord ecosystems

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Keywords: Marine communities, Arctic fjords, Functional Traits

Glaciers have a strong impact on the marine ecosystem in Arctic fjords. Turbidity, water temperature, stratification and sea ice and iceberg distribution are thereby often considered the most important environmental factors in structuring marine fjord communities. With ongoing warming, glacial freshwater water runoff is predicted to increase, and other parameters to change along with it. Although marine fjord communities have been studied extensively in the past, we are currently not able to predict how marine communities and the ecosystem functions they control will be affected by these changes. One reason is that our insight into the functional composition of fjord communities is still limited. Here we show based on benthic community data from several fjords on the Svalbard archipelago how trait-based approaches (i.e. such that consider the functional composition of a community and its relationship to environmental parameters) can enhance our insight into current fjord ecosystem functioning and aid our attempt to predict future scenarios.

ASTER-derived glacier volume changes in Alaska or Norway

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TBD

The relationship between albedo and spring warming over Canada's largest glaciated elevation gradient

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Keywords: Albedo, Amplified warming, MODIS

Atmospheric warming appears to be amplified at high elevations and in the Arctic, but the contribution from declining snow cover and albedo or changes in cloud cover remain elusive. The amount of warming related to snow and ice albedo decline is difficult to measure because the decline is both a response and a cause of warming. To further complicate the issue, daytime cloud cover changes, which modifies the surface energy budget, can warm or cool the Earth's surface. Much of the problem in attributing warming to specific processes is related to determining the accuracy of the measurements of change, particularly in glaciated and high elevation locations where few measurements of energy balance or albedo have been made. Here, we report on an ongoing project that aims to attribute the causal factors of temperature amplification through a quantitative comparison of surface feedbacks and warming rates between a latitudinal and elevational gradient in northern Canada.

In the initial stage of the project we analysed downscaled surface temperature and MODIS infrared temperature, albedo, snow cover and cloud cover for a 5000m forest-to-icefield elevation gradient in the St. Elias Mountains, Yukon, to compare temperature patterns across elevational bands characterized by differential spring snowmelt between 2000 and 2014. Over this period, we show differential surface warming of 0.01°C yr-1 1000 m-1 in May (from 0.14°C yr-1 at 1000m to 0.19°C yr-1 at 5000m), and uniform cooling of 0.09°C yr-1 in June for all elevations. In May, the albedo trend for the St. Elias Icefield was increasingly negative with elevation and the trend in daytime cloud cover was negative at higher elevation, but positive at lower elevation. In June, negative temperature trends occurred while daytime cloud cover increased and albedo trends were negative or unchanging. May temperature trends at different elevations were highly correlated despite different albedo changes. Furthermore, snow cover mediated albedo declines resulted in infrared temperature increase, as expected with a feedback, however these were insufficient to alter monthly average air temperature. These findings indicate that monthly averaged temperature and snow albedo trends are largely insensitive to the snow albedo feedback and that a synoptic influence is responsible for surface temperature variation.

Preferential water flow in snow and firn: evidences, consequences and simulation

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Keywords: firn, preferential flow, water infiltration

Infiltration and refreezing of liquid water in accumulation zones of glaciers can significantly affect the subsurface temperature, density as well as the amount of runoff. It thus has to be taken into account by the models describing mass and energy fluxes at glaciers in local, regional and global scales. Although it is common to assume that water infiltration is laterally uniform, field observations suggest highly horizontal variability in rate of vertical water flow. Subsurface temperature, stratigraphy and GPR data from the snow/firn pack at Lomonosovfonna, Svalbard, provide evidences of preferential flow. Potential implications for modelling of the subsurface processes in the accumulation zones of glaciers are discussed and possible parameterization strategies are suggested.

Long-term projection of Arctic valley glaciers based on finite element simulations

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Keywords: Arctic, Austre Lovénbreen, IPCC scenario, Finite element simulation

In order to study the response of Arctic mountain glaciers to the global climate change, a long-term projection of Arctic Austre Lovénbreen was carried out using finite element simulations, which is a systematic answer to when and how will the glacier retreat and disappear. Firstly, a steady state simulation was solved to select the best parameters related to the ice flow model, then transient state simulations were solved to project the future glacial evolution.

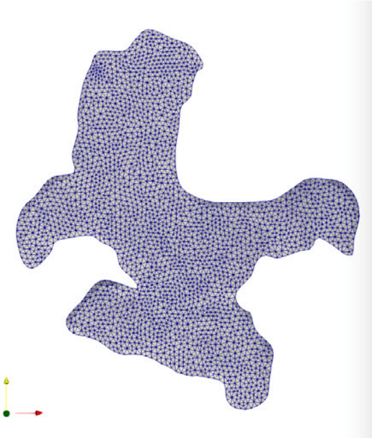
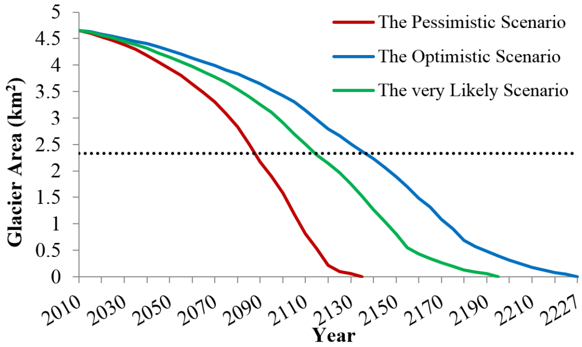


Figure 1. Mesh of Austre Lovénbreen for simulation

The long-term evolutions, including the area, volume, thickness and ice-flow velocities, were estimated based on three climatic scenarios: the pessimistic, the very likely and the optimistic ones. Simulated results show that the Austre Lovénbreen will continue to diminish until death in all the three scenarios, and the extinction time is 126, 185, and 218 years, respectively. In other words, the glacier will disappear between 2135 and 2227, very likely around 2194.



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Assessment of proglacial moraine response to climate shift, an Arctic basin as a witness

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TBD

Continuous monitoring of ice motion and discharge of outlet glaciers of Greenland and Artic ice caps by Sentinel Satellites

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Keywords: ice velocity; ice discharge; Arctic ice caps, Sentinel satellites

The Sentinel-1A and 1B satellite constellation offers excellent opportunities for operational monitoring of the Earth's surface, including ice sheets, ice caps and their outlet glaciers. The Interferometric Wide Swath (IWS) mode of Sentinel-1 is the standard operation mode over land surfaces and inland ice. Applying Terrain Observation by Progressive Scans (TOPS) acquisition technology, it provides spatial resolution of about 4 m and 22 m in slant range and azimuth, respectively, with a swath width of 250 km. With these powerful imaging capabilities, in combination with a coordinated acquisition strategy, the Sentinel-1A and 1B constellation has become the main source for regular and comprehensive monitoring of ice motion and discharge of Greenland and the Arctic Ice caps.

The Sentinel-1 acquisition planning for Greenland includes an annual ice sheet wide campaign with 4 to 6 repeat acquisitions for each track. During winter 2016/2017 the third ice sheet wide Sentinel-1 campaign was carried out, which was the first campaign including both, Sentinel-1A and 1B, satellites providing 6-day repeat pass observations. From January to March 2018 the next annual campaign with full 6-day repeat coverage is planned. For generating ice sheet velocity, we apply an iterative offset tracking algorithm using coherent and incoherent image cross-correlation. The full spectrum of flow velocities is mapped by using variable matching windows sizes. We present Sentinel-1 velocity maps of Greenland, with 250 m pixel spacing, for 2015, 2016 and 2017, and show first data of the 2018 winter campaign. Besides, we also present annual velocity maps of the main Arctic ice caps in the Canadian Arctic, Svalbard, Iceland, Franz-Josef Land, Novaya Zemlya, and Severnaya Zemlya.

The Sentinel-1 ice velocities agree very well with velocities derived from high-resolution TerraSAR-X Stripmap mode data which are available for several outlet glaciers. We show also dense time series of Sentinel-1 flow velocities, documenting on short-term variations and temporal trends for outlet glaciers in Greenland and on Arctic ice caps. The time series prior to the Sentinel-1 era are based on other SAR sensors (PALSAR, TerraSAR-X, TanDEM-X, ERS). Especially the continuous 6-day repeat observations of Sentinel-1A and 1B reveal remarkable short-term, weekly to seasonal, variations of ice velocities of outlet glaciers, with striking differences even between adjacent glaciers. We will show examples for several major outlet glaciers of Greenland and marine terminating glaciers of Svalbard and Russian Arctic ice caps. For major outlet glaciers we compiled time series of ice discharge based on ice thickness data from airborne RES campaigns and ice velocities across flux gates.

Enhanced models for mass balance and ice dynamics of Svalbard glaciers

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Keywords: Mass balance, Calving, Simulation

We present several recently established simulation techniques concerning the mass balance of land and marine terminated glacier: 1) an inversely determined surface mass balance distribution from a series of DEM's supported by flow simulations using a full-stress Stokes model applied to Midtre Lovènbreen 2) a mixed continuum and discrete element approach to determine either the crevassing used to identify potential water routing paths to trigger surge behaviour at Austfonna, Basin 3 or the calving behaviour of a tidewater glacier (Kronebreen).

The importance of shear-margin softening for abrupt velocity variations at Upernavik Isstrøm, Greenland

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Keywords:
Outlet glacier dynamics, ice velocity variations, marine mass loss, Greenland ice sheet

Understanding the physical mechanisms behind rapid velocity variations of marine-terminating outlet glaciers is key to the correct representation of marine mass loss in large scale ice sheet models. While the penetration of surface meltwater to the bed of glaciers is known to affect ice velocity, ice streams represent an extreme case with a spatially complicated velocity and temperature structure. Here we use an observed abrupt synchronous slowdown event at three neighboring ice streams in Northwest Greenland in late summer 2014 to evaluate different hypotheses regarding the spatial sensitivity of ice flow to changes in surface melt rates through changes in resistive forces. Using the Ice Sheet System Model (ISSM; Larour et al., 2012) we investigate the sensitivity in the velocity of the three ice streams to changes in meltwater production through perturbations of basal friction and shear margin softness. We find that to best capture the spatial structure of the observed slowdown, basal friction has to change relatively more in the ice stream trough compared to the upstream area and increasingly so towards the front. Additionally, our results indicate that changes in the shear margin softness and the internal heat production are likely playing an important role for the ice flow sensitivity to changes

in friction.

On the link between glacier-freshwater runoff and summer phytoplankton growth in seas around Svalbard

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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. Ocean primary production, i.e. the production rate of organic carbon or phytoplankton, is an important measure of biological productivity. Phytoplankton dynamics in the Arctic are commonly linked to a strong seasonality in environmental conditions. The return of daylight in springtime and the decline in sea ice cover triggers a typical spring bloom in phytoplankton biomass. Recent pilot studies in Greenland revealed a second primary-production bloom, coincident with the peak meltwater runoff from the Greenland ice sheet.

Here, we focus on Svalbard in the Eurasian Arctic, where glaciers cover 34000 km^2 or 57% of the total land area. Tidewater glaciers drain 68% of the glacierized area, with a total calving-front length of ∼740 km. We divide Svalbard into 14 hydrological regions for each of which we investigate the relationship between surface chlorophyll-a concentrations (an indicator of phytoplankton biomass) and glacier meltwater runoff. We also consider other known drivers of phytoplankton dynamics, such as sea-ice fraction, sea-surface temperature and mixed-layer depth. Freshwater runoff for the period 2003 to 2013 is extracted from a 10-year simulation of the climatic mass balance of all glaciers on Svalbard using a coupled atmosphere-glacier model. Surface chlorophyll-a concentrations derived from ocean colour, as well as physical ocean and sea-ice variables for the period 1998–2014 are provided by the Copernicus Marine Environmental Monitoring Service. We use a statistical model to identify significant relationships between chlorophyll-a concentrations and the various environmental factors during summer months. Significant positive correlation between chlorophyll-a and glacier runoff exists for 6 out of 14 regions and within 10 km distance from the coast. These 6 regions can be characterized as sheltered fjord systems, where the glacier meltwater is distributed over a relatively small marine area and freshwater residence time is anticipated to be long.

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