IASC Workshop on the dynamics and mass budget of Arctic glaciers

Abstracts and program

Network on Arctic Glaciology annual meeting &
IASC cross-cutting activity on **“Glacier-ocean interactions and their impact on Arctic marine ecosystems”**

28-30 January 2020, Obergurgl, Austria

Organised by:
Thorben Dunse, Ward van Pelt, Jakob Abermann and Michael Kuhn

IASC Network on Arctic Glaciology

Cover photo: Pancake ice and bergy bits from surging Tunabreen mix at the head of Tempelfjorden in Svalbard. (Photo: T. Dunse)

Participants of the 2020 IASC workshop on Arctic Glaciology in Obergurgl, Austria. (Photo: T. Dunse)

Contents

Preface

This year's IASC Workshop on the Dynamics and Mass Budget of Arctic Glaciers & the IASC Network on Arctic Glaciology Annual Meeting took place at the University Centre Obergurgl, in Obergurgl, Austria, 28-30 January 2020. The workshop hosted a cross-cutting activity on "Glacier-ocean interactions and their impact on Arctic marine ecosystems" and attracted 41 participants representing 14 countries. The workshop was jointly sponsored by the IASC Cryosphere and Marine Working Groups, involved in the cross-cutting activity. This also allowed for travel support of twelve early-career scientists.

Two-and-a half days of scientific sessions with oral presentations and posters addressed a variety of topics related to glacier mass balance, dynamics and glacier-ocean interactions. Across the Arctic, glacier mass budget and dynamics strongly correlate with air temperature. The influence of oceanic forcing on tidewater-glacier dynamics and frontal ablation varies with region and appears to be less important in Arctic Canada (Copland et al.) than in Greenland (Catania et al.). In her keynote talk, Ginny Catania demonstrated that the strong heterogeneity in dynamic response of tidewater glaciers in Greenland is linked to bedrock topography. Advances in satellite remote sensing facilitate monitoring of glacier flow across the Arctic at high temporal and spatial resolution (Wuite et al.). Several talks highlighted the importance of subglacial discharge plumes for marine primary production in glacier fjords (e.g. Kanna et al.). However, plumes have only a positive effect on marine productivity, if they reach surface waters. This depends on discharge volume and depth, but also fjord stratification (De Andrés). A better understanding of water masses and fjord circulation is thus needed when assessing impacts of glacier runoff on marine ecosystems. Timeseries of glacier freshwater runoff in both solid and liquid form are now becoming available for various Arctic regions (e.g. Wuite et al., Mankoff et al. and Van Pelt et al.). Statistical modelling helps to enhance the performance of climatic mass balance models and improved uncertainty assessments of model parameters and climatic input data (e.g. Rounce et al. and Zolles et al.).

During the open forum meeting, Ward van Pelt was elected new chairman of the IASC Network on Arctic Glaciology. He will be supported by Wesley van Wychen as new vice-chair. I wish the new team best of luck with upcoming network activities. Finally, I would like to thank all participants for their contributions to the workshop. I hope we all meet again at the next workshop and annual meeting in Poland (2021), followed by workshops in Japan in 2022, and again, Obergurgl, Austria in 2023.

Sogndal, Norway – February 2020

Programme

The meeting takes place at the University Centre in Obergurgl, Austria, 28 - 30 January, 2020.

Monday 27 January

ARRIVAL

19:00 - 21:00 **Dinner**
Please inform the University Center if you arrive late and whish dinner after 21:00

Tuesday 28 January

08:30 - 09:00 Registration: pick up your name badge and copy of program. Please upload your presentations for the morning session.

09:00 - 09:10 **Welcome**

Session I: **Remote sensing (part I)**

Convener: *Tobias Zolles*

09:10 - 09:30 5 Years of Arctic Land Ice Velocity and Discharge observed by Sentinel-1 **Jan Wuite**, Thomas Nagler, Markus Hetzenecker, Ludivine Libert, Lars Keuris, Helmut Rott

09:30 - 09:50 Calculating ice volume changes of a small icefield within the Canadian High Arctic using Structure from Motion **Braden Smeda**, Dorota Medrzycka, Luke Copland, Laura Thomson

09:50 - 10:10 Albedo of the Cryosphere from Sentinel-3 **Jason Box**, Baptiste Vandecrux, Alex Kokhanovsky, Adrien Wehrlé, Kenneth Mankoff

10:10 - 10:40 Coffee break

Session II: **Calving & Frontal ablation**

Convener: *Julia Liu*

10:40 - 11:00 Multi-year observations of calving activity and front geometry of two marine terminating outlet glaciers **Andrea Walter**, Martin P. Lüthi, Martin Funk, Andreas Vieli

11:00 - 11:20 Recent increase in marine ablation of Svalbard glaciers **Geir Moholdt**, Jack Kohler, Ashley Morris, Josephine Maton, Alex Gardner, Johannes Fürst

11:20 - 11:40 How oceanic melt controls tidewater glacier evolution **Martin Lüthi**, Rémy Mercenier, Andreas Vieli

11:40 - 12:00	The effect of debris cover and frontal ablation on projections of glacier mass change in Alaska using the Python Glacier Evolution Model (PyGEM) **David Rounce**, Regine Hock
12:00 - 15:45	Lunch & ski break
15:45 - 16:15	Coffee break
16:15 - 17:00	**Poster introductions** (1-2 slides and max. 2 minutes per person)
Convener:	*Jakob Abermann*
17:00 - 18:30	**Poster session**
19:00 - 20:30	Dinner

Wednesday 29 January

Session III:	**Cross-cutting session (part I)**
Convener:	*Thorben Dunse*
09:00 - 09:30	[Keynote] Understanding ice-ocean interactions with detailed observations of terminus behavior **Ginny Catania**, Mason Fried, Denis Felikson, Leigh Stearns
09:30 - 09:50	Fjord stratification controls surface emergence of glacial plumes **Eva De Andrés**, Donald A. Slater, Fiamma Straneo, Jaime Otero, Sarah Das, Francisco Navarro
09:50 - 10:10	Greenland liquid water runoff from 1979 through 2017 **Ken Mankoff**, Andreas Ahlstrøm, Xavier Fettweis, Brice Noël
10:10 - 10:30	Coffee break
Session IV:	**Cross-cutting session (part II)**
Convener:	*Shin Sugiyama*
10:30 - 10:50	Causes and patterns of tidewater glacier retreat in the Canadian Arctic **Luke Copland**, Alison Cook, Brice Noel, Chris Stokes, Michael Bentley, Martin Sharp, Robert Bingham, Michiel van den Broeke
10:50 - 11:10	Comprehensive ocean observations in Inglefield Bredning, Northwestern Greenland **Naoya Kanna**, Shin Sugiyama, Takuto Ando, Izumi Asaji, Yefan Wang, Yuta Sakuragi
11:10 - 11:30	Land-ice mass imbalance across the Arctic driven by atmosphere and ocean forcing **Noel Gourmelen**, Paul Tepes, Michel Tsamados, Pete Nienow, Andrew Shepherd, Flora Weissgerber
11:30 - 12:00	Cross-cutting discussion

12:00 - 15:30	Lunch & ski break
15:30 - 16:00	Coffee break
Session V:	**Glacier dynamics**
Convener:	*Will Kochitzky*
16:00 - 16:20	Reinterpreting the surge of Good Friday Glacier, Axel Heiberg Island, Canadian Arctic **Dorota Medrzycka**, Luke Copland, Wesley Van Wychen, David Burgess
16:20 - 16:40	Decadal scale ice velocity change in the interior of the Greenland Ice Sheet **Josh Williams**, Noel Gourmelen, Pete Nienow
16:40 - 17:00	Short-term ice speed variations near the calving front of Bowdoin Glacier, northwestern Greenland **Shin Sugiyama**, Shun Tsutaki, Daiki Sakakibara, Izumi Asaji
17:00 - 17:10	Short break
17:10 - 18:30	IASC Network on Arctic Glaciology – Open forum meeting
19:00 - 20:30	Dinner

Thursday 30 January

Session VI:	**Glacier mass budget**
Convener:	*Danielle Hallé*
09:00 - 09:20	The uncertainty of average precipitation forcing **Tobias Zolles**, Andreas Born
09:20 - 09:40	IPCC's Special Report on the Oceans and the Cryosphere in a Warming Climate - Key messages for the Arctic **Regine Hock**
09:40 - 10:00	Future climatic mass balance, snow conditions and runoff in Svalbard **Ward van Pelt**, Thomas Schuler, Veijo Pohjola
10:00 - 10:20	Snow Cover Reflection Properties on Hansbreen (South Spitsbergen) based on radio-echo sounding **Mariusz Grabiec**, Barbara Barzycka, Michał Laska, Dariusz Ignatiuk, Kamil Kachniarz
10:20 - 10:50	Coffee break
Session VII:	**Remote sensing (part II)**
Convener:	*Nicole Clerx*
10:50 - 11:10	Mapping glacier extent in Norway using Sentinel-2 **Liss Marie Andreassen**, Teodor Nagy
11:10 - 11:30	Investigating spatiotemporal patterns in Greenland glacier terminus changes using automated edge detection in satellite images **Julia Liu**, Ellyn Enderlin, Andre Khalil

11:30 - 11:50	Photos to Elevations: a photogrammetry pipeline **Will Kochtitzky**, Dorota Medrzycka, Braden Smeda, Brittany Main, Moya Painter, Luke Copland, Alex Culley, Warwick Vincent, Christine Dow
11:50	**Final words** followed by lunch / skiing / side events / early departure
19:00 - 20:30	Dinner

Posters

- Arctic land ice regional albedo products from Sentinel-3, **Adrien Wehrlé**, Jason E. Box, Baptiste Vandecrux, Ken D. Mankoff
- First results from new automated instruments measuring snow water equivalent (SWE) and position/ elevation/ tilt/ rotation on the Greenland Ice Sheet in the INTAROS project, **Andreas P. Ahlstrøm**, Robert S. Fausto, Michele Citterio, Roberta Pirazzini, Teijo Arponen, Jason E. Box
- Local climate of Zachary glacier, North East Greenland, **Carleen Reijmer**, S.A. Khan, E.J. Rignot, M.R. van de Broeke
- Predicting Runoff from Ungauged Partially Glaciated Basins in South West Greenland, **Danielle Hallé**, Irina Rogozhina, Signe Hillerup Larsen, Andreas Ahlstrøm
- Estimating the contribution of trace metal contaminants from Devon Ice Cap, NU to the Ocean (2005-2015), **David Burgess**, James Zheng, Wesley van Wychen
- Impact of frontal ablation on the ice thickness estimation of marine-terminating glaciers in Alaska, **Fabien Maussion**, Beatriz Recinos, Ben Marzeion
- An icestream margin as seen with high resolution radar, **Heinrich Miller**, Daniel Steinhage, Daniela Jansen, Veit Helm, Dorthe Dahl Jensen, Yan Jie, Prasad Gogineni
- On current changes of the Greenland Runoff Limit, **Horst Machguth**
- The potential of the Wegener Greenland expedition material for modern glaciological research, **Jakob Abermann**, Wolfgang Schöner
- Glacier retreat in Sørkapp Land, Spitsbergen, from 1961 to 2010 based on aerial photographs, **Justyna Dudek**
- Changes in snow cover structure on Hansbreen from repeated radio-echo sounding, **Kamil Kachniarz**, Mariusz Grabiec, Michał Laska, Bartłomiej Luks
- Patterns and mechanisms of flood release from glacier dammed Donjek Lake, Yukon, **Moya Painter**, William Kochtitzky, Luke Copland, Christine Dow
- Synoptic conditions and atmospheric moisture pathways associated with virga and precipitation over coastal Adélie Land, Antarctica, **Nicolas Jullien**, Etienne Vignon, Michael Sprenger, Franziska Aemisegger, Alexis Berne
- Hydrological processes in firn at the runoff limit on the Greenland Ice Sheet, **Nicole Clerx**, Horst Machguth, Andrew Tedstone
- Basal conditions of Kongsvegen at the onset of surge - revealed using seismic vibroseis surveys, Anja Diez, Emma C. Smith, **Olaf Eisen**, Coen Hofstede, Jack Kohler

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Young scientists receiving IASC travel support are marked *.

Minutes of the cross-cutting discussion

Moderator: Thorben Dunse
Minutes: Adrien Wehrlé and Nicolas Jullien, with additions by Carleen Reijmer

Introduction

Thorben Dunse presents the cross-cutting activity, led by the Cryosphere Working Group (Network on Arctic Glaciology) and the Marine Working Group. It aims to bring together experts within glaciology, oceanography and marine biology/ecology.

The two main objectives of the activity are:

- Glacier-ocean interactions: physical and bio-geochemical processes at tidewater glacier margins
- Marine pro-glacial ecosystems and their response to glacier processes and glacier change in a warming climate

The activity follows up the previous cross-cutting activity "The importance of Arctic glaciers for the Arctic marine ecosystem" (two workshops in 2018 and 2019).

Extended discussion about today's talks

In relation to **Ginny Catania**'s presentation, **Jason Box** raises the need to identify key glaciers to study. Better bed maps are needed, especially to study key glaciers. Long term observations are also needed. **Martin Lüthi** discusses the importance to understand which glaciers will change soon to monitor them before the beginning of the change. **Olaf Eisen** mentions the quality problem of ice-thickness products. Often only profile lines are surveyed, but grids are generally preferable over single lines, as those may miss out overdeepenings. Icesheet bedrock maps like "Bedmachine" are not reliable everywhere, because of limited survey data. Several people mention that also the bathymetry in front of glaciers is often unknown, a knowledge gap which needs to be addressed by future projects.

Key knowledge gaps and how to address?

Thorben Dunse refers to a slide by **Lorenz Meire** presented during last year's cross-cutting discussion: "What we need from glaciologists". It contained the following points:

- Total freshwater flux to individual fjords (both ice and liquid runoff)
- Daily runoff estimates for individual catchments
- In-situ discharge observations
- Volume of subglacial discharge
- Data on large events/lakes

Thorben Dunse adds "sediment fluxes and biogeochemical composition of glacial freshwater discharge" to the list of variables that glaciologists may provide to marine ecologists. He points out that the first two points with regards to estimating glacier freshwater discharge in form of both meltwater runoff and frontal ablation, were addressed in many presentations at this workshop.

As previously mentioned, the need for better bedrock/ice thickness maps and bathymetry is highlighted, as well as ice-dynamic modelling, to improve estimates of frontal ablation.

The need for oceanographic information when assessing ice-ocean interactions were highlighted in **Eva De Andres**' talk, with respect to understanding subglacial discharge-plume dynamics and whether or not they reach the sea surface. **Ginny Catania** suggests future studies coupling field measurements and modelling with remote sensing.

Andreas P. Ahlstrøm touches on glacial sediment fluxes. There are not that many requests at the moment but it could become important. GEUS monitores the Watson river near Kangerlussuaq, Greenland. **Jakob Abermann** underlines that the Zackenberg site in Greenland has some data on sediment fluxes. It is noted that satellite derived ocean-color provides information on the surface extent of sediment plumes.

Follow-up/suggestions for new cross-cutting activities?

Thorben Dunse reports on the legacy from cross-cutting activity "The importance of Arctic glaciers for the Arctic marine ecosystem" (two workshops in 2018 and 2019). A review article has been submitted to The Cryosphere, entitled "How does glacier discharge affect marine biogeochemistry and primary production in the Arctic" by Mark Hopwood et al., 2019 (https://doi.org/10.5194/tc-2019-136). **Thorben** presents key figure 9 of the paper, summarizing direct and indirect effects on how glaciers may fertilize marine ecosystems and the associated spatial scale at which these processes operate.

Concerning new cross-cutting activities, **Regine Hock** suggests the topic of atmosphere-glaciers interactions. This suggestions finds broad support. A group is formed that will work on a proposal and establish contact with the Atmosphere Working Group of IASC, including Ward van Pelt, Regine Hock, Carleen Reijmer, Tobias Zolles and Jason Box.

Minutes of the IASC-NAG open forum meeting

Chair: Thorben Dunse
Minutes: Danielle Hallé and Nicolas Jullien
Invited to attend: all participants of the workshop.

Agenda

1. Introduction to IASC, IASC-CWG and NAG
2. Election of new chair/co-chair
3. Network Activities and funding opportunities
4. Upcoming annual meetings
5. Book of extended abstracts
6. Anything else?

Ad. 1

Thorben Dunse presents an overview of the International Arctic Science Committee (IASC) and its 5 working groups. IASC is a non-governmental organization promoting all aspects of Arctic research. IASC provides no research funding, but supports workshops that stimulate research activity and knowledge exchange. During the past years, interdisciplinary work is particularly encouraged, by support of cross-cutting activities. These are endorsed by at least 2 WGs, and ideally bridge between social and human and natural sciences. Networks operate within the framework of the working groups and have a specific research focus. The Network on Arctic Glaciology is a program of the Cryosphere WG and formed out of the Working Group on Arctic Glaciology (1994-2011). The organizational structure consists of a chair (Thorben Dunse, since 2016) and vice-chair (Ward van Pelt, since 2019) and 18 national contacts.

Ad. 2

Prior to the meeting **Thorben Dunse** informed all national contacts about the nomination of **Ward van Pelt**, Uppsala University, Sweden, as the new chair. Ward served as vice-chair since 2019. There was only positive response to this suggestion, if any.

- Any objections among the audience or other candidate suggestions? All agree with **Ward van Pelt** as the new chairman.
- For vice-chair position: one suggestion to swap the vice chair and chair positions.
- Open to suggestions: suggestions to have more diversity for the position, within gender and geographical diversity.
- **Luke Copland** suggested **Regine Hock** as Vice-chair. Regine nominates **Shin Sugiyama**. Shin nominates Regine.

- How much time does it involve? Setting up cross cutting activities and setting up meeting, proposal writing.
- Everyone agrees to have North American vice chair, potentially **Laura Thompson** or **Wesley van Wychen**: positive reaction to this suggestion. Inform potential candiates by email.
- Final decision next morning: **Wesley van Wychen**, University of Waterloo, Canada, is willing to serve as vice chair. The nomination is accepted by the audience.

Update of national correspondents: There is a 2-year rule stating that in case of no participation in the network for 2 years, then the national correspondent should be updated. The audience went through the list of the national correspondents. The following changes were decided/considered:

- Austria: Jakob Abermann takes over after Michael Kuhn
- Canada: Martin Sharp retired. Luke Copland new national contact.
- Germany: Olaf Eisen takes over after Heinz Miller.
- Sweden: Ask Per Holmlund to double-check his continued interest to be national contact.
- UK: potential change; Pete Nienow is mentioned as potential candidate
- Greenlandic position? Greenland is a not a member country. Kirsty Langley is mentioned as potential candidate.

Ad. 3

- Proposals of special activities offer funding opportunities.
- Higher chance of funding for cross-cutting activities, involving at least 2 IASC working groups.
- Very good to have funding for ECS. Previous years were able to cover all expenses but this year was only partial cover.
- Current call for proposals has deadline 1st of March 2020. Next annual meeting is covered by the funding period.
- Suggestions for follow-up and new cross cutting activities:
- **Regine Hock** suggests moving to atmosphere–ice interactions, incl. for example effects of rain on glacier dynamics.
- Any suggestion for whom to contact: contact working group chair and circulate a list of topics; Steven Arnold from UK is chair of the Atmosphere Working Group.
- Are there any volunteers to write a short proposal to circulate to the working group? **Regine Hock, Carleen Tijm-Reijmer, Tobias Zolles and Jason Box** agree to write proposal together with **Ward van Pelt**. They will start with brainstorming now or tomorrow.

Ad. 4

Suggestions for the next annual meeting are Poland, Japan or North America.

Mariusz Grabiec presents options for Poland and suggests Szczryk, close to Krakow and Katowice. Mariusz and his Polish colleagues have offered to host the meeting for the last two years and are willing to organize the meeting in 2021 or 2022. The offer finds very positive response among the audience and so it is agreed that Poland will host the meeting in 2021. **Shin Sugiyama** and **Luke Copland** briefly introduce options for Japan and Canada. A vote among the audience decides in favour of Japan, as host of the 2022 workshop. The workshop will likely take place in Niseko, Hokkaido. Obergurgl is booked for the end of January 2023.

Ad. 5

- A book of abstracts, including program, participant list and minutes from both the open forum meeting and XC discussion will be published on the IASC-NAG website.
- Suggestion to keep publishing abstract and programme book, but to drop extended abstract. Fine for everyone.
- Participants are encouraged to submit updates and/or corrections of their abstract (these may inlcude a figure). Any updates should be send to Ward van Pelt until 07.02.2020.

Ad. 6

- Reminder to form a task group to work on proposal for cross-cutting activity.

Abstracts

Arctic land ice regional albedo products from Sentinel-3

Adrien Wehrlé[1], Jason E. Box[1], Baptiste Vandecrux[1], Ken D. Mankoff[1]

[1] GEUS, Denmark

Keywords: ice albedo, Sentinel-3

For much of the pre-melt and melt season, sunlight absorption can be the dominant melt energy source for snow and ice on land, glaciers, seas, and lakes. The Copernicus ESA Sentinel-3 A and B platforms host two sensors with optical bands: the Ocean Land Color Instrument (OLCI) and the Sea and Land Surface Temperature Radiometer (SLSTR). These data enable production of snow/ice albedo for areas of limited terrain complexity. Algorithms to retrieve snow and ice albedo are after the SICE project using the GitHub repository `https://github.com/mankoff/SICE`. The goal is to produce a 3 year daily 1 km albedo product for seven glacierized areas: Greenland, Arctic Canada, Russian High Arctic (Frans Josef Land, Novaja Zemlja, Severnaya Zemlya), Iceland and Svalbard. Processing is made using the PolarTEP system and the CREODIAS real-time big data repository. Regional examples are given, starting with Greenland and Iceland and on to other regions in this pan-Arctic albedo assessment.

Multi-year observations of calving activity and front geometry of two marine terminating outlet glaciers

Andrea Walter[1,2], Martin P. Lüthi[1], Martin Funk[2], Andreas Vieli[1]

[1] University of Zurich, Switzerland
[2] ETH Zurich, Switzerland

Keywords: Calving, multi-year observations

By using a terrestrial radar interferometer, pressure sensors and a time-lapse camera we observed two outlet glaciers in West- and Nordwest-Greenland over six and two years, respectively. The two glaciers are characterised by different geometries and velocity fields. The resulting very detailed dataset provides us new insights on the calving process and the changes in front geometry. With the time-lapse camera alone, all calving events of different sizes and styles can be detected but the volume cannot be quantified. The pressure sensors and the terrestrial radar interferometer are limited to detect calving events of a minimum size. However, the terrestrial radar interferometer allows us to quantify the volumes of aerial calving events and calving waves measured with the pressure sensors enable us to distinguish between aerial and subaquatic events. We find that the calving style and size as well as the front geometry is mainly controlled by the bed topography and the presence of a subglacial discharge plume. The location of the plume can change from year to year, which leads also to changes in the calving pattern. Calving style and pattern as well as glacier velocity patterns and geometry changes are additionally compared with environmental conditions such as the temperature and the presence of ice-mélange in the proglacial fjord.

First results from new automated instruments measuring snow water equivalent (SWE) and position/ elevation/ tilt/ rotation on the Greenland Ice Sheet in the INTAROS project

Andreas P. Ahlstrøm[1], Robert S. Fausto[1], Michele Citterio[1], Roberta Pirazzini[2], Teijo Arponen[2], Jason E. Box[1]

[1] GEUS, Denmark
[2] FMI, Finland

Keywords: instruments, Greenland ice sheet, observations, weather stations

The monitoring of the Greenland Ice Sheet carried out in PROMICE includes in-situ observations from more than 20 automatic weather and mass balance stations situated on the ice, mainly in the ablation zone. These stations gather and transmit data in a highly challenging physical environment, with stations experiencing up to 9 m of ice melting per year, several metres of snowfall with subsequent compaction, temperatures below -40 degrees C, several months of complete darkness, ferocious Piteraq winds known to destroy entire villages in Southeast Greenland and potential destructive visits from polar bears and Arctic foxes. As we can only visit the remote stations every few years, instrumental development has to pay primary attention to structural robustness, power supply and data transmission economy, besides from instrument performance. Yet, the fast changes in the Arctic environment requires new or improved instrumentation, as new parameters needs to be observed, such as rain on the ice sheet. Here we present the first results from experimental deployment on the Greenland Ice Sheet of the SnowFox instrument from HydroInnova, designed to measure the water equivalent of the overlying snow (SWE) through the attenuation of cosmic-ray neutrons. The sensor records neutron events over a regular interval and to derive SWE, the raw neutron counting rate of the sensor must be corrected for variations in barometric pressure and solar activity. We will also present the concepts of a new GNSS instrument developed to improve the determination of position and elevation of the station as it moves with the flowing and melting ice, as well as our development of instrument characterization facilities and tilt/rotation instruments to improve the quality of short- and longwave radiation observations.

Calculating ice volume changes of a small icefield within the Canadian High Arctic using Structure from Motion

Braden Smeda[1], Dorota Medrzycka[1], Luke Copland[1], Laura Thomson[2]

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Keywords: Glaciology, Mass Balance, Photogrammetry, Remote Sensing

There has been a marked increase in melt season length over the past two decades on glaciers and ice caps within Canada's Queen Elizabeth Islands (QEI). Prior to the year 2000 (1958-1995) land ice was in a state of slightly negative mass balance (-11.9 +/- 11.5 Gt yr^{-1}), but recent GRACE measurements suggest that mass losses between 2003 and 2015 averaged -33 +/- 5 Gt yr^{-1}. These losses have mainly been attributed to meltwater runoff, which makes the QEI one of the largest recent contributors to sea level rise outside of the ice sheets. Despite these losses, there is a paucity of information concerning how a warming climate is affecting small (<1 km^2) ice bodies, which are considered sensitive indicators of change due to their short response time.

In this study we describe the use of historical and contemporary aerial photographs, high-resolution optical satellite imagery, and ground penetrating radar (GPR) surveys to determine the area and volume changes of Adams Icefield within Expedition Fiord (Axel Heiberg Island) over the past six decades. Historical (1959) and contemporary (2019) digital elevation models (DEMs) were created via aerial photo surveys using Structure from Motion photogrammetry. The DEMs were accurately co-registered by combining direct measurements of camera positions using an aircraft-mounted dual-frequency GPS system, and multiple ground control points situated around the study region. Volume changes derived from DEM differencing were validated using 36 years of in-situ mass balance measurements from Baby Glacier (an ice body within Adams Icefield) collected intermittently between 1959 and 2019, together with 2014 and 2019 GPR surveys. The results from this study indicate that small ice masses are rapidly declining within the QEI, and support future projections of the life expectancy of these small ice bodies.

Local climate of Zachary glacier, North East Greenland

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Keywords: Weather stations, Greenland, in situ, climate

In August 2016, two automatic weather stations (AWS) were placed on Zachariae ice stream, North East Greenland. They were installed in support of a project investigating the surface mass balance, ice velocity and calving conditions of Zachariae ice stream. The stations are full energy balance stations, i.e. they measure all parameters (air temperature, wind speed, relative humidity, air pressure, and short and long wave incoming and outgoing radiation) necessary to derive the full surface energy balance. In addition, the stations are equipped with a sonic height ranger in combination with a draw wire to measure snow accumulation and ice melt, respectively, and a GPS to monitor glacier velocity. These stations provide insight in the local climate of north east Greenland, a region for which only limited in situ data is available.

The AWS were located initially at ~145 m a.s.l., about 13 km from the glacier front (S22), and at ~535 m a.s.l., about 35 km from the glacier front (S23). Both are moving reasonably fast (0.5 – 1.5 km/yr) towards the front, which has an impact on observed variables mainly since station elevation decreases, although changing (surrounding) topography might impact wind and radiation observations. First results show that both sites exhibit a strong katabatic signature, with directional constancies around 0.9, and wind speeds in winter being twice as strong as in summer. Temperature difference between the sites reflect the height difference, and is smaller in summer due to the melting surface impacting the near surface temperature. The lapse rate increases from ~0.5°C/100 m in summer to ~0.7°C/100 m in the other seasons. The lower station, S23, is located in the ablation zone and has experienced on average 2.1 m ice melt over the past 3 years. At the higher station the mass budget appears to be in balance over this period.

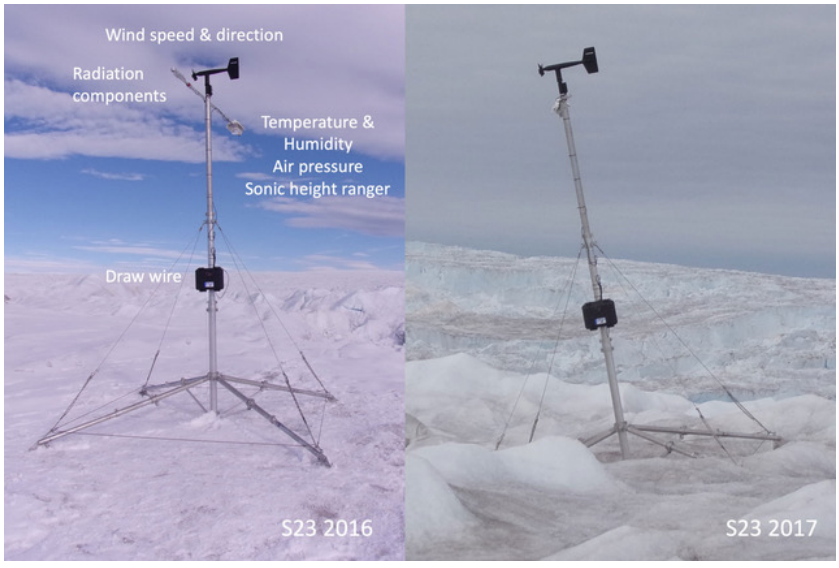

Figure: Site S23 at installation in August 2016 (left) and in August 2017 (right). Instruments are marked in the left image.

Predicting Runoff from Ungauged Partially Glaciated Basins in South West Greenland

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Keywords: downscaling, glacier meltwater runoff, Greenland glaciers and ice caps

As meltwater runoff increases from local glaciers and ice caps in Greenland it motivates the need to have better quantification of runoff to improve understanding for better estimates of global sea level rise and gauging the potential for natural resource exploitation. 12% of the world's glaciers and ice caps are contained around the periphery of Greenland and the vast majority lie in partially glaciated basins that are ungauged and without weather stations. Thereby, resulting in a gap of data available for calculating runoff and leaving climate models as the key for best estimates and predictions. Currently, calculating meltwater runoff with coarse resolution general circulation models or even regional climate models do not capture the intricacies of the terrain in a partially glaciated basin and can create large potential for error. This study will present the strengths and shortcomings of several climate models by comparing them with in situ observations with a focus on the disparities of the models across Greenland. With the aim to more accurately calculate and predict runoff. Downscaling will be applied as a tool to better resolve 2m temperature and precipitation in partially glaciated basins. Temperature will be downscaled according to the lapse rate and dynamical downscaling will be applied for precipitation data. The established method for the predicted runoff will be applied to catchments in Greenland that are of interest in hydropower development and drinking water exports.

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

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Keywords: Glacier, metals, melt, calving

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.

The effect of debris cover and frontal ablation on projections of glacier mass change in Alaska using the Python Glacier Evolution Model (PyGEM)

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Keywords: debris, frontal ablation, alaska

Glaciers in Alaska are one of the largest contributors to present-day sea level rise and are projected to continue to be a major contributor in the future as well. Understanding the response of these glaciers to future climate forcing is therefore important for all coastal communities. Alaska is unique in that it has a large mixture of tidewater, lake-terminating, clean-ice, and debris-covered glaciers. This makes Alaska an excellent study area to investigate how frontal ablation and debris cover affect projections of glacier mass change. Given these processes are poorly accounted for in existing global glacier evolution models, there is a critical need to advance how we account for these processes. In this study, we apply a new method to estimate the debris thickness of debris-covered glaciers in Alaska. These debris thickness estimates are used to develop a new module in the Python Glacier Evolution Model (PyGEM) that explicitly accounts for the effects of debris cover. Projections of glacier mass change from 2000-2100 for an ensemble of general circulation models (GCMs) and representative concentration pathways (RCPs) are used to quantify how debris cover and frontal ablation affect glacier mass loss and Alaska's contribution to sea level rise.

Reinterpreting the surge of Good Friday Glacier, Axel Heiberg Island, Canadian Arctic

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Keywords: Glacier surging, Ice dynamics, Arctic Canada

Previous studies suggested that Good Friday Glacier (78°33'N, 91°30'W), a marine-terminating outlet glacier in southwestern Axel Heiberg Island (Canadian Arctic), may have been actively surging in the 1950-60s, 1990s, and again in 2000-15. However, the length and characteristics of the active phase(s) remained poorly constrained due to the lack of observations between studies.

Based on previous reports extending back to 1948, and a uniquely long (nearly 60 years) dataset of remotely sensed data, this study is the first to reconstruct the evolution of (what is known as) a surge-type glacier in the Canadian Arctic. We report a sustained advance of ~9 km spanning the last seven decades, which corresponds to the longest advance ever observed in the Canadian Arctic, and contrasts with the regional trend of accelerated mass loss and glacier retreat over this period. Potential mechanisms for this asynchronous behaviour include a delayed response to past mass balance conditions and/or dynamic instabilities.

The evolution of ice motion and glacier geometry patterns in the terminus region throughout the advance underlines the role of bedrock features, including topographic highs and overdeepenings, in modulating ice motion. We suggest that what has previously been interpreted as the start of a surge in the 1950s, may instead have been a localised response to small-scale perturbations in bedrock topography. At this point there is insufficient evidence to attribute the seven decades of uninterrupted advance to glacier surging in the classic sense of the term.

Fjord stratification controls surface emergence of glacial plumes

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Keywords: Glacier-fjord interactions, fjord freshening, subglacial discharge plumes, nutrient upwelling

Meltwater and sediment-laden plumes at tidewater glaciers, resulting from the localized subglacial discharge of surface melt, influence submarine melting of the glacier and the delivery of nutrients to the fjord's surface waters. It is usually assumed that increased subglacial discharge will promote the surfacing of these plumes. Here, at a west Greenland tidewater glacier, we investigate the counterintuitive observation of a non-surfacing plume in July 2012 (a year of record surface melting) compared to the surfacing of the plume in July 2013 (an average melt year). We combine oceanographic observations, subglacial discharge estimates and an idealized plume model to explain the observed plumes' behavior and evaluate the relative impact of fjord stratification and subglacial discharge on plume dynamics. We find that increased fjord stratification prevented the plume from surfacing in 2012, show that the fjord was more stratified in 2012 due to increased freshwater content, and speculate that this arose from an accumulation of ice sheet surface meltwater in the fjord in this record melt year. By developing theoretical scalings, we show in general that fjord stratification exerts a dominant control on plume vertical extent (and thus surface expression), so that studies using plume surface expression as a means of diagnosing variability in glacial processes should account for possible changes in stratification. We introduce the idea that despite projections of increased surface melting over Greenland, the appearance of plumes at the fjord surface could in the future become less common if the increased freshwater acts to stratify fjords around the ice sheet. We discuss the implications of our findings for nutrient fluxes, trapping of atmospheric CO2 and the properties of water exported from Greenland's fjords.

Impact of frontal ablation on the ice thickness estimation of marine-terminating glaciers in Alaska

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Keywords: tidewater glaciers volume inversion

Frontal ablation is a major component of the mass budget of calving glaciers, strongly affecting their dynamics. Most global-scale ice volume estimates to date still suffer from considerable uncertainties related to (i) the implemented frontal ablation parameterization or (ii) not accounting for frontal ablation at all in the glacier model. To improve estimates of the ice thickness distribution of glaciers, it is thus important to identify and test low-cost and robust parameterizations of this process. By implementing such parameterization into the ice thickness estimation module of the Open Global Glacier Model (OGGM), we conduct a first assessment of the impact of accounting for frontal ablation on the estimate of ice stored in glaciers in Alaska. We find that inversion methods based on mass conservation systematically underestimate the mass turnover and, therefore, the thickness of tidewater glaciers when neglecting frontal ablation. This underestimation can amount to up to 19% on a regional scale and up to 30% for individual glaciers. Our sensitivity studies also show that differences in thickness between accounting for and not accounting for frontal ablation occur mainly at the lower parts of the glacier, both above and below sea level. This indicates that not accounting for frontal ablation will have an impact on the estimate of the glaciers' potential contribution to sea-level rise.

Recent increase in marine ablation of Svalbard glaciers

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Keywords: calving, glacier, marine, Svalbard

Frontal ablation of tidewater glaciers represents a significant but poorly quantified part of the overall mass budget of Arctic glaciers, as well as an important source of calved ice and freshwater for marine ecosystems. Here, we will present a detailed analysis of frontal ablation for all Svalbard's 200 tidewater glaciers for the period 2013-2018. We account for annual changes in frontal position, surface velocity and ice thickness, and separate mass losses into components of glacier retreat and ice discharge. The actual physical processes of ice melting and calving at the fronts could not be separated. The results show that ice discharge dominates the total frontal ablation, but that the contribution from frontal retreat is more variable from year to year, with a closer link to climate conditions. About half of the total frontal ablation is related to a handful of glaciers that are surging. For both surging and non-surging glaciers, we find a marked increase in frontal ablation between the years 2014-2015 and 2016-2018. We will discuss potential drivers for this sudden change in context of recent atmospheric and oceanic conditions in the Barents region.

Understanding ice-ocean interactions with detailed observations of terminus behavior

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Keywords: glacier terminus; ice-ocean interactions;

The terminus region of marine-terminating outlet glaciers represents the regions where the ice sheet, ocean, and atmosphere all act together through a suite of processes to impact glacier behavior. Several mechanisms have been identified that can cause terminus retreat, however the long-term impact to glacier dynamics has not been well understood. In part, this is because not all glaciers behave the same after a terminus perturbation; some glaciers undergo significant retreat and thinning and others do not. In this talk I explore the role that fjord and glacier topography plays on the dynamic response of outlet glaciers to terminus perturbations by examining the topography both at the glacier terminus, and inland, where it can impact how thinning spreads into the ice sheet interior. This reveals that topography plays an important role in controlling the total sea-level rise from marine-terminating glaciers over the next century and we identify smaller glaciers that have a high potential to contribute to sea-level rise because their topography will allow thinning to spread far inland. Additionally, heterogeneous patterns of glacier geometry around the Greenland Ice Sheet are to a large degree responsible for the observed, modern heterogeneity in glacier dynamics.

An icestream margin as seen with high resolution radar

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Keywords: Ice stream, radar

In connection with the East Grip ice core drilling project airborne and groundbased multichannel radar systems were used to look in detail at the internal structures inside and outside of the Northeast Greenland Icestream. While the icestream margins surface expression is just delineated by slight depressions their internal structures are characterized by rather complicated multifold elements. These features hopefully can be used to better characterize the dynamics inherent in icestream systems.

On current changes of the Greenland Runoff Limit

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Keywords: Greenland, firn, hydrology, mass balance

Meltwater running off the flanks of the Greenland Ice Sheet contributes roughly 60% to its current mass loss, the rest being due to calving. Only meltwater originating from below the elevation of the runoff limit leaves the ice sheet, contributing to mass loss; melt at higher elevations refreezes in the porous firn and does not drive mass loss. Therefore, any shift in the runoff limit modifies mass loss and subsequent sea level rise contribution.

Here we use Landsat and AVHRR satellite imagery to map the visible runoff limit along the K-Transect, south-west Greenland. Our analysis covers the time period 1985 to present and includes the time of direct mass balance measurements along the K-Transect (1990 to present). Based on the available satellite imagery, we determine for each melt season the maximum elevation of the visible runoff limit. Comparing the latter to in situ measured equilibrium line elevation (ELA), we observe that the two parameters fluctuate in parallel until roughly the year 2002. Subsequently, they appear decoupled, with maximum visible runoff limit increasing linearly from year to year while ELA continues to fluctuate strongly.

We interpret this loss in synchronisation in the context of changing firn properties. We postulate that the decoupling of visible runoff limit and ELA is a direct result of a strong increase of ice content in the near-surface firn. Continuous ice horizons have formed which nowadays force meltwater to run off. Earlier, when visible runoff limit and ELA where still synced, meltwater could percolate into porous firn and refreeze. The observed change in surface hydrology has the potential to increase mass loss along the K-Transect.

The potential of the Wegener Greenland expedition material for modern glaciological research

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Keywords: historical glacier changes; geodetic balance; Greenland

Alfred Wegener contributed extraordinarily to early days of scientific explorations in Greenland. Involved in three expeditions, we present unique historical data that is stored at Graz University, where Wegener filled his last academic position until his tragic death in Greenland in 1930. As a first step, we compare the snow and firn densitiy data that have been collected during the 1912/13 traverse with the recent comprehensive compilation by (Fausto and others, 2018). Furthermore, we focus on the interesting 1929/1930 expedition during which pioneering interdisciplinary approaches have been performed. Coincidentally, this expedition was carried out during a very warm period that was in fact comparable to recent years (Chylek and others, 2006; Abermann and others, 2017). We compare melt rates from the years 1929/1930 obtained at Qaamarujuup in West Greenland (Machguth and others, 2016) with geodetically derived thickness changes since the 1980s and hypothesize on the different drivers for these changes since the strong mass change during the Wegener expedition occurred during a time with significantly lower Greenhouse gas levels than today. We discuss overall volume changes by orthorectifying historical map material and present a potential research avenue to work on process-based quantification of the drivers for the observed changes, back in the 1930s and today.

5 Years of Arctic Land Ice Velocity and Discharge observed by Sentinel-1

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Keywords: Ice Velocity, Discharge, Sentinel-1, SAR

Recent years have seen major advancements in satellite Earth observation of polar land ice. Among the most notable are the developments facilitated by the Copernicus Sentinel program, including the Sentinel-1 SAR mission. The Sentinel-1 constellation, with a dedicated polar acquisition scheme, has provided the opportunity to derive ice flow velocity of Arctic glaciers and ice sheets at an unprecedented scale and temporal sampling. In Greenland, a continuous observational record of the margins since October 2014, augmented by dedicated annual ice sheet wide mapping campaigns, enabled the operational monitoring of key climate variables like ice velocity and glacier discharge. In 2019 six additional tracks have been added to the regular acquisition scheme, covering now also the slow-moving interior of the Greenland Ice Sheet, opening up new opportunities for interferometric applications and permitting to derive monthly ice sheet wide velocity maps. Based on repeat pass Sentinel-1 SAR data, acquired in IWS mode, we have generated a dense archive of ice velocity maps of the polar regions covering the entire mission duration, now spanning well over 5 years. Including the latest observational data, we present ice velocity maps of Greenland and other Arctic ice caps, focusing on time series of ice flow fluctuations of major outlet glaciers. The ice velocity maps, complemented by ice thickness data derived from RES, form the basis for studying ice dynamics and discharge fluctuations and trends at sub-monthly to multi-annual time scales. Our results reveal a complex and versatile pattern of ice flow and discharge. This presentation highlights some of the latest developments and results of Sentinel-1 ice flow mapping in the Arctic, emphasizing the importance of long-term comprehensive monitoring of the polar ice masses. This is essential for understanding and predicting their response to climatic changes.

Albedo of the Cryosphere from Sentinel-3

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[1] GEUS, Denmark

Keywords: albedo

For much of the pre-melt and melt season, sunlight absorption can be the dominant melt energy source for snow and ice on land, glaciers, sea, and lakes. Snow and ice melt feedbacks play a role in Arctic amplification of climate warming. The Copernicus ESA Sentinel-3 A and B platforms host two sensors with optical bands: the Ocean Land Colour Instrument (OLCI) and the Sea and Land Surface Temperature Radiometer (SLSTR). We show OLCI and SLSTR data can be used to produce optical products (chiefly albedo but also snow surface grain diameter and specific surface area) at high accuracy. This presentation presents algorithms, validation, products and a near realtime processing chain. The albedo product used in data assimilation efforts will be presented. Albedo, an essential climate variable (ECV) along with snow cover (also designated an ECV) may be unified now that the Sentinel-3 mission carries the torch after a very impressive and long (20 year) performance of the NASA MODIS sensor. The overlap with MODIS now spanning three years means we can bridge snow albedo to provide a climate scale measurement of snow albedo, a unified ECV.

Decadal scale ice velocity change in the interior of the Greenland Ice Sheet

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Keywords: Greenland Interior Ice Velocity

Observations of ice dynamical change in the interior of the Greenland Ice Sheet, at distances > 100km from the ice-margin, are sparse, exhibiting very low spatial and temporal resolution (i.e. Sole et al., 2013; Doyle et al., 2014; Van de Wal et al., 2015). As such, the behaviour of interior Greenland ice represents a significant unknown in our understanding of the likely response of the ice sheet to oceanic and atmospheric forcing. The observation of a 2.2% increase in ice velocity over a three year period at a location 140 km from the ice margin in South West Greenland (Doyle et al., 2014) has been inferred to suggest that the ice sheet interior has undergone persistent flow acceleration. It remains unclear, however, whether this observation is representative of wider trends across the ice sheet.

Here, we investigate changes in ice motion within Greenland's interior by utilising recent satellite-derived ice velocities covering the period 2013-2018 (Gardner et al., 2019) in conjunction with GPS velocities collected every 30km along the 2000m elevation contour during the mid-1990s (Thomas et al., 2000). Previous observations from the late-1990s/early-2000s through to late-2000s/early-2010s have revealed significant speed-ups at many of Greenland's tidewater glaciers (i.e. Bevan et al., 2012; Murray et al., 2015), in contrast to widespread deceleration within the ablation zone of the South West land-terminating margin (i.e. Tedstone et al., 2015; Van de Wal et al., 2015; Stevens et al., 2016). The recent availability of satellite data enables us to compare annual ice velocities from the period 2013-2018 to those collected at GPS stations in the mid-1990s, thereby enabling us to detect any long-term changes in ice-sheet wide inland ice motion during a period of potentially significant dynamic change.

Investigating spatiotemporal patterns in Greenland glacier terminus changes using automated edge detection in satellite images

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Keywords: automated glacier mapping

The glaciers peripheral to the Greenland Ice Sheet are estimated to have lost 38 Gt/yr from 2003-2009, making them the second largest contributor to glacier mass loss outside of the ice sheets (Gardner et al. 2013). The difference between total mass loss estimates and modeled surface mass balance anomalies over this time period suggests that mass loss due to increased ice discharge is on the order of 10-20 Gt/yr but there have not been any ice discharge estimates to confirm this value. To address this gap in knowledge, we investigate changes at these peripheral glaciers' termini. In order to efficiently map terminus position changes for hundreds of glaciers, we developed an automated image analysis method adapted from a program used previously in biomedical and other applied science image analyses. The adapted 2D Wavelet Transform Modulus Maxima (WTMM) segmentation method places edge detection lines along regions with the greatest gradient in intensity in the image, such as the contrast between glacier ice and water or glacier ice and sea ice. We demonstrate that the method is capable of mapping glacier terminus position changes over a wide range of image conditions with a 1-pixel uncertainty. Here we use the automated terminus delineations from this method to generate time series of glacier terminus position for 10 sample glaciers over the Landsat-8 record (2013-present). With these time series, we are able to resolve sub-seasonal to annual temporal patterns as well as regional patterns in terminus position change for these glaciers. Future work will focus on applying the method to the full Landsat record and full set of peripheral glaciers in order to investigate longer-term trends in glacier retreat.

Glacier retreat in Sørkapp Land, Spitsbergen, from 1961 to 2010 based on aerial photographs

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Keywords: Geodetic mass balance, DEM extraction from aerial photos, Sørkapp Land, Spitsergen

Intensification of climate change in the polar regions translates into evolution and dynamics of the entire environment, including glacier systems. The visible effect of glacier response to the contemporary warming is their negative mass balance and frontal recession. This phenomenon is particularly pronounced in southern Svalbard, where glaciers are losing mass at an accelerating pace. This work presents changes in the geometry of glaciers located in Sørkapp Land, the southern peninsula of Spitsbergen, over the period of 1961 to 2010. A baseline dataset for this investigation consisted of aerial photographs, captured by Norwegian Polar Institute in summer seasons of 1961, 1990 and 2010 and two consecutive scenes of Landsat 5 TM acquired in the summer of 1990. Using both scanned analog and digital photographs, as well as digital maps and digital elevation models derived from their processing, changes in glacier extent and thickness have been assessed in the following periods: 1961-1990, 1990-2010 and 1961-2010. Results show that the area occupied by glaciers of Sørkapp Land decreased in the years 1961-2010 by 130 km^2, i.e. by slightly over 15%. The rate of glacier area change varied over time and amounted to 2 km^2/yr in the period 1961-1990 and speeded up to 4 km^2/ yr after 1990. This process was accompanied by glacier surface lowering at an average rate of 1-2 m/yr.

Changes in snow cover structure on Hansbreen from repeated radio-echo sounding

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Keywords:

Snow cover plays a key role in the functioning of glacial system. Thermal conductivity up to 20 times lower than the ice and the albedo reaching 90% make the snow cover an efficient insulator. Furthermore, the snow layer is a freshwater reservoir that initiates supraglacial, englacial and subglacial drainage. Climate change in particularly sensitive Arctic area is manifested by general warming, more frequent winter thaws and shorter snow cover duration. The main purpose of the work is to determine the structure of snow cover on the glacier and its inter-seasonal variability based on repeated high-frequency radio-echo sounding. Field studies were carried out on Hansbreen, southwestern Spitsbergen, at the end of the 2018 and 2019 accumulation seasons. With simultaneous usage of two antennas of different frequencies: 800 MHz and 1.6 GHz, the snow cover stratification and their spatiotemporal changes were carried out. Based on the wavelet analysis up to 17 layers within snow cover were determined, and validated based on properties derived from manual snow pits analysis. The abilities of recognition the boundaries within snow cover depends on both snow properties and the vertical resolution of the antennas used. Obtained results were combined with meteorological data from automatic weather stations, installed on Hansbreen and at the Polish Polar Station in Hornsund, referring to sequences of thaws and refreezing that favour formation of the melt-freeze crusts within snow layers. The above data contribute to determination of the snow metamorphisms rate.

Greenland liquid water runoff from 1979 through 2017

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Keywords: Hydrology, Runoff

We present a new data set capturing high spatial and temporal liquid water flux into Greenland fjords and coastal seas. Freshwater runoff from the ice and land impacts glacier dynamics, subglacial discharge plumes, marine terminating glacier frontal melt, fjord properties (water dynamics, sediment load and deposition, marine biology, ice formation), and a variety of other properties near the ice, tundra, and coastal seas.

We use ERA forced regional models (MAR and RACMO) based runoff at 1 km spatial and daily temporal resolution from 1979 through 2017. Model outputs are routed through a 90 m digital elevation model to determine where the water flows. Runoff is routed from the ice sheet to the ice margin and from the ice sheet and land to the coast, where basin outlets accumulate upstream runoff and deliver it to the fjord.

Mapping glacier extent in Norway using Sentinel-2

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Keywords: glacier, mapping, sentinel,

The previous complete inventory of glaciers in mainland Norway is based on Landsat imagery (30m) from the period 1999-2006. Here we present first results on a new mapping of glacier extent in Norway using Sentinel-2 imagery of 10 (20) m resolution from 2018 (North Norway) and 2019 (South Norway). The results are compared with independent validation data such as aerial imagery of 0.25 m resolution and Pleiades satellite imagery of 0.5-2 m resolution.

Causes and patterns of tidewater glacier retreat in the Canadian Arctic

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Keywords: Tidewater glacier; Canadian Arctic; Ocean warming; Surface melt

The Canadian Arctic Archipelago (CAA) contains >300 tidewater-terminating glaciers, but little is known about long-term changes in their frontal positions. Here, we examine changes in glacier terminus positions since the 1950s and investigate the relative influence of oceanic versus atmospheric temperatures in accounting for these. Over 94% of tidewater glaciers in the CAA retreated between 1958 and 2015, with a region-wide trend of gradual retreat before ~2000, followed by a 5x increase in retreat rates up to 2015. Retreat patterns show no correlation with changes in ocean temperature, but strong correlations with changes in surface melt. This suggests that increased atmospheric temperature has been the primary driver of recent rapid tidewater glacier frontal retreat in this region.

Snow Cover Reflection Properties on Hansbreen (South Spitsbergen) based on radio-echo sounding

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Keywords: GPR, snow density, Internal Reflection Power (IRP)

Monitoring of the snow cover properties on Hansbreen (S Spitsbergen) using Ground Penetrating Radar (GPR) is one of the longest and the most comprehensive on Svalbard. Snow depth is frequently the only feature derived from shallow radio-echo sounding. In this study radiophysical properties of the snow cover have been analysed. The reflection properties of the snow cover are the result of the complex snowpack characteristics like size and shape of grain conglomerates, presence of hard layers, snow hardness, etc. The snow density represents complex physical nature of snow cover and its variation in vertical profile fits well with the distribution of maximum absolute reflection amplitude with a correlation coefficient of 0.82 at specific traces. The reflection power from the snowpack column can be expressed as Internal Reflection Power (IRP) factor which represents the average reflected power and can be considered as index of bulk snow density. The IRP index generally decreases with elevation and increasing snow depth, and corresponds well to similar relations with bulk snow density derived from numerous snow pits at Hansbreen in 2008 - 2018. At lower elevations bulk snow density is generally higher due to complex processes such as more frequent winter thaws and winter rains leading to formation of hard layers. The same snow structures increase the reflection power. Application the IRP index as the bulk snow density factor can efficiently improve winter mass balance calculations.

How oceanic melt controls tidewater glacier evolution

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Keywords: calving, oceanic melt, tidewater glacier, dynamics

The recent rapid retreat of many Greenland outlet glaciers has been attributed to increased oceanic melt, but the relationship between oceanic melt and iceberg calving remains poorly understood. We employed a transient finite-element model that simulates oceanic melt and ice break-off at the terminus. The response of an idealized tidewater glacier to various submarine melt rates and seasonal variations is investigated. Our modeling shows that without any oceanic melt, the rate of volume loss at the front is higher than for intermediate melt rates. Only very high melt rates lead to increasing volume losses. These results highlight the complex interplay between oceanic melt and calving and question the general assumption that increased submarine melt leads to higher calving fluxes and hence enhanced retreat. Models for tidewater glacier evolution should therefore consider calving and oceanic melt as tightly coupled processes rather than as simple, additive parametrizations.

Patterns and mechanisms of flood release from glacier dammed Donjek Lake, Yukon

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Keywords: GLOF, Yukon, remote sensing, glaciology

Donjek Glacier, located in the St Elias Mountains, Yukon, is a surge-type glacier with a repeat surge interval of approximately 12 years since the 1930s. Donjek River runs perpendicular to the terminus of the glacier from its headwaters on the Kluane Glacier and surrounding ice bodies. Past surges have regularly caused the terminus to advance and block the river, leading to the formation of an ice-dammed lake. The lake has drained catastrophically several times over the past 3 decades, resulting in risks and damage to downstream infrastructure.

Surges and subsequent retreat of the glacier terminus have caused Donjek River to move between several channels in the past depending on the position of the ice and nearby landforms. Analysis of historical satellite imagery since 1990 indicates three mechanisms by which the lake or river will drain depending on the ice extent and time since the last surge: 1) subglacially under the glacier terminus, 2) subaerially through a canyon cut through the terminus of the glacier or 3) ice-marginally past the terminus. Subglacial and subaerial drainage of the lake can lead to a catastrophic release and downstream flooding. Analysis of the patterns and timing of these drainage events provides a better understanding of the interplay between glacier dynamics and the mechanisms of flood release, and how these will evolve in the future.

Comprehensive ocean observations in Inglefield Bredning, Northwestern Greenland

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Keywords:

Glacial fjords in Greenland are characterized by high productivity, which has been attributed to meltwater discharge from glaciers. Previous our studies in northwestern Greenland have revealed the importance of meltwater discharge from a marine-terminating glacier on the biogeochemical processes in a fjord (Kanna et al., 2018; Naito et al., 2019; Nishizawa et al., 2019). Marine-terminating glaciers in our study region have been retreating (Sakakibara and Sugiyama, 2018). Changes of the glaciers are possibly affecting marine ecosystems in the surrounding ocean. Despite increased interest in the impact of meltwater discharge on marine ecosystems in northwestern Greenland, it remains challenging to observe glacial fjords comprehensively. In the summer 2019, we conducted comprehensive observations of water properties, sedimentation processes and marine production in Inglefield Bredning, a 100 km long fjord system in northwestern Greenland. As a part of a Japanese glacier and ocean research project in Qaanaaq region, Inglefield Bredning has been studied since 2018. About ten marine-terminating glaciers are flowing into Inglefield Gulf, which terminate at depths from several ten to over 600 m. In order to clarify the influence of meltwater discharge on water properties and marine productivity, we conducted boat-based ocean measurements using a conductivity-temperature-depth profiler near the glaciers (Tracy, Heilprin, Farquhar and Melville glaciers) including ocean depth measurements. Seawater was collected from several depths to analyze macronutrients, trace metals (e.g., iron), organic carbon and phytoplankton assemblages using an acid-cleaned Niskin-X water sampler. Zooplankton samples were also collected with a single-NORPAC net (mesh size 335 μm) through two water columns of 50 and 100 m depths. Sea floor sediments were also collected near the terminus of Heilprin glacier using an Ekman-Birge grab sampler to clarify sedimentation process of minerals and organic matters. Additionally, we conducted boat-based marine mammals surveys and hydrophone recording near the glacier termini to know how many and what kind of marine mammals utilize this fjord. In this contribution, we present details of the field activity in this summer.

Synoptic conditions and atmospheric moisture pathways associated with virga and precipitation over coastal Adélie Land, Antarctica

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Keywords: Air parcel backtrajectories, radar measurements, synoptic circulation, low-level sublimation

Over polar regions, a large fraction of moisture coming from oceans is brought by extratropical cyclones and their associated fronts. Meanwhile, the edges of the Antarctic and Greenland ice sheets experience katabatic winds. The coastal regions of Antarctica often experience low-level sublimation of precipitation due to katabatic wind bringing dry air from the interior's Plateau, reducing the amount of precipitation that reaches the surface. We investigate the synoptic conditions and the atmospheric transport pathways of moisture that lead to virga - when precipitation is completely sublimated - or actual surface precipitation at Dumont d'Urville (DDU) station, coastal Adélie Land, Antarctica. We combine ground-based radar measurements with Lagrangian back-trajectories and Eulerian diagnostics of extratropical cyclone and front identification based on ERA5 reanalysis to improve our understanding about virga and surface precipitation. Precipitating systems are often associated with warm fronts. Virga periods - corresponding to 36% of the precipitating events - often precede and sometimes follow surface precipitation periods. Cyclone positioning, warm front progress and back-trajectories of the precipitating air parcels show different signatures for each of the three periods. Analysis of moisture atmospheric transport pathways shows the following characteristics: precipitation falling above DDU during virga happening before surface precipitation periods have an oceanic origin farther away (30 degrees more to the west) from Adélie Land than the one that precipitates down to the ground surface. It is further shown that moisture uptakes occur closer to the coast when sea-ice extent is minimum, and further north when sea-ice extent is maximum.

Hydrological processes in firn at the runoff limit on the Greenland Ice Sheet

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Keywords: Greenland; firn; hydrology; mass balance

The Greenland ice sheet loses mass at an accelerating rate. The majority of current mass loss is due to surface melt running off into the ocean. The runoff limit is the highest elevation from which meltwater finds its way off the ice sheet in one melt season. The location of the runoff limit plays an important role in the mass balance of the Greenland Ice Sheet. Recent findings have shown that widespread ice slabs have developed on the Greenland ice sheet close to the runoff limit (Fig. 1), impeding meltwater from percolation and refreezing, and hence accelerating surface runoff.

Hydrological processes like meltwater percolation and refreezing in snow have been studied extensively, but existing research is generally focused on vertical percolation rather than lateral runoff. Compared to snow science, the hydrology of the ice sheet firn area has received less attention. In situ measurements of firn hydrology affecting the location and evolution of the runoff limit in time and space are scarce.

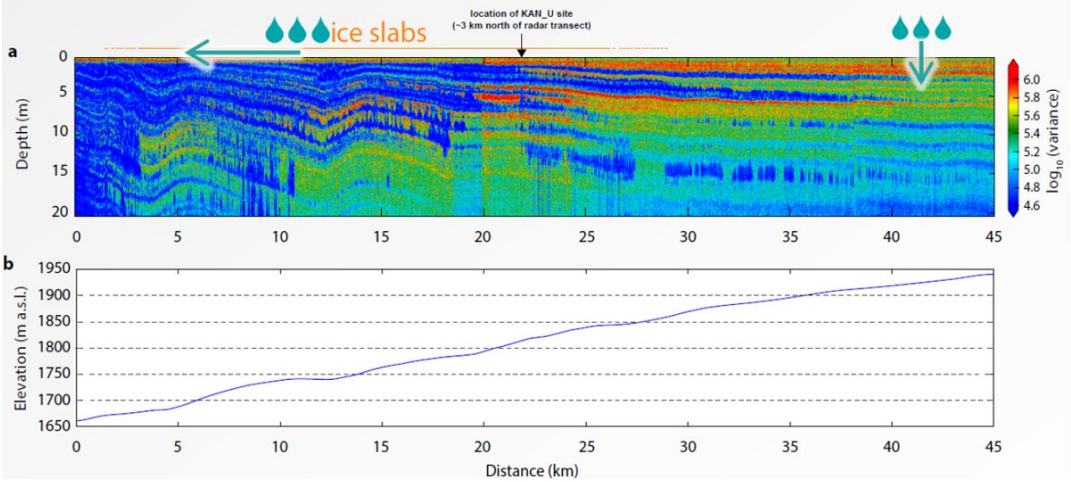

Figure 1. a) 45 km radar profile along the 2013 core transect at KANU (1849 m a.s.l.), close to the runoff limit. Blue indicates ice and cyan to red indicates lower density firn. Arrows visualize hypothesized pathways of surface melt. b) Hypsography of the ice sheet surface along the radar transect (elevation in meters above the EGM2008 ellipsoid). Modified after Machguth et al. (2016), Nat. Clim. Change).

In 2020, we will carry out fieldwork in spring and summer on the Greenland ice sheet, close to the current runoff limit. Aim of the fieldwork is to measure the firn hydrology parameters required for quantifying vertical and lateral meltwater flow and their influence on the runoff limit. In spring, firn stratigraphy and permeability will be measured and firn stations will be installed to track changes in liquid water presence in the firn and snow layer throughout the melt season. We will use the ROSA (Rain On Snow Appliance) to measure in situ hydrological properties of firn. Summer fieldwork will be carried out during the melt season and focus on measuring surface meltwater flow as well as lateral meltwater flow inside the firn. Here we present the ROSA (Fig. 2), a portable lysimeter originally designed for measuring hydrological processes during rain-on-snow events. We

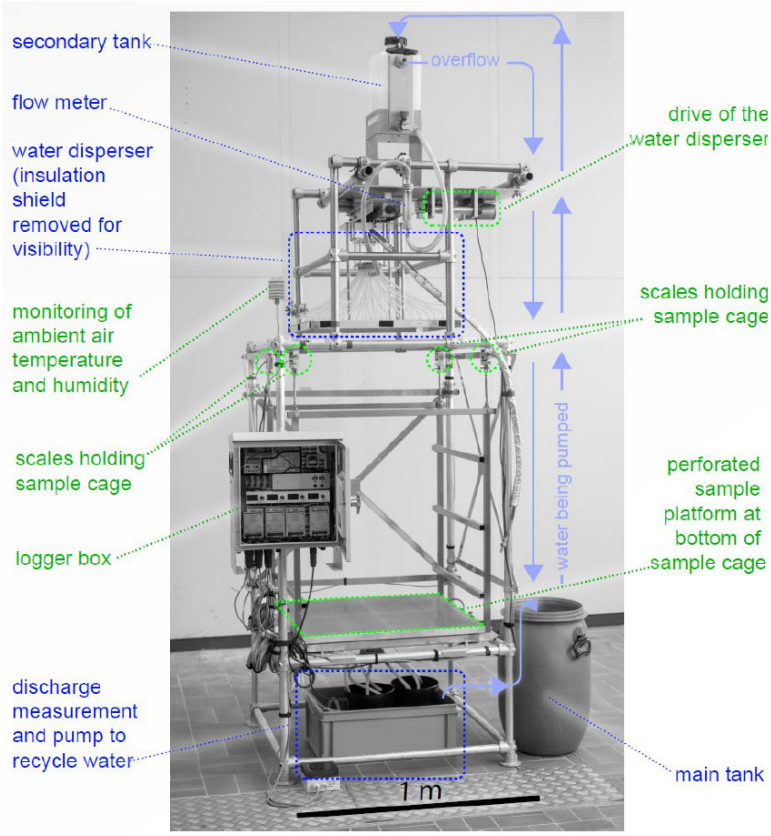

Figure 2. The rain on snow appliance (ROSA). Items related to the water circulation are in blue, other parts are highlighted in green. Hoses between discharge measurement, main and secondary tank are only visualised with arrows.

have adapted and upgraded the device to be able to carry out hydrological measurements of firn properties and changes herein due to meltwater percolation on the Greenland ice sheet.

Land-ice mass imbalance across the Arctic driven by atmosphere and ocean forcing

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Keywords: Glaciers and ice caps, Mass balance, Geodetic

Arctic glaciers and ice caps (AGIC) accounted for 35% of global sea-level rise since the early 2010s, are key players in the local freshwater budget, impact thermohaline forcing in the North Atlantic. They store 40% of the global GIC ice volume, equating to 144 mm of sea level equivalent, and their losses are currently increasing as atmospheric and oceanic forcing intensify and as Arctic sea ice cover shrinks. Furthermore, the dynamic response of land ice to climate forcing constitutes the main uncertainty in global sea level projections for the next century. To address this knowledge gap, observations of the relative contribution of both surface mass balance (SMB) and ice dynamics (D) to the total losses are necessary, an information which is currently lacking at the Arctic scale. Estimating GIC mass budgets for the entire Arctic region from satellite altimetry is challenging because satellite ground track spacing and footprints of modern altimetry sensors are coarse compared with the small size of GICs, their steep slopes and complex topography. Within the European Space Agency Mountain Glacier and Ice Caps project, we exploit globally a novel method to extract elevation from full waveform analysis of the CryoSat interferometric radar altimeter. High-definition so-called swath processing of CryoSat-2 radar altimetry data allow us to quantify ice losses across the Arctic and outside of Greenland between 2010 and 2017, and to partition loss between surface and dynamic processes. We find that while changes in meteorology are responsible for 87% of AGIC ice loss, dynamic imbalance is increasing in the Barents and Kara Seas where it now accounts for 43% of total ice loss, locally exceeding fresh water volume from receding sea-ice. This pattern suggests that profuse warm Atlantic water incursions, or Atlantification, of the sector has a major impact on the loss of Arctic land ice, and that this effect should be considered in global sea level projections. Our results draw attention to the importance of quantifying ocean warming in the Arctic to improve regional climate projections and to reduce uncertainty in the parametrisation of future-generation climate models.

Basal conditions of Kongsvegen at the onset of surge - revealed using seismic vibroseis surveys

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Keywords: Svalbard, basal properties, active seismics

Kongsvegen is a well-studied surge-type glacier in the Kongsfjord area of northwest Svalbard. Long-term monitoring has shown that the ice surface velocity has been increasing for the past 4 years; presenting a unique opportunity to study the internal ice structure, basal conditions and thermal regime that play a crucial role in initiating glacier surges. In April 2019, three-component seismic vibroseis surveys were conducted at two sites on the glacier, using a small Electrodynamic Vibrator source (ElViS). Site 1 is in the ablation area and site 2 near the equilibrium line, where the greatest increase in ice-surface velocity has been observed.

Initial analysis indicates the conditions at the two sites are significantly different. At site 1 the ice is around 220 m thick, sitting on a relatively flat and uniform bed, with no clear change in the bed reflection along the profile. There is a horizontally layered sediment package ~60 m thick underlaying the bed. The ice column shows no internal layering. By contrast at site 2 (Fig. 1), where the ice is around 390 m thick, there is much more complex internal ice structure. Clear internal ice reflections are visible between 150-250 m depth – where we expect a transition from cold to temperate ice. Further reflections in the 100 m above the bed indicate there could be shearing or sediment entrainment in this area. Below the bed, cross-cutting layers are clearly visible and the bed reflection itself shows changing reflection polarity – suggesting water or very wet sediment is present in some areas. This suggests ice movement by basal sliding and shearing is likely.

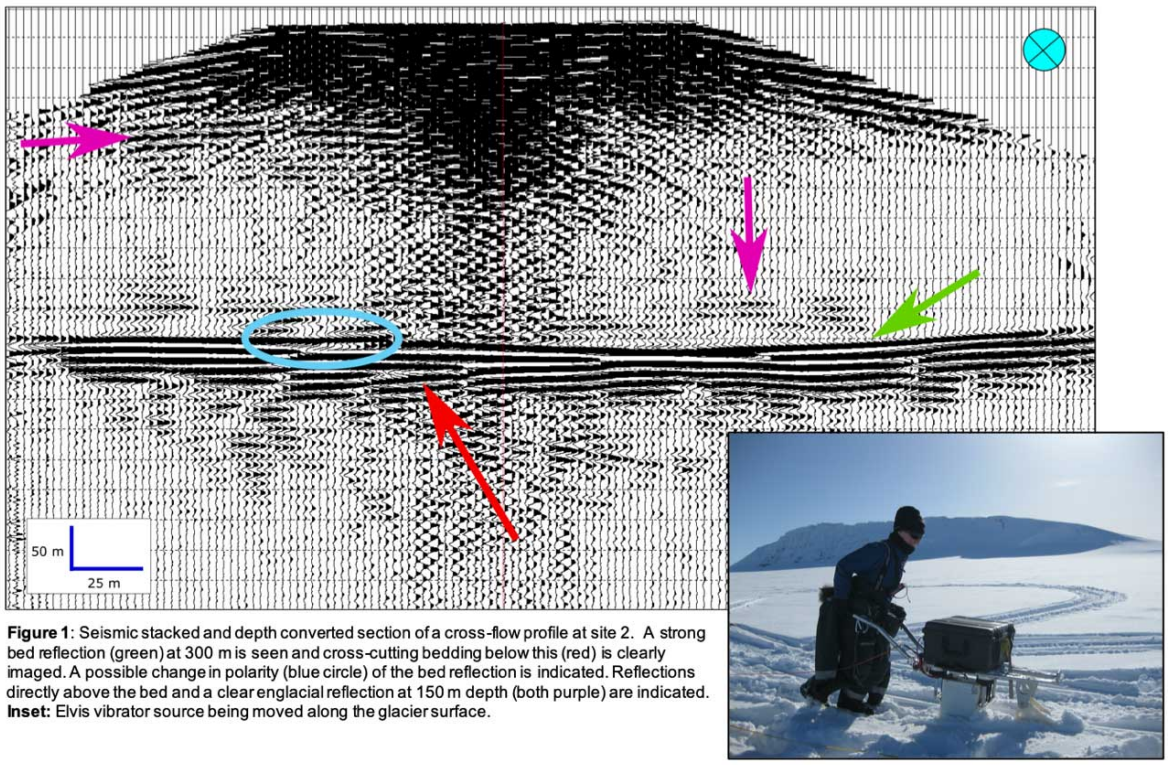

Figure 1: Seismic stacked and depth converted section of a cross-flow profile at site 2. A strong bed reflection (green) at 300 m is seen and cross-cutting bedding below this (red) is clearly imaged. A possible change in polarity (blue circle) of the bed reflection is indicated. Reflections directly above the bed and a clear englacial reflection at 150 m depth (both purple) are indicated. **Inset:** Elvis vibrator source being moved along the glacier surface.

IPCC's Special Report on the Oceans and the Cryosphere in a Warming Climate - Key messages for the Arctic

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Keywords: climate change, cryosphere, Arctic, glaciers

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Short-term ice speed variations near the calving front of Bowdoin Glacier, northwestern Greenland

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Keywords: ice speed, tidewater glacier, Greenland, GPS

Ice flow speed near the glacier front controls discharge from tidewater glaciers. Once accelerated, increase in discharge leads to rapid glacier mass loss, as recently observed in Greenlandic and other Arctic tidewater glaciers. Ice dynamics near the front of a tidewater glacier is sensitive to basal and ocean perturbations, because relatively small driving stress is balanced by stresses acting at the bed and the front. To forecast the response of tidewater glaciers to climate and ocean changes, it is crucial to understand mechanisms driving ice speed variations. Nevertheless, high frequency ice speed data are sparse near the front of tidewater glaciers because in-situ measurements are technically difficult. To investigate short-term ice speed variations of a tidewater glacier, we operated GPS receivers within about 4 km from the front of Bowdoin Glacier in northwestern Greenland. Three dual frequency GPS receivers were mounted on aluminum poles drilled into the ice, and operated continuously for several weeks in July 2013-2017 and 2019. Total duration of the measurements over the six summer seasons was about 13 weeks. GPS data were post processed with reference data recorded nearby the glacier to obtain ice displacement every 15 min with an accuracy of several millimeters. Ice speed showed complex high frequency variations, which were associated with melt, tides and rain. For example, lowermost GPS station at several hundred meters from the calving front (1.6 m a^{-1}) accelerated by 70% during an intensive melt period in July 2016. Speed was tidally modulated for most of the time, and its amplitude in 2015 was up to 30%. Heavy rain storm (5 mm h^{-1}) triggered short-lived speed up events in July 2013 and 2014. Our observations indicated that tidewater glacier dynamics is susceptible to meltwater and ocean forcing at the basal and frontal boundaries.

The uncertainty of average precipitation forcing

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Keywords: Energy balance, Greenland Ice Sheet, modeling, climatology

Although climate undergoes natural variability, it is a common practice that simulations of past ice sheets use climatological instead of transient forcing . We test the sensitivity of the surface mass balance (SMB) of the Greenland ice sheet with the energy balance model BESSI. An ensemble of climate forcings with average values of temperature, precipitation, long and short-wave radiation, and dew point is generated and compared with the fully transient simulation. This is furthermore compared to daily climatological forcing as well as individual components of the forcing as averages. The climatological forcing leads to an almost 50% larger SMB. Reordering the forcing years in a synthetic transient simulation has a negligible effect of 2% on average Greenland-wide surface mass balance. Mixed forcings of all but one forcing variable transient and the last one climatological and vice versa revealed that the biggest driver for the much larger SMB in the climatological case is the precipitation followed by temperature. To further investigate the effect of averaging precipitation, which changes its nature from event-based to continuous, alternative climatological forcing were created. To retain the event (storm) based nature of precipitation, monthly climatologies were used instead and the sub-monthly variability taken from one of the original transient members. Additionally, synthetic regular sub-monthly frequencies of precipitation were used as another calculation method. By using monthly averages with natural sub-monthly the SMB error of the climatological forcing can be reduced to below 20%. We conclude that forcing energy balance models with climatological forcings creates a substantial error in the SMB, which can mainly be attributed to the precipitation forcing. As long as the amplitude of the intra-annual variability is known, the order of the years has only a marginal impact on the Greenland wide SMB.

Future climatic mass balance, snow conditions and runoff in Svalbard

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Keywords:

In a recent modelling experiment, we have generated a long-term (1957–2018) distributed dataset of climatic mass balance for the glaciers, snow conditions, and runoff across Svalbard (Van Pelt et al. 2019). Following up on this experiment, we now use the same model to make future projections under RCP4.5 and RCP8.5 scenarios for 2019-2060. Future meteorological input for the model is constructed from a combination of 1) long-term trends in Arctic CORDEX regional climate model output, and 2) short-term past variability extracted from a downscaled ECMWF reanalysis product (NORA10). 3-Hourly output is generated for both glacier- and land-covered parts of Svalbard at a 1x1-km spatial resolution and for two emission scenarios (RCP4.5 and RCP8.5). For the RCP4.5 scenario, results indicate an accelerated decrease of the climatic mass balance from close to zero in recent decades to about -1.5 m w.e. a^{-1} in 2050-2060 (-2.0 m w.e. a^{-1} for RCP8.5), primarily due to expansion of ablation zones. By the end of the simulation period, during some years the ELA extends above the maximum elevation of all glaciers in Svalbard. Firn degradation causes complete firn removal in southern Svalbard and strong retreat in the northern parts. Despite shrinking firn zones, increased winter rainfall and melt cause the refreezing trend to be close to zero. As a result of ablation zone expansion, runoff from glaciers is found to about triple between 2019 and 2060. Comparing the seasonal snow season duration during the periods 1957-2018 and 2019-2060 reveals largest changes in coastal regions across Svalbard, and most pronounced in the south, with snow arriving up to two months later in autumn and disappearing up to two months earlier in spring.

Photos to Elevations: a photogrammetry pipeline

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Keywords: elevation change; photogrammetry; Canada; remote sensing

Elevation measurements are fundamental to observing glacier dynamics and mass balance. However, high resolution (<1 m) and accurate elevation measurements are still rare for glaciers worldwide. Here, we present a semi-automated pipeline to create high resolution orthomosaic images and digital elevation models (DEM) from aerial photographs. We do this using a Nikon D850 SLR camera attached to a high-precision GPS mounted on a fixed wing aircraft or helicopter. We wrote custom software in R and Python to determine the precise positions of the photos based on the GPS record, which is processed using PPP methods from Natural Resources Canada. We then use high performance supercomputing to process the data using Agisoft Metashape-Pro. We are able to produce DEMs and orthographic mosaics at a scale of 10 cm - 1 m for tens of square kilometers from hundreds to thousands of photos at once. Here, we showcase examples from the Canadian Arctic and Yukon St. Elias Mountains and show that airborne photo surveys can be an effective tool to rapidly measure the elevation of Earth features at landscape scales with sub-meter level precision. This data can be applied to measure the mass balance of glaciers with annual surveys, and can shine new light on glacier dynamics. These methods can help provide substantial new insights into many different Earth processes, including ice-ocean interactions.