IASC Workshop on the dynamics and mass budget of Arctic glaciers

Abstracts and Programme

IASC Workshop, 23-25 March 2015 Obergurgl (Austria)



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IASC Workshop & Network on Arctic Glaciology annual meeting, 23-25 March 2015, Obergurgl (Austria)

Organised by C.H. Tijm-Reijmer and M. Sharp



Cover photo: South Greenland August 2014. Photo by J.E. Box.

ISBN: 978-90-393-6379-9

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Preface

The 2015 annual workshop and open forum meeting of the IASC Network on Arctic Glaciology took place in our favorite conference center, Obergurgl University Center, Obergurgl, Austria. The combination of hotel and conference center in one building, located in the beautiful Austrian Ötztal, staffed by very friendly and helpfull people makes this a perfect place for our workshop.

The 2015 meeting attracted 35 participants from 12 different countries. The IASC Cryosphere Working Group generously supported our meeting which included support of eleven young scientists to attend the meeting. These 35 participants presented cutting edge science in 22 talks and 7 posters. The open forum meeting provided many ideas to initiate as a community. An overview of the meeting, especially abstracts of the presented work, can be found in this book.

The activities are not limited to the conference room, but extent, as always, to the skiing slopes around the conference facility. On the slopes and afterwards in the bar, the discussions related to, amongst others, science and fieldwork continued resulting in once again a succesful and informal event. Next year the meeting will take place in Benasque, Spain, from 25 - 27 January, 2016. I hope to meet you all there.

C.H. Tijm-Reijmer June 2015

Program

The meeting will take place in the University Center Obergurgl, Austria. Note: Coffee breaks are included in the conference fee, lunches not. Those participants not staying at the University Center can join dinner at the center. To join: register and pay (€29,- per diner) at the front desk of the center before noon.

Monday 23 March

08:30 - 09:00	Registration
Convener:	Carleen Reijmer
09:00 - 09:10	Welcome <i>C.H. Reijmer</i>
09:10 - 09:30	Capabilities of the Sentinel-1 SAR mission for operational monitoring of ice sheets Jan Wuite , <i>T. Nagler, M. Hetzenecker, H. Rott</i>
09:30 - 09:50	The geodetic campaign 2014 for studies in mass balance, ice dynamics and validation of satellite data in the Swiss Camp area, West Greenland Manfred Stober , H. Rott, M. Hönes, G. Grom, D. Floricioiu
09:50 - 10:10	Recent glacier and ocean changes in Northeast Greenland Gordon Hamilton
10:10 - 10:30	Calving of tidewater glacier driven by melting at the waterline <i>Michał Pętlicki</i> , M. Ciepły, J.A. Jania
10:30 - 11:00	Coffee break
Convener:	Gordon Hamilton
11:00 - 11:20	"Slow" surge of the Vavilov Ice Cap, Severnaya Zemlya Andrey Glazovsky , I. Bushueva, G. Nosenko
11:20 - 11:40	Detailed investigation of glacier calving with a terrestrial radar interferometer <i>Martin Luethi</i>
11:40 - 12:00	Poster presentations by authors
12:00 -	Very Long Lunch

18:30 - **Dinner**

Tuesday 24 March

Convener: Andreas Ahlstrøm

- 09:00 09:20 The use of airborne radar reflectometry to derive near-surface snow/firn properties on Devon Ice Cap, Canadian Arctic **Anja Rutishauser**, C. Grima, M. Sharp, D.D. Blankenship, D.A. Young, J.A. Dowdeswell
- 09:20 09:40 Successive and intense melt rapidly decreases Greenland meltwater retention in firn **Horst Machguth**, M. MacFerrin, D. van As, J.E. Box, C. Charalampidis, W. Colgan, R.S. Fausto, H.A.J. Meijer, E. Mosley-Thompson, R.S.W. van de Wal
- 09:40 10:00 Snow cover dynamics on a small polar glacier using high spatio-temporal monitoring: 7 years of observations on Austre Lovén glacier. *Éric Bernard*, J.M. Friedt, F. Tolle, S. Schiavone, *M. Griselin*
- 10:00 10:20 Firn line delineation using Envisat SAR imagery from 2005-2010 over Penny Ice Cap, Baffin Island, Nunavut *Nicolle Schaffer, L. Copland, C. Zdanowicz*
- 10:20 10:50 **Coffee break**
- Convener: Florian Tolle
- 10:50 11:10 Ice thickness measurements and volume estimates for glaciers in Norway *Liss Andreassen*, *M. Huss, K. Melvold, H. Elvehøy*, *S.H. Winsvold*
- 11:10 11:30 Queen Elizabeth Island glacial mass loss from airborne altimetry 1995-2012 **Colleen Mortimer**, M. Sharp
- 11:30 11:50 Application of terrestrial 'structure-from-motion' photogrammetry on a medium-size Arctic valley glacier: potential, accuracy and limitations **Bernhard Hynek**, D. Binder, G. Boffi, W. Schöner, G. Verhoeven
- 11:50 12:10 Dissipative meltwater production in glaciers *Hans Oerlemans*
- 12:10 15:30 Very Long Lunch
- 15:30 16.30 Coffee break and POSTER SESSION
- 16:30 18:00 IASC Network on Arctic Glaciology Open Forum meeting *C.H. Reijmer / M. Sharp*
- 18:30 **Dinner**

Wednesday 25 March

- Convener: Liss Andreassen
- 09:00 09:20 Scientific results and data from the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) **Andreas Ahlstrøm**, S.B. Andersen, D. van As, M. Citterio, R.S. Fausto, M.L. Andersen, J.E. Box, W.T. Colgan, M. Veicherts, H. Machguth, R. Forsberg, H.

Skourup, S.L.S. Sørensen, S.M. Hvidegaard, S.S. Kristensen, J. Dall, A. Kusk, D. Petersen

- 09:20 09:40 Comparing the Geodetic and Glaciological mass budgets of White Glacier, Axel Heiberg Island, NU *Laura Thomson*, *L. Copland*, *M. Zemp*
- 09:40 10:00 A multivariate approach of the factors impacting a small arctic glacier **Sophie Schiavone**, F. Tolle, É Bernard, J.-M. Friedt, M. Griselin, D. Joly
- 10:00 10:20 Revisiting "The Mass Balance of Circum-Arctic Glaciers and Recent Climate Change" *Martin Sharp*
- 10:20 10:50 **Coffee break**

Convener: Horst Machguth

- 10:50 11:10 Modeling the evolution of the Juneau Icefield using the Parallel Ice Sheet Model (PISM) F.A. Ziemen, **Regine Hock**, A. Aschwanden, C. Khroulev, C. Kienholz, A. Melkonian, J. Zhang
- 11:10 11:30 Modeling the response of the Juneau Icefield to climate change *Aurora Roth*, *R. Hock*, *B. Anderson*, *F. Ziemen*
- 11:30 11:50 Comparison of century-plus Greenland ice surface mass balance reconstructions **Jason Box**, X. Fettweis, T. Kobashi
- 11:50 12:10 Relationships between summer melt and winter motion at Kaskawulsh Glacier, Yukon *Luke Copland*, *E. Herdes*
- 12:10 12:20 Final words C.H. Reijmer / M. Sharp
- 12:20 Lunch / Departure / Skiing
- 19:00 **(Dinner)**

Posters

- Using time lapse photogrammetry to examine spatial temporal variations in Greenland outlet glacier dynamics *Philip Christiansen*, J.E. Box, A. Ahlstrøm, A. Messerli, A. Grinsted
- The structural glaciology of Austre Brøggerbreen, northwest Svalbard **Stephen Jennings** M.J. Hambrey, N.F. Glasser, B. Hubbard
- A comprehensive data base of glacier surface mass balance observations from the ablation area of the ice sheet and the local glaciers of Greenland *Horst Machguth*, H.H. Thomsen, A. Weidick, J. Abermann, A.P. Ahlstrøm, M.L. Andersen, D. van As, R.J. Braithwaite, C.E. Bøggild, J. Box, W. Colgan, R.S. Fausto, K. Gleie, B. Hynek, H. Oerter, K. Steffen, M. Stober, R.S.W. van de Wal
- Snow cover, ice loss, and rock debris quantification in an arctic glacier basin through terrestrial laser scanning surveys *Alexander Prokop*, F. Tolle, É. Bernard, J.-M. Friedt, M. Griselin
- Investigating the dynamics of Store Glacier, West Greenland Using UAVS Jonathan Ryan, A. Hubbard, N. Toberg, P. Christoffersen, J. Box, N. Snooke
- Dynamics and Changes in Extent of Bylot Island and Barnes Ice Caps, Nunavut, Canada Wesley Van Wychen, F. Delaney, L. Copland, D.O. Burgess, L. Gray
- Cascading effects of sea ice losses on the formation and preservation of tidewater glacier tongues and ice shelves on northern Ellesmere Island, Nunavut, Canada *Adrienne White*, *L. Copland*

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- 35. Jan Wuite (Jan.Wuite@enveo.at)

(Young scientists receiving support are marked *).

Minutes of the Open Forum meeting

Chair: Carleen Tijm-Reijmer Vice Chair: Martin Sharp Minutes: Lindsey Nicholson Invited to attend: all participants of the workshop.

Agenda

- 1. Other items for the agenda
- 2. Background on IASC and NAG
- 3. Meeting minutes 2016
- 4. Location IASC-NAG workshop
- 5. Network activities
- 6. National contacts
- 7. Extended Abstracts
- 8. Anything else

Ad. 1

No additional items for the agenda.

Ad. 2

Short Introduction to International Arctic Science Committee (IASC):

- Background to IASC (not IACS!)
- IASC has 5 working groups
- NAG can cross cut the IASC working groups
- Need to demonstrate Network activity to ensure funding and support

Ad. 3

An overview was given about what was discussed last year.

Ad. 4

Location for future meetings: - 2016 in Spain Benasque

- In Gran Hotel Benasque (***): conference room and hotel at same location, cheaper accomodation available nearby.

- No objections to 2016 decision
- Risk involved in needing to meet an unspecified minimum attendance
- No objections to 2017 plan is to go to N. America
- Appeal for suggestions for locations for 2017: no suggestions given.

Extra information since the meeting:

Meeting dates for 2016 are now set at: Monday 25 - Wednesday 27 January 2016.

Ad. 5

Overview of topics discussed last year and activities related to them:

- Tidewater glacier initiative (Joined activity IASC Cryospheric Working group and NAG)

* Workshop on 'Glacier and ice-stream calving: Observations and Modelling' was organized in Grenoble, France (2-3 June 2014).

* All presentations, talks and discussions are available online

* Review paper being written on tidewater glacier dynamics is being written to be submitted to Reviews Geophysics

- The 'IMBIE' like project for small ice caps: GIC-IMBIE

* Discussed first 2 years ago as a possible initiative but so far has not really been taken up by anyone.

Extra information since the meeting: The idea is taken up again by making a plan for a small workshop to bring together people who can take this further.

- Firn processes

* Subject well suitable to take up as a comunity. * Jason Box already involved in a workshop to be organised in spring 2016.

* Can we include NAG in Jason's initiative?

- Arctic glaciers mass balance records (MAGICS). * Goal is to extent the data sets gathered by NAG in the MAGICS project to present, by Martin Sharp. * Extended this record since 1997 (up to 1994 data). Now updated to 2013.

* Focussed on long term records.

* Found errors in WGMS, will update them

* New analysis draws new conclusions compared to the 1997 report (presented by Martin Sharp in this meeting)

* Plan to update the website with this extended dataset

Suggestions for new focus areas:

- Regine Hock:

Global comparison of mass balance models, Little effort for big gain Comment Martin Sharp: data check would be required and may be inadequate

- Gordon Hamilton

Greenland icesheet and ocean working group (GRISO) (http://web.whoi.edu/griso/) Workshop in 2013: Extended from this workshop with focus on understanding GIS dynamics

1) improved bathymetry through data mining

2) surface runoff \rightarrow subglacial \rightarrow grounding line controls

3) GIS ocean interaction observing system

Anyone can propose an additional focus topic, it should be community led Comment Carleen Tijm-Reijmer: how to connect it to NAG?

Answer Gordon Hamilton: GRISO affiliated to CliC so can make a focus session in next NAG meeting

Comment Carleen Tijm-Reijmer: advantage of getting involved in ocean connections Comment Gordon Hamilton: advantage to learn from non GIS analogues/locations

- Carleen Tijm Reijmer

UAV (unmanned aerial vehicle) applications to NAG

Is it worth having a half day of NAG dedicated to this?

Comment Andreas Alstrøm: does it overlap other technical workshops, or is there a good idea to have an additional specific practical workshops

Comment Carleen Tijm-Reijmer: possibility to run meetings back-to-back

Comment Liss Andreassen: also using UAVs in Iceland (Jarosch) and Norway (Andreasson/Immerzeel), so can be a useful NAG development

Conclusion Carleen Tijm-Reijmer: a useful addition to next years program

Ad. 6

No changes in National contacts. Attempt to activate them more.

Ad. 7

Abstracts:

- Published as .pdf online on NAG website
- Deadline for extended abstracts 12 May 2015
- Published as pdf 01 Aug 2015

- Michael Kuhn offers to publish abstracts in Zeitschrift für Gletscherkunde und Glazialgeologie (ZGG) (ISBN, no impact factor). Challenge is that to be published in the year of the meeting would require the abstracts to fill 80 pages

- Can make room for extended abstracts and include figures
- Review of abstracts would be carried out primarily by NAG Meeting attendees
- No charge for publication, but optional charges €260 for 16 color pages
- $\pm 50\%$ group is interested in this
- ZZG option would not be available online
- Publication date of December 2015 requires deadline of June 2015
- Additional online access is not clear, MK will check this

- Luke Copland and Carleen Tijm-Reijmer stated preference for online access

Extra information since the meeting:

This year the abstracts will not be published in ZGG. In case we decide to do this, it should be announced with the meeting announcement so participants are aware of this.

Abstracts

Scientific results and data from the Programme for Monitoring of the Greenland Ice Sheet (PROMICE)

A.P. Ahlstrøm¹, S.B. Andersen¹, D. van As¹, M. Citterio¹, R.S. Fausto¹, M.L. Andersen¹, J.E. Box¹, W.T. Colgan¹, M. Veicherts¹, H. Machguth², R. Forsberg³, H. Skourup³, S.L.S. Sørensen³, S.M. Hvidegaard³, S.S. Kristensen³, J. Dall³, A. Kusk³, D. Petersen⁴

- ¹ GEUS Geological Survey of Denmark and Greenland, Copenhagen Denmark
- ² DTU Artek Arctic Technology Centre, Kemitorvet, Lyngby, Denmark
- ³ DTU Space National Space Institute, Elektrovej, Lyngby, Denmark
- ⁴ ASIAQ Greenland Survey, Nuuk, Greenland

Recent scientific and data contributions from the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) include an estimate of Greenland ice sheet mass loss partioned in SMB/frontal ablation for each major basin, an improved icemask based on aerial photos, comparison of RCM runoff against observed discharge, a new comprehensive database of historical mass balance measurements in Greenland, airborne measurements of elevation and ice thickness over the entire ice sheet margin, as well as a freely available, long, stable and well-documented time series of measurements from an AWS network in the ablation zone. Other products include satellite-derived ice velocity maps from the ice-sheet -wide marginal zone and GPS velocity time series from selected outlet glaciers. These recent results and available datasets will be presented in an overview, including the instrumental development of the PROMICE AWS which is now made to order.

Ice thickness measurements and volume estimates for glaciers in Norway

L.M. Andreassen¹, M. Huss^{2,3}, K. Melvold¹, H. Elvehøy¹, S.H. Winsvold^{1,4}

¹ Norwegian Water Resources and Energy Directorate, NVE, Oslo, Norway

- ² Department of Geosciences, University of Fribourg, Fribourg, Switzerland
- ³ Laboratory of Hydraulics, Hydrology and Glaciology (VAW), ETH Zurich, Zurich, Switzerland

⁴ Department of Geosciences, University of Oslo, Oslo, Norway

Glacier volume and ice thickness distribution are important variables for the water resources management in Norway and for the assessment of future glacier changes. Since the 1980s ice thickness measurements have been carried out by radio-echo sounding (RES) on many glaciers in Norway. Measurements were conducted on smaller mountain glaciers as well as on the largest ice caps. So far, however, a total ice volume estimate for Norway has not yet been derived from these data. Here, we provide an overview of ice thickness measurements available for mainland Norway, use a distributed model to interpolate data and to derive an ice volume estimate for all individual Norwegian glaciers, and compare measured ice volume with results from various volume-area scaling relations.



Figure 1. Location map of glaciers with ice thickness measurements in Norway used in this study. Insets show southern Norway (1), Svartisen (2), Blåmannsisen (BLÅ) and Langfjordjøkelen (LAJ). Glaciers with ice thickness measurements are in blue, others in grey. Numbers refer to glacier ID and letters to glacier complex code (Andreassen *et al.*, 2012).

We used all ice thickness data that were available in digital format (Fig. 1). The source of the data is NVE's database with a few additions from collaborators. Information on the data collection and processing is documented in individual reports and papers (Andreassen *et al.*, 2015). Glacier outlines from a Landsat-derived inventory from 1999-2006 covering an area of $2692 \pm 81 \text{ km}^2$ were used as input (Andreassen *et al.*, 2012). We compiled a rich set of ice thickness observations collected over the last thirty years. Altogether, interpolated ice thickness measurements were available for 870 km², or 32%, of the current glacier area of Norway with a total ice volume of $134 \pm 23 \text{ km}^3$. Ice thickness data were used to calibrate a physically-based distributed model (Huss and Farinotti, 2012) for estimating ice thickness of unmeasured glaciers. The results were also used to calibrate volume-area scaling relations and revealed that scaling was sensitive to the dividing of glacier complexes into units and to the sample of measured glaciers. The calibrated total volume estimates for all Norwegian glaciers ranged from 257 to 300 km³.

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- Andreassen, L.M., S.H. Winsvold (eds.), F. Paul and J.E. Hausberg, 2012. Inventory of Norwegian glaciers. *NVE Report 38*, 236pp. (available at: www.nve.no/glacier)
- Huss, M., and D. Farinotti, 2012. Distributed ice thickness and volume of all glaciers around the globe. J. Geophys. Res., **117**(F04010). doi:10.1029/2012JF002523.

Snow cover dynamics on a small polar glacier using high spatio-temporal monitoring: 7 years of observations on Austre Lovén glacier.

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¹ ThéMA, université de Franche-Comté, Besançon, France

² FEMTO-ST, université Franche Comté, Besançon, France

Arctic glaciers are known to be reliable indicators of global climate changes as their behaviour are strongly linked to it. Within this context, the observed evolutions are becoming faster and more unpredictable. Snow and ice dynamics are directly affected, and following processes becomes challenging: some fast but key events can be missed since they are short but significant.

In order to better understand these processes, Austre Lovén glacier (4.5 km²), located on the Brøgger peninsula (78°N, Spitsbergen) has been systematically instrumented and monitored since 2007. Air temperatures have been recorded continuously through a network of 20 sensors distributed on the whole glacier surface. Hourly temperature is thus available and can be spatialized by interpolating data: this gives the thermal state of the glacier. Moreover, with the aim of observing the most accurately snow cover dynamics and melt water phenomena, 6 automatic photos stations were installed around the glacier basin so as to cover the largest area. Geometric corrections of the photos, using reference points located on the glacier using GPS receivers, yield quantitative information from initially qualitative images. Projecting the resulting mosaic on a GIS allows for the precise monitoring of ice-related processes, and especially the snow coverage evolution over time.

This work is based on seven years of observations. By crossing temperature data with the glacier cover typology (binary snow or ice), we can estimate accurately the potential of snow/ice melting. This is established by applying a *k* coefficient in degree-day model. Thus, cumulative maps of potential melt water allows to assess the protection of snowcover and how warm summers could be destructive if the glacier is not or not enough covered by snow.

Comparison of century-plus Greenland ice surface mass balance reconstructions

J.E. Box¹, X. Fettweis, T. Kobashi

¹GEUS - Geological Survey of Denmark and Greenland, Copenhagen Denmark

This presentation focuses on a comparison of Greenland ice surface mass balance reconstructions for the past century-plus. Comparisons are made among reconstructions and versus ice cores, meteorological station temperature series, and borehole temperature inversions. The compared reconstructions include that from Box (2013) based on in-situ observations and that from the regional climate model MAR v3.5.0 driven by 1.) the 1871-2012 NOAA 20th Century Re-analysis (NOAA

20CR) and by 2.) the 1900-2010 ECMWF ERA-20C as well as MAR v3.5.2 forced by ERA-20C (respectively NOAA 20CR) with a temperature correction of $+1^{\circ}$ C (respectively -1° C) to the MAR boundary conditions given that ERA-20C (respectively 20CR) is $\sim 1^{\circ}$ colder (respectively. warmer) over Greenland than ERA-Interim data over 1980-2010. By comparison with 20CR, ERA-20C is not an ensemble mean which may be advantageous for forcing regional models. Indeed, part of the MAR-20CR accumulation increase is due to the decrease of the spread in 20CR and then its is due to an apparent increase of the pressure gradient at the MAR boundaries which impacts the humidity advection and then precipitation amount in MAR.

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Using time lapse photogrammetry to examine spatial temporal variations in Greenland outlet glacier dynamics

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Using time lapse photogrammetry, several outlet glaciers at the Greenland ice sheet are monitored in order to evaluate the sensitivity of the glacier motion to different forcings such as: surface melting, calving, ocean tides, basal melting and others. Knowing the sensitivity is desirable as the discharge from outlet glaciers, and thereby the mass loss of the Greenland ice sheet, depends on the surface velocity.

Beginning in 2007, cameras were placed at the outlet glaciers as a part of the The Extreme Ice Survey. The velocity field of the glaciers is measured from repeated photos using the newly developed open source feature-tracking software ImGRAFT. By examining time lapse sequences from different glaciers over single years and interannually, this study examines the spatial and temporal variations of glacier motion. The study incorporates records of land and sea surface temperature, sea ice concentration, and tides, to interpret glacier velocity variations.

Relationships between summer melt and winter motion at Kaskawulsh Glacier, Yukon

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A near-continuous 5 year record of velocities measured with 4 differential GPS (dGPS) units along the Kaskawulsh Glacier reveals marked inter-annual and intraannual variations in motion. Shortly after the onset of melt each spring there is a rapid acceleration of the glacier, with velocities increasing up to triple above winter values. The acceleration starts near the glacier terminus and propagates upglacier over the space of a week or so. Enhanced motion continues throughout the summer, and then rapidly drops once melt stops in the early fall. Velocities in the fall and winter are low, but quite variable between years, with a strong inverse connection between the amount of summer melt and fall/winter motion. In some winter months, for example, motion is >30% slower at all dGPS stations after a summer with high melt (>5 m), in comparison to a summer with low melt (<3 m). This suggests that a negative feedback process may operate on large alpine glaciers which reduces their velocity response to increased melt under a warming climate.

"Slow" surge of the Vavilov Ice Cap, Severnaya Zemlya

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We use satellite imagery (1963- 2015) and airborne radar data (September 2014) to document rapid acceleration and surge of western sector of the Vavilov ice cap, Severnaya Zemlya.

In the 1960s-70s, the ice margin there was stable and followed the general smooth outline. Only slight advance by 80 meters in average occurred in this decade. Thereat the margin was land-terminated and separated from sea by rampart of "dead" sediment-laden ice up to 0.5 km width.



Figure 1. Surge of the Vavilov Ice Cap, Severnaya Zemlya, 15 September 2014 (by A. Glazovsky).

In 1980s- 2000s the margin began to bulge towards the sea with mean rate 70 m a^1 , so that in 2012 the outlet lobe of 2.4 km length, 8 km width, and 12.36 km² area was formed. When advancing it pushed forward the "dead" ice belt that framed the front.

In 2012, the protrusion of front dramatically accelerated: rate of advance increased from 180 to 1540 m a^1 (maximum up to 2.4 km a^1).

In September 2014 the area enlargement rate reached 37 000 m² d¹. The surging lobe with 3.142 km³ of ice occupied an area of 30.14 km², and embossed into the sea by 4.5 km. Its thickness reached 178 m (104 m mean), with bedrock at average depth -40 m (minimum -67 m) below sea level. The framing rampart almost completely collapsed; the margin spread and spitted into fingers, but, nevertheless, it advanced further by February 2015. Only shallows waters seems to prevent the major eruption of icebergs and front destruction. Radarograms show no large barriers or overdeepenings on bedrock, but reveal a feature that might be remains of marginal structure of 1963, also traceable through ice on imagery. Possibly, it is the roots of the cold-based plugging belt that was in most part cut off and pushed to the sea, where ice movement accelerated on soft unfrozen marine sediments.

Recent glacier and ocean changes in Northeast Greenland

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The northeastern sector of Greenland has so far not experienced the profound series of changes observed elsewhere around the margin of the ice sheet. One explanation is the relatively cold ocean waters of the Fram Strait, far removed from the warming waters of the subpolar gyre that are hypothesized to have provided the forcing for the changes observed elsewhere. We discuss recent results which suggest this relatively stable situation might not persist.

The Northeast Greenland Ice Stream (NEGIS) is the dominant feature in this sector of the ice sheet. It feeds ice from the interior into three marine-terminating glaciers: Nioghalvfjerdsfjorden (79N), Zachariae Isstrøm (ZI), and Storstrømmen. NEGIS sits in a trough that is below sea level far inland of the current grounding line, making is particularly susceptible to rapid retreat and dynamic thinning. ZI recently lost its floating tongue in 2013 and ice speeds at the grounding line have increased. The much larger floating tongue of 79N (the largest ice shelf in the northern hemisphere) remains intact, but an updated balance assessment indicates a \sim 35% increase in submarine melt rate from 1998 to 2012. Increased melting might be the result of a slight warming (\sim 1°C) of waters circulating in the sub-ice cavity.

Additional evidence for changes in the ocean environment comes from an analysis of the Norske Ø Ice Barrier (NØIB), an extensive region of perennially fast ice abutting the terminus of 79N. NØIB varies in size from year to year but, until recently, complete breakups were a rare event. It reportedly broke up in the 1950s and was observed to breakup in August, 1997. More recently, the NØIB disintegrated during the summers of 2001-2005, 2008, and 2010-2014. A statistical analysis indicates that June surface air temperatures and regional cyclones are good predictors of the NßIB breakup but warming ocean waters circulating benath the ice barrier are probably also involved.

Modeling the evolution of the Juneau Icefield using the Parallel Ice Sheet Model (PISM)

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Here we study the evolution of the Juneau Icefield, one of the largest icefields in North America (4149 km²), using the Parallel Ice Sheet Model (PISM). We test two climate data sets of air temperature and precipitation; the first was dynamically downscaled by the Weather Research and Forecasting Model (WRF) and the second is based on spatial interpolation of the Climate Research Unit (CRU) global reconstruction by the Scenarios Network for Alaska Planning (SNAP). Good agreement between simulated and observed surface mass balance could only be found after substantially adjusting WRF precipitation to account for orographic effects while SNAP's precipitation pattern is incompatible with observations of surface mass balance. By 2100 the model projects a decrease in ice volume by 58% to 68% and a 57-63% area loss compared to 2010. Under current (1971-2010) climate the icefield reaches an equilibrium state after roughly 200 years at 86% of the 2010 volume. Repeating the 2070-2099 climate beyond the 21st century almost eliminates the icefield within by 2200, while stabilizing the climate earlier causes the icefield to reach a new equilibrium after several 100 years, although at substantially reduced ice volumes. If all ice was removed, under current climate conditions, the icefield would regrow to a similar volume as if the model was started with current initial ice volume. Despite large projected volume losses, the complex high-mountain topography makes the Juneau Icefield less susceptible to climate warming than other Alaskan low-lying icefields and allows for multiple retreat states under varying climate conditions.

Application of terrestrial 'structure-from-motion' photogrammetry on a medium-size Arctic valley glacier: potential, accuracy and limitations

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Terrestrial photogrammetry was the standard method for mapping high mountain terrain in the early days of mountain cartography, until it was replaced by aerial photogrammetry and airborne laser scanning. Modern low-price digital single-lens reflex (DSLR) cameras and highly automatic and cheap digital computer vision software with automatic image matching and multiview-stereo routines suggest

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the rebirth of terrestrial photogrammetry, especially in remote regions, where airborne surveying methods are expensive due to high flight costs. Terrestrial photogrammetry and modern automated image matching is widely used in geodesy, however, its application in glaciology is still rare, especially for surveying ice bodies at the scale of some km², which is typical for valley glaciers.

In August 2013 a terrestrial photogrammetric survey was carried out on Freya Glacier, a 6 km² valley glacier next to Zackenberg Research Station in NE-Greenland, where a detailed glacier mass balance monitoring was initiated during the last IPY. Photos with a consumer grade digital camera (Nikon D7100) were taken from the ridges surrounding the glacier. To create a digital elevation model, the photos were processed with the software photoscan. A set of 100 dGPS surveyed ground control points on the glacier surface was used to georeference and validate the final DEM.

Aim of this study was to produce a high resolution and high accuracy DEM of the actual surface topography of the Freya glacier catchment with a novel approach and to explore the potential of modern low-cost terrestrial photogrammetry combined with state-of-the-art automated image matching and multiview-stereo routines for glacier monitoring and to communicate this powerful and cheap method within the environmental research and monitoring community.

The structural glaciology of Austre Brøggerbreen, northwest Svalbard

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Many glaciers in Svalbard have receded and thinned substantially from their Neoglacial maximum c. 1900 AD. Thinning of Austre Brøggerbreen, a predominantly cold-based valley glacier located in northwest Spitsbergen, has revealed the former internal structure of the glacier in remarkable detail. From this, changes in the glacier's dynamics can be inferred in a way that is applicable to other valley glaciers that are receding rapidly. Detailed structural mapping of Austre Brøggerbreen from aerial photography (NERC imagery acquired in summer 2004) has enabled the formation and evolution of different suites of structures to be documented. The glacier comprises multiple broad accumulation basins that coalesce into a narrow and comparatively short tongue. Despite not being very dynamic at present, the structure of Austre Brøggerbreen is dominated by fractures that originated high in the glacier's accumulation area, indicating that the glacier was substantially more dynamic during the Neoglacial time than at present. Furthermore, the persistence of these fractures through the ablation zone to the glacier's terminus indicates that they initially penetrated to great depths, possibly all the way to the glacier's bed. Individual suites of fractures are usually contained within discrete flow units, with transverse fractures becoming increasingly arcuate down-glacier as a result of ductile flow. In two cases, initially transverse fracture sets have become sufficiently reorientated at flow-unit boundaries to develop a fracture-derived longitudinal foliation. The results of this study provide a unique view of the internal structure of a Svalbard valley glacier, and illustrate how reorientation of relict fracture sets can lead to the formation of a new fracture-derived longitudinal foliation.

Detailed investigation of glacier calving with a terrestrial radar interferometer

M. Luethi

We investigate ice dynamic processes related to glacier calving with a terrestrial radar interferometer (TRI), and complementary well established methods. The target glacier, Eqip Sermia, West Greenland, is a small tidewater outlet glacier of the Greenland Ice Sheet which recently accelerated and started to retreat at high rate. The glacier is calving several times per day with occasional large calving events that lead to tsunamis in the embayment. TRI measurements allow us to obtain displacement fields and DEMs in minute intervals, thus facilitating the determination of calving volumes and tsunami waves of big calving events. From the displacement fields we can extract strain rates which are essential for understanding of the fracture processes of crevassing preceding glacier calving.

Successive and intense melt rapidly decreases Greenland meltwater retention in firn

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About half of the current mass loss of the Greenland ice sheet is attributed to runoff from surface melt. At higher elevations, however, melt does not automatically equal runoff, because meltwater refreezes in the porous near-surface snow and firn. Recent studies suggest that all or most firn pore space is available for meltwater storage, which would make the firn an important buffer against Greenland's surface melt contribution to sea level rise.

Here, we challenge the notion that all firn pore space is available for meltwater retention based on field observations (Fig. 1), analysed in the context of historical legacy data. Our observations frame the recent exceptional melt summers of the years 2010 and 2012 and reveal a distinctive pathway of firn changes induced by successive and intensive melt. At the lower end of the pathway, where melt is most abundant, porous firn loses its capability to retain meltwater.



Figure 1. Stratigraphy of the nine major firn cores drilled in late April to mid May 2013. Ice lenses are in blue and given at 1 cm vertical resolution. Density at 10 cm resolution is in black. The dotted vertical line indicates the density of pure ice (917 kg m⁻³); the thin inclined line denotes dry firn density. Dashed areas mark the end of the cores. The association of each core with the three hypothesized firn regimes is indicated at the top.

At 67°N, in the lower percolation zone of the western flank of the ice sheet, the formation of thick near-surface ice layers ("regime (3)" in Fig. 1) renders $32\pm10\%$ of firn pore space inaccessible and forces meltwater to enter the surface discharge system rather than percolating and being retained in the underlying firn. As a direct consequence, ice sheet mass loss is intensified; in summer 2012 $9\pm3\%$ of total runoff originated in the zone of perched ice layers (~1680 to 1870 m a.s.l.).

Strong evidence suggests that the above described processes take place over extended areas of the lower Greenland percolation zone.

A comprehensive data base of glacier surface mass balance observations from the ablation area of the ice sheet and the local glaciers of Greenland

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Glacier mass balance measurements on Greenland started nearly a century ago. While accumulation measurements have been compiled in a number of studies, no comprehensive overview of the data from the ablation zone of the ice sheet and from the local glaciers exists. These data are missing in the evaluation of modelled



Figure 1. Map of the location and temporal description of the Greenland melt area and local glacier surface mass budget observations contained in the database.

glacier mass balance, but they also bare the potential of specifying changes in glacier melt independently from modelled data.

Here we present a comprehensive data base of glacier mass balance observations from the ablation zone of the Greenland ice sheet and the local glaciers. The data base contains a total of >2400 mass balance observations from 36 sites (Fig. 1). For each mass balance observation X, Y and Z coordinates, starting and ending dates and quality flags are provided. Sources are given for each entry and for all metadata. The mass balance data is accompanied by a literature base.

Most data were collected from grey literature and unpublished archive documents. 50% of the data have not been published before and were thus inaccessi-

ble to the scientific community. Only 13% of the data already existed in tabulated form including dates and coordinates.

The data cover all regions of Greenland except for the southernmost part of the east coast. The earliest measurements date from 1938. Numerous extensive and systematic campaigns were carried out but nearly all of them were discontinued after a few years, only the observations along the K-Transect and at Swisscamp exceed 20 years. Once published, the mass balance data base including all sources becomes openly accessible.

Queen Elizabeth Island glacial surface elevation change from airborne altimetry 1995-2012

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Rapid warming and enhanced melt from glaciers and ice caps have made the Queen Elizabeth Islands (QEI), Arctic Canada, one of the largest glacier contributors to the non-steric component of global sea level rise, after the major ice sheets in Greenland and Antarctica (Gardner *et al.*, 2013). Between 2005 and 2009 mean summer surface temperatures in the QEI were 0.8°C to 2.2°C warmer than those of the previous pentad (2000-2004) (Sharp *et al.*, 2011) and field based mass balance measurements show 2005-2009 was the most negative pentad since records began in the early 1960s (Koerner, 2005). In light of the observed warming and mass changes it would be expected that glacier surface elevations in the QEI will have decreased since the year 2000.

The rate of surface elevation change (dH/dt) was computed from repeat laser airborne altimetry data from 1995, 2000, 2006, 2005 and 2012. Between 1995 and 2012 surface lowering was observed in most regions of the QEI below 1100 m.a.s.l. Thinning was greatest at low elevations, decreasing with increasing elevation. Temporal variability in dH/dt was investigated by dividing the period 1995-2012 into three epochs of roughly equivalent length: 1995-2000, 2000-2006, 2006-2012. No significant difference in the magnitude of dH/dt or the relationship between dH/dt with elevation was observed between the first two epochs with the exception of Muller Ice Cap where dH/dt was on average 0.2 m yr⁻¹ less negative above 700 m.a.s.l. during the second epoch (2000-2006) compared to the first (1995-2000). In contrast to the first two epochs where thickening was observed at higher elevations, during the most recent epoch dH/dt was negative at all elevations in all glaciated regions for which data was available. Between 2006 and 2012 dH/dt was on average five times more negative compared to the first two epochs.

Observed changes in surface elevation change were interpreted in the context of summer land surface temperatures and summer minimum surface albedos derived from MODIS satellite data. We find that since 2000 (first available MODIS data), the QEI has experienced an increase in the duration and intensity of the summer melt season and a decrease in the minimum summer albedo. Surface lowering is usually assumed to indicate a reduction in glacier mass, but higher rates of firn compaction in a warmer climate can also result in surface lowering. Firn and ice cores from the Devon and Penny ice caps reveal an increase in firn density since 1955 (Bezeau *et al.*, 2013; Zdanowicz *et al.*, 2012). These field measurements are consistent with our analysis of the MODIS data where warmer land surface temperatures would be expected to generate more melt, leading to both increased runoff and compaction of the firn. Melt and an increase in snow metamorphism would also be expected to result in lower surface albedos, further enhancing melt.

Snow, firn and ice have different reflectance properties allowing the use of surface albedo, derived from satellite imagery, to identify regions corresponding to each. To evaluate height changes occurring in the firn zone we use MODIS white sky albedo data to identify regions that are most likely firn and those that are most likely glacier ice. During the last epoch thinning was observed in both firm and glacier ice covered areas and was accompanied by a decrease in the average minimum summer surface albedo and an increase in melt intensity. Qualitatively this suggests that some of the observed thinning in the firn zone may be the result of firn compaction. We hypothesize that a portion of the observed thinning in the firn zone during the most recent epoch (2006-2012) is the result of firn compaction and therefore does not equate to a loss in glacier mass. Our hypothesis is corroborated by field measurements on the Devon Ice Cap which found a 13-80% increase in firn density above 900 m.a.s.l. between 2004 and 2012 (Bezeau et al., 2013), however, information about changes in ice flow are required in order to quantify the proportion of elevation change that is due to changes in dynamics versus the component that is the result of changes in surface mass balance.

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Dissipative meltwater production in glaciers

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Glaciers are dissipative systems through which mass (snow, ice, water) travels downwards to leave the system at the glacier front. This process involves the conversion of potential energy, delivered by the atmosphere during precipitation events, into kinetic energy and finally dissipation. From the theory of ice mechanics it is known that the dissipation is given by the convolution of the stress and strain rate tensors. To do such a calculation for a real glacier is a tedious exercise for which a detailed and precise numerical model is needed. However, to obtain a feeling for characteristic numbers it is useful to consider a glacier system as an entity, which makes it much easier to estimate the total disspitation.

By estimating the dissipation from the loss of potential energy there is no need to make a distinction between solid and liquid precipitation. In the end all the mass leaves the glacier at the glacier front, and the loss of energy is entirely determined by the altitude difference between the location of mass deposition and the glacier front.

When a glacier is (almost) temperate, disspative heating will involve melting of ice. To illustrate the concept, schematic calculations are presented for a number of glaciers with different geometric characteristics. Typical dissipative melt rates, expressed as water-layer depth averaged over the glacier, range from a few cm per year for relatively dry Arctic glaciers to half a meter per year for Franz-Josef Glacier, one of the most active glaciers in the world (in terms of mass turnover).

In a next step, meltwater production resulting from enhanced ice motion during a glacier surge is calculated. The total generation of meltwater during a surge is typically half a meter. For Variegated Glacier a value of 70 cm is found, for Kongsvegen 20 cm. These values refer to water layer depth averaged over the entire glacier. The melt rate depends on the duration of the surge. It is generally an order of magnitude larger than the water production by 'normal' dissipation. On the other hand, the additional basal melt rate during a surge is comparable in magnitude to the water input from meltwater and precipitation.

Calving of tidewater glacier driven by melting at the waterline

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In this contribution we present the study of the development of thermo-erosional notch at the waterline and its influence on calving of Hansbreen, a medium size grounded tidewater glacier in southern Svalbard. The study is based on the results of repeated terrestrial laser scans (TLS), analysis of time-lapse camera images acquired year-round and oceanographic surveys of the sea water properties close to the ice front. Measured depths of the undercut reach values of 4 m and vary largely in time. The calving activity of Hansbreen was signicantly lower in 2011 than in 2012 due to the persistent presence of the ice pack in Hornsund fjord. Calving on Hansbreen is controlled by a local imbalance of forces at the front due to thermo-erosional undercutting at the sea waterline. Calving activity is therefore sensitive to changes in sea water temperature and wave height. It may be expected that calving rates will rise with increased advection of warm oceanic water to the Arctic.

Snow cover, ice loss, and rock debris quantification in an arctic glacier basin through terrestrial laser scanning surveys

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For 3 consecutive years, terrestrial laser scanning surveys have been conducted in the glacier basin of Austre Lovénbreen (Svalbard, 79°N). Each year, high density point clouds were acquired on the glacier surface and on the surrounding slopes. Two yearly scanning sessions were required in order to spatialize and quantify snow cover. The first session was done late April at the expected annual snow maximum. The second session was done in August near the end of the melting season and before the first potential significant snow falls.

On the glacier itself, laser scans were produced on the glacier snout, in the area close to the equilibrium line, and in the upper reaches of the glacier. Manual snow drilling measurements and glacier mass balance data were subsequently used to validate snow cover results.

In the steep slopes surrounding the glacier, scans were acquired on slopes at various altitudes and orientations in order to get a representative view of different snow cover settings. Particular attention was granted to snowdrift and avalanche processes, and their consequences on remaining packed snow stored in perennial snow accumulation at the bottom of slopes.

A good knowledge of the dynamics of the snow cover is of particular interest in a glacier undergoing a clear retreat. Snow is slowing the melting of the ice for part of the season, and snow is also providing what will constitute future glacier ice in the upper reaches of the basin.

Snow on slopes is also of importance as avalanches reaching on the glacier can contribute to the overall mass balance. Snow cover, by keeping the slopes permafrost from thawing early in the season, or by providing liquid water affecting it later in the season, is also playing a key role in the glacier basin morphology and its interactions with the glacier body.

Modeling the response of the Juneau Icefield to climate change

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We project the future mass changes and evolution of the Juneau Icefield, one of the largest icefields in North America (\sim 4100 km²) using a coupled mass balance and flow model. Surface mass balance is modeled using a spatially-distributed

temperature-index model and ice flow is modeled using a 2-D shallow ice approximation model. Input climate data of air temperature and precipitation are dynamically downscaled by the Weather Research and Forecasting Model (WRF) from one of the Coupled Model Intercomparison Project Phase 5 (CMIP5) simulations by the Community Climate System Model 4 for the historical period 1971-2005 and for future projections 2006-2100 at 20 km resolution. Surface mass balance, ice thickness, and ice velocity are simulated on a 300 m grid for each month for the period of 1971-2010 and compared to available observations to calibrate the model. Parameters including a snow degree-day factor, ice degree-day factor, and a precipitation correction factor are tuned to yield the best agreement between model results and observations. Once calibrated, the model was then run for the 2010-2100 time period. Preliminary calculations indicate an ice volume decrease and ice area decrease by 2100 that is significantly less than previous projections made by the Parallel Ice Sheet Model PISM (63% volume loss projected, 62% area loss projected) and projections made a global model mass balance model (79%-90% volume loss projected) for the same time period. We plan to incorporate a runoff model to the current coupled mass balance and flow model to make projections for the icefield's freshwater input to the Gulf of Alaska and to assess the effects of the icefield's wastage on streamflow.

The use of airborne radar reflectometry to derive nearsurface snow/firn properties on Devon Ice Cap, Canadian Arctic

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In direct response to recent increases in summer air temperatures, ice caps in the Canadian Arctic Archipelago now experience significant summer melt at almost all elevations (Sharp *et al.*, 2011). In the percolation zone, this meltwater percolates into the firn and refreezes as ice layers and lenses. Knowledge of the near-surface firn density and stratigraphy, especially the spatial distribution of refrozen ice layers/lenses, and their changes over time is important when computing mass change estimates from altimetry data.

Here, we present an approach for characterizing the near-surface snow/firn properties using the surface echo from airborne radio-echo sounding (RES) measurements. The radar surface echo is a combination of a coherent (Pc) and a scattering signal component (Pn). Pc is related to the dielectric constant of the probed surface (upper 5-10 m), whereas Pn is related to the near surface roughness. Hence, different near-surface snow/firn properties can be investigated by analyzing the signal components Pc and Pn and their spatial variability. The Radar Statistical Reconnaissance (RSR) methodology (Grima *et al.*, 2013) allows the extraction of Pc and Pn from the radar signal, and also generates estimates of the surface reflectivity and roughness. We apply the RSR method to RES data collected on Devon Ice Cap and determine Pc, Pn and the near-surface reflectivity.

We hypothesize that Pn is largely influenced by the presence/absence of ice layers/lenses within the firn, and use this component for a firn facies classification. Further, we modeled the radar reflectivity for the ablation zone in response to different winter snowpack densities and thicknesses. From these results, we hypothesize that the RSR derived reflectivity values might be used as a measure for the thickness of snowpack overlying glacier ice. Finally, we investigate how the surface echo from airborne RES measurements and the RSR results might be used to estimate the amount and thickness of refrozen ice layers/lenses within the firn.

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Investigating the dynamics of store glacier, west Greenland using UAVs

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Unmanned Aerial Vehicles (UAVs) offer exciting opportunities for acquiring highresolution data that bridge the gap between satellite imagery and ground-based measurements. We present results from a two month field campaign during which the terminus of Store Glacier, Greenland was surveyed repeatedly using a fixedwing UAV. Around 90,000 overlapping aerial images were captured which allowed the production of high-resolution (<50 cm) orthophotos and digital elevation models using stereophotogrammetry. These products provide us with a unique opportunity to investigate glaciological processes at a fine spatial and temporal scale.

Feature tracking of the images are used to extract daily surface velocity fields and strain rates. These results are combined with meteorological and satellite data to explore the dynamics of the ice mélange and glacier before, during and after the ice mélange breakup. The distribution of water-filled crevasses and changes in the position and size of the meltwater plume emerging from the calving front are also assessed. These results enable the investigation into the impact of water-filled crevasses and meltwater plumes on calving rates through the deepening of crevasses and submarine melting, respectively. We conclude that the results and techniques used in this study demonstrate the applicability of repeat UAV surveys to assess the short-term dynamics of tidewater outlet glaciers.

Firn line delineation using Envisat SAR imagery from 2005-2010 over Penny Ice Cap, Baffin Island, Nunavut.

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Increased mass loss associated with rising temperatures has been observed over the southern Canadian Arctic from geodetic measurements, particularly since 2005. To assess the impact of this warming on glacier facies, the location of the firn line on Penny Ice Cap (\sim 66°N) was mapped with Envisat SAR imagery from May 2005 - October 2010. Data are validated against in-situ ground-penetrating radar (GPR) transects and compared to ELA positions determined from mass balance stake measurements. The firn line observed on a GPR transect recorded in May 2011 on the southwestern edge of the ice cap matches well with the firn line position identified from differences in backscatter in Envisat imagery from the same mass balance year. Applying this backscatter relationship to other years, the firn line here remains relatively constant in location through time, possibly due to a local peak in snow accumulation. In contrast, on the western side of the ice cap the firn line has migrated up-glacier across a gently sloping region, moving 540 m upglacier between 2005-2008 and 550 m between 2009-2010. This aligns with increased mass loss in this region since 2005. At both locations, the stake measurements indicate that the ELA is located >15 km upglacier from the Envisat-derived firn line. This displacement of the ELA relative to the firn line suggests that Penny Ice Cap is considerably out of balance with current climate, with old firn at depth being exposed in what is now the ablation zone. This is consistent with warming of $\sim 10^{\circ}$ C recorded at a depth of 10 m in the firn region since the mid-1990s (Zdanowicz et al., 2012).

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A multivariate approach of the factors impacting a small arctic glacier

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Arctic glaciers are good indicators of the ongoing climate change as their dynamics are strongly linked to it. This study is focused on the Austre Lovén glacier, on the Brøgger peninsula in Spitsbergen (Svalbard, 79°N). The aim is to understand how contrasted climate and snow conditions over the course of a year can lead to multiple consequences, sometimes unexpected, on mass balance. In 2014, a negative budget was expected, but data analysis has shown the first positive mass balance in 7 years. The objective here is to (i) identify and qualify the combination of factors affecting an arctic glacier mass balance. Three primary indicators seem to display the greatest influence: summer temperatures, liquid precipitations and winter snow accumulation. A specific focus would also be to (ii) understand the seasonal chronology and to rank parameters that have the greatest influence on glacial dynamics.

The Austre Lovén glacier (4,5km²) has been systematically instrumented and monitored since 2007. Mass balance is measured yearly at the end of September with an evenly-spaced 36 stakes network. 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. The last parameter we are mainly interested in for this study is liquid precipitation data. It could not be continuously recorded in situ because of technical reasons. Hence it was reconstructed with data from the closest meteorological station, in Ny Ålesund, about 6km from the site.

These parameters were then used as explanatory variables to identify their influence on the Austre Lovén glacier. Data being recorded punctually was subjected to spatial generalization at the scale of the glacier. Factors conditioning accumulation area are not necessarily analogous to the ones having a great influence in the ablation area. Observed data need to be prepared in order to provide more explicit indicators as input for the statistical analysis. For example, a degree-days indicator allows to considerate only positive temperatures which have the greatest influence on the glacier. All of the original and derived factors are then constituting the basis of all subsequent multivariate analysis.

Revisiting "The Mass Balance of Circum-Arctic Glaciers and Recent Climate Change"

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With acknowledgements to G. Wolken, A. Arendt, S. O'Neil, M. Pelto, D. Burgess, G. Cogley, R. Koerner, J. Kohler, and L. Andreassen.

One of the first activities of the IASC Working group on Arctic Glaciology (WAG) (now the Network on Arctic Glaciology, NAG) was to produce a review of in situ mass balance measurements on glaciers from across the Arctic for the period 1946 to 1994. This work was published in Quaternary Research in 1997 with Julian Dowdeswell as lead author and 10 co-authors (D97) (Dowdeswell *et al.*, 1997). A further 20 years of mass balance measurements have accrued since that time and the number of sites being monitored on a regular basis has increased. It is therefore time to update the 1997 analysis, which reported predominantly negative mass balances across the Arctic but a lack of any uniform mass balance trend - although Alaskan glacier mass balances were reported to be becoming more negative while those in maritime Scandinavia and Iceland were becoming more positive due to increasing precipitation.

Since 1994, surface mass balance has been measured on 28 Arctic glaciers, compared with 18 in D97. These are located in Alaska (3), Arctic Canada (4),

Iceland (9), Svalbard (4) and northern Scandinavia (8) - though not all have been measured every year (the annual sample size ranges from 12-27). In total, 524 balance years of measurements (out of a possible 588) were made between 1994 and 2014. Consistent with D97, mean regional mass balances for the "Low Arctic" (Alaska, Iceland and northern Scandinavia) were more negative and had higher standard deviations (-599 to -875 \pm 738 to 869 kg m⁻² a⁻¹) than those for the "High Arctic" (Arctic Canada and Svalbard; -344 to -347 \pm 389 to 393 kg m⁻² a⁻¹). Only 86 (16%) of the measured annual balances were positive. 53 of these were from Low Arctic regions (15.1% of measured balance years) and 33 from the High Arctic (21%). Mean annual mass balances for individual glaciers differed from zero by between 0.1 and 2.1 standard deviations of the mean (average of 1.04 standard deviations from zero). For 18/28 glaciers, the mean differed from zero by more than 1 standard deviation. Cumulative mass balances for the 14 complete series (1994-2013) ranged from -19,683 kg m⁻² (Gulkana Glacier, Alaska) to +2789 kg m⁻² (Engabreen, Norway - the only measured glacier with a positive cumulative mass balance).

D97 reported trends of increasingly positive annual surface mass balance for glaciers in Iceland, Norway and Sweden prior to 1994. These trends were reversed starting around 1993-1995, since when cumulative mass balances in these regions have become increasingly negative. Plots of regional cumulative mass balance versus time show recent accelerations in rates of mass loss from glaciers in Alaska (starting ca.1988), Arctic Canada (starting ca.1986 with a further acceleration after 2004), and for the Arctic as a whole (starting after 1993). If we compare the regional cumulative mass balances for the twenty-year periods 1974-1993 and 1994-2013 the differences range from -511 kg m⁻² in Svalbard to - 16,570 kg m⁻² in northern Scandinavia. This calculation cannot be made for Iceland due to lack of data from the earlier epoch, but it is clear that the increase in the 20 year cumulative mass loss from glaciers in the High Arctic. The significance of this difference is, however, reduced by the fact that the glaciated area in the High Arctic is more than double that in the Low Arctic.

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The geodetic campaign 2014 for studies in mass balance, ice dynamics and validation of satellite data in the Swiss Camp area, West Greenland

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Introduction

The long-term studies in the Swiss Camp area were continued by the most re-



Figure 1. Cumulative geodetic and surface mass balance at Swiss Camp 1991-2014.



cent campaign in 2014. Since 1991 until 2014 the author now has performed 12 geodetic campaigns. In average every second year we had measured a deformation network consisting of 4 stakes forming a triangle with a central stake. There are two research areas: 1) Swiss-Camp in an altitude of 1170 m and 2) ST2 in an altitude of 1000 m. We measured geodetic elevation changes, surface mass balance at stakes, ice flow velocities and deformation of the ice surface. Comparisons with elevation and elevation change data from CryoSat-2 and TanDEM-X were applied for validation of the satellite data.

Results

The long-term project is able to deduce the mass balance in respect to the climate change. At **Swiss-Camp** (SWC) the accumulated geodetic mass balance (GMB) and the specific surface mass balance (SMB) at stakes are shown in Figure 1. The negative geodetic mass balance is increasing. Starting with -0.2 m/a in the period 1991 - 2002, we get now in the period 2011-2014 an elevation change rate of -1.46 m/a and the geodetic mass balance -1.31 m w.e./a. In comparison, for the surface mass balance from the stakes we get -1.21 m w.e./a. The difference can be explained by the long-term dynamic thinning due to the accelerated ice flow velocity (Fig. 2).

It is well known that in summer time the ice is flowing faster (Zwally *et al.*, 2002; Stober *et al.*, 2013). In Figure 3 the mean ice flow velocities between campaigns (1 up to 3 years) are shown compared to those of a summer day, calculated by Precise Point Positioning (PPP). In most years the summer speed was significantly higher, but on August 5th, 2014, the ice flew slower than in average 2011-2014. At ST2 the summer flow velocity in August 2014 was equal to the average speed





Figure 3. Summer ice flow velocities at Swiss Camp, derived by Precise Point Positioning (PPP).



Figure 4. Cumulative geodetic and surface mass balance at ST2 2004-2014.



Figure 5. Ice flow velocities at ST2 2004 - 2014.

2011-2014.

At the research area **ST2** which is situated in a lower altitude and closer to the ice margin we have observations since 2004 until now 2014. Here we find partly opposite results. The negative geodetic mass balance (Fig. 4) is continuously increasing from -0.35 m w.e./a (2004-2005) up to -1.47 m w.e./a (2011-2014) and the surface mass balance from -1.18 m w.e./a up to -1.55 m w.e./a respectively. In opposite to Swiss-Camp the ice flow velocity (Fig. 5) is here slower and has decelerated, probably due to the bedrock topography. Bedrock and ice thickness data (Bamber *et al.*, 2013; DTU, 2013) show at ST2 the ice flowing against a ridge, while at Swiss Camp it flows into a trough.

Deformation and strain rates are calculated by an affine transformation of the stake networks between the successive campaigns 2011 and 2014. Due to the over-determined system (redundancy 2) we calculate the parameters by a leastsquares adjustment which gives also the standard deviations of the unknowns. At **Swiss Camp** we get the principal strain rates e1 = 2985 + 533 ppm/a (azimuth = 195 gon) and $e^2 = -3760 + -533 \text{ ppm/a}$ (azimuth = 95 gon). The areal distortion is given by the sum e1+e2 = -775 ppm/a and indicates a shrinking area. With application of the continuity condition e1+e2+e3=0 we get the vertical component $e_3 = +775$ ppm/a. Neglecting the variation of a depth dependent velocity variation and together with the local ice thickness (H=1180 m) we get a positive vertical velocity of $e3^{H} = +0.91$ m/a, but no mass gain, because of the assumed continuity condition and incompressibility of the ice. The same calculation at ST2 in the years 2011-2014 leads to the horizontal strain rates e1 = +5911 ppm/a (azimuth 171 gon) and $e^2 = -3550$ ppm/a in perpendicular direction and so in vertical $e_3 = -2361$ ppm/a. The resulting distortion in area yields to an enlargement of +2361 ppm/a and with the ice thickness H = 600 m the vertical velocity results in the dynamical elevation change -1.42 m/a. The continuity condition postulates elevation change in spite of constant mass. The decreasing horizontal ice flow velocity at ST2 indicates a diminished in-flow into the ST2 area compared to the long-term equilibrium state. The geodetic mass balance (Figure 1, 4) is the result of all geometrically measurable effects including all dynamical and meteorological parts; SMB contains only the meteorological part.

The high quality of our digital terrain models are used for comparison with elevations and elevation change data from CryoSat-2 and TanDEM-X. The CryoSat-2 data were provided by Helm *et al.* (2014) with elevation change results between 1/2011 and 1/2014. Our comparison shows on average differences in temporal elevation change of 0.25 m/a (SWC) and 0.57 m/a (ST2). Few days after our



Figure 6. Height discrepancies (after best fit) between TanDEM-X (August 16th, 2014) and GPS ground measurements (August 5th, 2014). The marginal regions are not representative due to bad constitution of the DEM here.

ground measurements at Swiss Camp the TanDEM-X satellite had passed the same area. The DLR (Rott and Floriciociu, 2015) provided us with one (uncalibrated) digital elevation model (DEM) with a very good horizontal resolution of 5 m. After correction with a systematic offset of 3.14 m the best fit all over the area (1847 points) achieves on average the standard deviation 0.025 m and for one point 1.07 m. The residuals of these 1847 points amount mostly between +1m and -1m (Fig. 6).

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Comparing the Geodetic and Glaciological mass budgets of White Glacier, Axel Heiberg Island, NU

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White Glacier is a 14 km polythermal glacier extending from 50-1800 m a.s.l on western Axel Heiberg Island, NU. It hosts the longest mass balance record for

an alpine glacier in the Canadian Arctic, now exceeding 50 years. In this study, we conduct a reanalysis of the mass balance record and update estimates of the systematic and random errors associated with generating geodetic and glaciological mass budgets. We compare the geodetically derived mass change of White Glacier from 1960 to 2014, with the cumulative results of glaciological mass balance observations.

The geodetic mass budget is derived from the volumetric difference between a 1:10,000 map of White Glacier created in 1960, and a new DEM created from aerial stereo-photographs collected in July 2014. Through careful co-registration, we minimized the uncertainty and systematic error to arrive at a geodetic balance of -9.05 \pm 1.69 m w.e. over the 54 year time period. Historically, the mass balance of White Glacier has been calculated using the hypsometry of the glacier at its 1960 extent with a localized update to the glacier geometry below 400 m a.s.l. in 2003, resulting in a cumulative reference balance of -11.35 m w.e.. To account for changing glacier geometry through time, we homogenize the glaciological mass balance observations through conversion to conventional balances using estimates of the changing glacier hypsometry. Over 54 years we find a resulting cumulative conventional balance of -11.26 \pm 2.73 m w.e.. We discuss the discrepancy between the geodetic and cumulative glaciological mass budgets, which in part reflects the generic differences between the two methods.

Dynamics and Changes in Extent of Bylot Island and Barnes Ice Caps, Nunavut, Canada

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Recent studies indicate a sharp increase in glacier mass wastage from the Canadian Arctic due to higher summer air temperatures (Gardner *et al.*, 2012; Sharp *et al.*, 2011). Previous comparisons of aerial photography and Landsat imagery indicate that between 1959/60 and 2000 the Bylot Island and Barnes Ice Caps decreased in areal extent by ~5% and ~2%, respectively (Sharp *et al.*, 2014). However, little is known about the detailed patterns within this period, or how these ice caps have changed since the start of the 21st century. To address these issues, we digitized the extents of these ice caps using Landsat 8 imagery acquired in the summers of 2013/2014, and used historical Landsat data to digitize the extent of both ice masses in each decade from 1980-2000. The Bylot Island Ice Cap total ice area decreased by ~3.8% between 1975 and 2013/14, with most ice loss concentrated on small, low elevation glaciers. The Barnes Ice Cap total ice area decreased by ~3.4% between 1980 and 2013/14, with most ice loss occurring in the stagnant northwestern region of the ice mass.

To determine the complete surface velocity field of each ice cap for the first time, we utilized speckle tracking of ALOS PALSAR (2007-2011) data. Generally, surface glacier velocities of the ice masses of Baffin and Bylot Island are low, with peak velocities of ~100 m a⁻¹ and mean velocities of ~30-60 m a⁻¹. The measured velocity structure reveals that peak velocities tend to occur near the

equilibrium line altitude on Penny and Bylot Island Ice Caps, while the fastest velocities on all other glaciers usually occur near the terminus due to relatively large accumulation areas draining through narrow outlets. These glacier velocity results provide baseline data from which future changes in ice dynamics can be detected, allow for the calculation of iceberg calving fluxes from the regions tidewater glaciers, and can be used as inputs for glacier flow models.

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Cascading effects of sea ice losses on the formation and preservation of tidewater glacier tongues and ice shelves on northern Ellesmere Island, Nunavut, Canada

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According to the study of Koenig et al. (1952), it was proposed that the ice shelves of northern Ellesmere Island form from floating tidewater glacier ice tongues that extend into sea ice and coalesce with other ice tongues. Observations on current ice shelves, such as the Milne and Petersen, suggest that glacier inputs may be locally important, but to date no assessment has been made of the controls on ice tongue formation and preservation on northern Ellesmere Island. Reports from early explorers (e.g., Peary, 1906) and observations of ice islands suggest that an ice shelf filled Yelverton Bay and its southern regions, Kulutingwak Fiord and Yelverton Inlet, until the 1940s. Field observations, aerial photographs (1950, 1959) and SPOT satellite imagery (1987) reveal that multiyear landfast sea ice (MLSI) filled Yelverton Bay after this, with eight glacier tongues (up to 4 km long) flowing into Yelverton Inlet and Kulutingwak Fiord. Observations of Landsat and ASTER satellite imagery reveal that partial losses occurred from most glacier tongues between 2003-2004 and again between 2005-2007. An open water event in summer 2008 led to the complete loss of glacier tongues (up to 4 km long) at the northern end of Yelverton Inlet, while an open water event in 2011 caused the complete loss of the remaining glacier tongues at the southern end of the inlet, including the entire glacier tongue (\sim 15 km) at the front of Yelverton Glacier. The timing of these losses was associated with the loss of >690 km² of MLSI from Yelverton Bay in August 2005, followed by removal of multi-year landfast sea ice (MLSI) from Yelverton Inlet and Kulutingwak Fiord in summers 2008 and 2010. Based on these losses, it is clear that perennial sea ice plays a crucial

role in stabilizing glacier tongues. Once this perennial sea ice is lost the floating portion of ice tongues are no longer preserved, thus disabling their ability to thicken amongst sea ice and potentially facilitate ice shelf formation.

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Capabilities of the Sentinel-1 SAR mission for operational monitoring of ice sheets

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Numerous studies indicate large and rapid changes on the Greenland Ice Sheet (GIS) in the last decade in response to changing boundary conditions, including record surface melt and dynamical changes of marine terminating glaciers. As a result the contribution of the GIS to global sea level rise has increased significantly. With the launch of the first satellite of the European Sentinel-1 SAR satellite series in April 2014, glaciologists are provided with a new tool to remotely measure ice flow velocity and monitor calving fronts and grounding line deformation. These are key parameters to determine calving fluxes and the dynamic response of the ice masses to climate forcing and to changes in mass balance.

In full deployment the Sentinel-1 mission is a constellation of two identical operational SAR satellites offering unique capabilities for regular and comprehensive repeat observations of the global ice masses. The Sentinel-1 satellites carry a Cband synthetic aperture radar instrument providing high resolution SAR images in different acquisition modes, including the Interferometric Wide-Swath mode (IWS), which will be the main acquisition mode over land areas. Data is acquired across 250 km swaths at a spatial resolution of about 5 m x 20 m. We use 12-day repeat pass SLC images of Sentinel-1 A acquired in autumn 2014 to obtain ice flow velocity fields of several large Greenland outlet glaciers. We apply an iterative offset tracking approach, permitting to acquire the full range of velocities in a single swath while keeping the matching window at a minimum. The results are compared with ice flow velocity fields derived from repeat pass data of other sensors, including ALOS PALSAR and the TerraSAR-X mission. Combined these data sets allow for a unique assessment of ice-velocity changes in recent years and highlights the potential of Sentinel-1 for ice sheet monitoring.